THERMAL PERFORMANCE PARAMETERS OF SOLAR COOKERS: A STUDY LEADING TO GENERALIZATION

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Abstract

Solar energy is one of the environmentally friendly energy sources that has always been available to the human kind and has immense potential to provide free energy to the low socio-economic habitats in rural areas of the developing countries such as India. Out of a range of solar energy applications solar cooking promises to be one of the cheapest, the most popular and having direct impact on the socio-economic development of rural masses of developing countries endowed with abundant solar energy. To harness solar energy for cooking purposes many types of cookers have been developed which, on the basis of the most dominant feature, may be classified into three types - (i) Indirect or box type, (ii) Direct or focusing type, and (iii) Advanced type. Each of these designs has its basic strength making it suitable for a particular cooking mode, location and food habit. Attempts to improve the designs have been made with limited impact. Non-availability of proper performance parameter to assess the performance of each of these designs may be one of the reasons. It may be noted that an improved design through a sound technological approach and local sensitivities may be able to address some of the problems faced in introducing new designs.

Several performance parameters and their corresponding test procedure are proposed in the literature to evaluate the performance of a solar cooker; however, they all suffer from one weakness to another. All these thermal performance parameters (TPPs) and test procedure (TP) have been claimed and reported for only one of these three types of cookers with the majority catering to Indirect or Box type.

Solar cookers, like any other solar device, inherently need a storage system, generally integrated, to address the problem of spoilage of food due to small

unpredictable and intermittent reduction/interruption in the radiation In the absence of any TPP and test procedure for such designs the thermal performance of latent heat storage system is evaluated through comparative analysis with an identical cooker without any storage system as bench mark The results of comparative analysis cannot be duplicated and/or repeated So there should be an absolute test procedure and TPP(s) should have absolute values which are dependent only on design parameters and independent of operational and climatic variables They should also provide a value which is inclusive/holistic i e which reflects the performance of the integrated system

For locations with low annual mean solar radiation some additions/modifications in the cookers' optical system is required to maintain the radiation flux above a required minimum level Most of these improvements may not get reflected in the values of existing TPP(s) because of the basic considerations in their development and highly design specific test procedure(s)

As stated above it is difficult to compare the performance of two cookers of the same type if small improvements in design and/or new features are incorporated Ideally there ought to be a test procedure that is based on certain thermal performance parameters that are dependent only on design parameters but independent of operational and climatic variables such that the performance of a solar cooker can be evaluated independently irrespective of its size, type and features This is in this context that the current thesis proposes guidelines to develop generalized thermal performance parameters (GTPPs) and generalized test procedure (GTP) for studying and comparing the performance of any types of solar cookers and their improvised variants

In addition to the analyses of these issues in detail the present thesis proposes some performance parameters to correlate and examine the existing TPPs for cookers of type (i) and type (ii) represented basically by common Box type cooker (BC) and Paraboloid concentrating cooker (PCC) Initially a generic approach has been adopted to propose, develop and analyze a new set of TPPs for only one type of cooker, namely PCC It is complemented with a corresponding test procedure To make it more general the measurable parameters and TP were developed very carefully The result was that the same TPPs and TP could be successfully used to test box type cooker as well. As it is beyond the scope of the present work to design all types of cookers the same TPPs and TP were carefully analyzed and found to be suitable for other cooker designs as well. The main objective of the work is to develop TPPs which are cooker-type independent, responsive to new features, holistic/inclusive and absolute, in addition to having a simple, absolute and generalized test procedure (GTP). Hence to further establish the TPPs and TP a new and innovative design change was introduced in the pot of box type cooker. The positive response of the TPPs to the new design enhanced the confidence level in the proposed TPP to declare them as GTPPs.

The report consists of seven chapters and three appendices

In chapter-1 a detailed literature survey with regard to cooker specific TPPs and test procedures for their determination has been done with a view to provide rationale of the work and to set the objectives.

Chapter-2 aims to correlate the existing TPPs For this a set of performance parameters named as Objective Parameters (OPs) have been proposed These are – i) Maximum achievable temperature, ii) Reference time, and iii) Heat retention duration

In chapter-3 attempts have been made to develop TPP(s) for CC from the basic HWB equation For CC, two TPPs considered to be more basic, simple and holistic have been proposed For their determination a generic and simple test procedure has been employed

Chapter-4 is dedicated to examine the employability of the two TPPs proposed earlier for PCC, to BC as well An attempt has been made to develop a common test procedure to determine them. A new parameter termed as Cooker Opto-thermal Ratio (COR), has also been defined.

Chapter-5 explores the possibility of generalization of the TPPs and test procedures for the cookers of all the three types. For generalization the parameters needed for determining TPPs and conditions set for carrying out the test must be same for all types of cookers.

In chapter-6 a new design for box type cooker is proposed. After that the cooker is evaluated using the proposed generalized TPPs and the corresponding test procedure

Chapter-7 concludes about the strengths and discusses about the scope of improvement in the proposed GTPPs and the GTP in carrying out inter-cooker and intra-cooker comparison

Appendix-I discusses about the possibility and merits of using photo catalysts in the case of box type cookers

In Appendix-II, the possibility of using plastic cover in place of glass cover in box type cooker is discussed

Appendix-III includes the details of existing thermal performance parameters for concentrating cookers and test procedure for their determination

DECLARATION BY THE CANDIDATE

The thesis entitled "**Thermal performance parameters of solar cookers: A study leading to Generalization**" is being submitted to the Tezpur University in partial fulfillment for the award of the degree of Doctor of Philosophy in Energy is a record of bonafide research work accomplished by me under the supervision of Dr. S. K. Samdarshi, Professor. Dept. of Energy, Tezpur University.

All helps received from various sources have been duly acknowledged.

No part of this thesis has been submitted elsewhere for award of any other degree.

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All helps received by him from various sources have been duly acknowledged.

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List of publications

1. Lahkar, P J., Samdarshi, S K., A review of thermal performance parameters of box type solar cookers and identification of their correlations, Renewable and Sustainable Energy Reviews 14, 1615-1621, 2010.

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4. Lahkar, P.J , Samdarshi, S.K., A generic test procedure for estimation of thermal performance parameters and their correlation with objective parameters for parabolic concentrator cooker, in the proceedings of National Convention on Renewable Energy, National Conference March 2010 at Tezpur University, Tezpur , Assam India

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Nomenclature

A	: Absorber area (m^2)
A_c	: Aperture area (m^2)
A_{ca}	: Collector area (m^2)
A_g	: Glazed surface area (for BC) (m^2)
A_t	: pot surface area (m^2)
C	: Concentration ratio
C_{pa}	: Specific heat per unit volume at constant pressure of the mixture
C_R	: Heat capacity ratio.
C_u	: Specific heat of cooking utensil (J/kg/°C)
C_w	: Specific heat Capacity of water (J/kg/°C)
C_1, C_2, C_3	: Coefficients used in equation (2.12)
D_i	: Inside diameter of the pot (m)
D_o	: Out side diameter of the pot (m)
F	: Fin efficiency factor
F'	: Heat exchange efficiency factor / Collector exchange efficiency factor.
F_1	: First figure of merit (m^2 K/W)
F_2	: Second figure of merit
G	: Solar irradiance (W/m^2)
$\overline{G}$	: Average solar radiation (W/m^2)
$\overline{G_b}$	: Average solar beam radiation on the plane of aperture (W/m^2)
G_{NR}	: Reference direct normal radiation (W/m^2)
$\overline{G_T}$	: Average total solar radiation on the plane of aperture (W/m^2)
Gr	: Grashof number
h_c	:convective heat transfer coefficient (W/m^2-K)
h_e	: mass transfer coefficient

h_{fi}	: Heat transfer co-efficient from fluid to inner wall of the pot (W/m^2-K)
h_r	: Radiative heat transfer coefficient (W/m^2-K).
h_w	: Wind heat transfer coefficient (W/m^2-K).
K	: Thermal conductivity of the pot (W/m -K).
L	: Length (m), spacing
M	: Mass / Mass of water,(Kg).
M_1	: Mass of water for BC (Kg)
M_2	: Mass of water for PCC (Kg)
N	: Number of pots.
Nu	: Nusselt number
P	: Cooking power (Watt)
P_s	: Standard cooking power (Watt)
P_T	: Total gas pressure (kg/m^2)
Pr	: Prandtl number
$\dot{Q}''$	: Rate of heat gain or loss /area (W/m^2)
$\dot{Q}_{in}$	: Energy absorbed (W/m^2)
$\dot{Q}_L$	: Total heat loss from the cooker (W/m^2)
$\dot{q}_f$	: Rate of heat added to the fluid.
S	: Absorbed radiation per unit area of unshaded aperture (W/m^2).
t	: Time interval (sec., unless otherwise specified), thickness (meter)
t_b	: Thickness of insulation
t_o	: *Decay constant in min.*
T	: Temperature (°C)
$\overline{T}_a$	: Average ambiant température (°C)
T_{m12}	: arithmetic mean temperature of absorber plate and glass cover.
T_{m23}	: arithmetic mean temperature of glass cover 1 and glass cover 2.
T_{ps}	: maximum plate surface temperature. °C
T_{px}	: maximum absorber plate temperature. °C

T_{fx}	: maximum achievable fluid temperature. ^oC
dt	:Time interval (sec)
ΔT	: Temperature difference (^oC)
U	: heat loss (W/m^2)
U_L	: Total heat loss factor.
$F'\eta_o$	: Optical efficiency factor.
$F'U_L$	: Overall heat loss factor (W/m^2K)
α	: Absorptivity.
β	: Collector tilt from the horizontal.
γ	: Intercept factor.
ε_g	: emittance of the glass plate.
ε_p	: emittance of the absorber plate.
ε_{eff}	: effective emmissivity
η	: Efficiency
η_c	: over all cooker efficiency
η_{opt}	: optical efficiency
η_u	: Utilizable efficiency
η_{io}	: *instantaneous* oven efficiency.
σ	: Stefen –Boltzman constant (W/m^2K^4)
τ	: Time interval, sec, unless otherwise specified, transmittance
τ_o	: Time constant, hrs, unless otherwise specified
τ_r	: Time taken to achieve a reference cooking temperature, min (unless otherwise specified)
τ_{hr}	: Duration of heat retention, min (unless otherwise specified)
$(\tau\alpha)$	: Transmissivity-absorptivity product.
ρ	: Specular reflectance

Subscripts:

a	- air, ambient
b	- bottom
c	- characteristic, cover,
c_1	- glass cover 1/ cover 1

c_2	- glass cover 2/ cover 2
f	- fluid
g	- glass
i	- insulation
io	- instantaneous oven
m	- mean value
opt	- optical
p	- absorber plate
p_1	- plate to glass cover
s	- specific, side
s in	- concentrator to oven
t	- top, thickness
u	- utensil, useful, utilizable
w	- water, water vapor, width
wg	- water to glass
w_1	- initial
w_2	- final
12	- glass cover 1 to glass cover 2
2a	- glass cover2 to ambient

Symbols used in programming and equations :(Appendix II)

ε_c	:emissivity of glass
e_p	: emissivity of absorber plate.
t_g	: thickness of glass.
k_g	: conductivity of glass.
k_p	: conductivity of plastic.
th_p	: thickness of plastic.
tau	: transmissivity of plastic (Teflon).
e_{pa}	: emissivity of plastic.
rauc	: reflectance of plastic.
t_a	: ambient temperature, °C.
tak	: ambient temperature in Kelvin.
tpm	: absorber plate temperature, in °C.
tpmk	: absorber plate temperature, in Kelvin.
sp	: gap between the cover plate.
ktap1	: thermal conductivity at temperature tap1.
hpc1	: convective heat transfer coefficient between absorber plate and cover plate 1.
hp12	:convective heat transfer coefficient between cover plate 1and 2.
hrpc1	: radiative heat transfer coefficient between absorber plate and absorber plate and cover plate 1.
hrc12	: radiative heat transfer coefficient between cover plate 1 and 2.
hrc2a	: radiative heat transfer coefficient cover plate 2 and ambient.
$1/qrc_1$-s	: ressitance between cover plate 1 and ambient.
tc1k	: temperature of the cover plate 1, Kelvin.
tc2k	: temperature of the cover plate 2 (here plastic), Kelvin.
tc1kn	: new temperature of cover plate 1 (after iteration), Kelvin.
tc2kn	: new temperature cover plate 2 (after iteration), Kelvin.
σ	: Stefen-Boltzmann constant
ε_g	: emissivity of glass

ε_{pa}	: emissivity of plastic
ε_{p}	: emissivity of plate
ρ_{c}	: reflectance of glass
β	: slope
ρ_{pa}	: reflectance of plastic
τ	: transmittance,
Sp	: Space between glass cover and plastic cover, meter.
h_{w}	: wind heat transfer coefficient. (W/m^{2}K)
k	: thermal conductivity of air, (W/mK)
k_{p}	: thermal conductivity of plastic. (W/mK)
k_{g}	: thermal conductivity of glass. (W/mK)
th_{pa}	: thickness of plastic, meter
t_{g}	: thickness of glass, meter.
L_{12}	: air gap spacing between absorber plate and glass cover, meter.
L_{23}	: air gap spacing between absorber plate and glass cover, meter.
Nu	: Nusselt number
P_r	: Prandtl Number
q_{t}	: rate at which heat is lost from the top,
R	: heat transfer resistance (K/W)
Ra'	: Rayleigh number,
T_{m12}	: arithmetic mean temperature between absorber plate and cover plate1 (K)
T_{m23}	: arithmetic mean temperature between cover plate1 and cover plate 2 (K)
T_{c1}, T_{c2}	: temperatures attained by the two covers,
T_{sky}	: effective temperature of the sky with which the radiative exchange takes place
T_{a}	: temperature of the surrounding air.

Abbreviations

AC	: Advanced type cooker.
ANOM	: Analysis of mean
ANOVA	: Analysis of variance
AOP	: Advanced Oxidation Process
OA	: Orthogonal Arrays
BC	: Box type cooker.
BEE	: Bureau of Energy Efficiency
CAZRI	: Central Arid Zone Research Institute
CC	: Concentrating cooker.
CVD	: Chemical vapour deposition
dB	: decibel
DoF	: Degree of freedom
ETC	: Evacuated tubular collector.
FPC	: Flate plate collector.
GT	: Gelatinization temperature.
GTP	: Generalized test procedure.
GTPP	: Generalized thermal performance parameter.
HRD	: Heat retention duration.
IME	: IME Co. Valsad, India.
MAT	: Maximum achievable fluid temperature.
OP	: Objective parameter.
PCM	: Phase change materials.
RT	: Reference time.
SPRERI	: Sarder Patel Renewable Energy Research Institute.
Temp.	: Temperature.
TPP	: Thermal performance parameter.
TP	: Test procedure
SoS	: Sum of the squares
S/N	: Signal-to-Noise

Chapter-1

Introduction

Chapter 1

Introduction

Energy is the life line of civilization. In the course of development of civilization the rate of energy consumption in all forms has been rising all over the world. This may be due to increase in population as well as change of lifestyle which attract people towards mechanization. So dependence on fossil fuel energy resources like oil, coal and gas as is increasing day by day. Increased use of fossil fuel not only reduces the earth's limited fossil fuel reserves, but also causes environmental problems both locally and globally. Considering future concern about the security of energy supply to sustain the economic growth, there is an urgent need to search for alternative energy sources, systems, and processes.

1.1. Solar energy resource:

Solar energy has emerged as the most important energy resource options with immense potential because it is renewable, abundant and environmentally conceivable. Its potential has been accepted since the age of composition of mythological books. Sun provides about 1367W/m^2 of energy flux outside the mean interface of earth's atmosphere. However earth's surface receives very less amount of solar energy flux as some portion of it is lost while passing through the air mass. Still the solar energy flux incident on earth's surface integrated over a few days is sufficient to meet the present global demand of energy in a year. It may be utilized fruitfully for a variety of applications in different sectors of human activities.

1.2. Applications of Solar Energy:

Mankind has been using solar energy for effortless domestic applications like drying of clothes, food products and comfort. Perhaps the first scientific application of solar energy is recognized in ancient architecture for human comfort. To utilize solar energy for various applications, its conversion into utilizable energy forms is necessary Now-a-days, Sun's energy offers a variety of viable energy applications through photo-thermal conversion, photo-voltaic conversion, photo-catalysis etc. The resultant energy forms are used for a range of purposes in industry, agriculture, household, transport and commercial energy needs as well as environmental remediation [1] Out of various conversion processes, conversion to thermal energy is the most simple and efficient process Thermal energy has got a number of applications such as water heating, desalination, drying, air-conditioning and cooking etc. [2]. For solar photo-thermal conversion a number of devices/ systems are available. They include collectors with and without concentrators, dryers, cooking ovens, solar ponds and various types of solar cookers The utilization of solar radiation by photothermal systems is independent of wavelength threshold: rather they absorb the complete solar spectrum These systems though provide low grade energy, their high efficiency and low cost makes them more attractive option compared to other solar conversion systems [1]. Amongst photo-thermal systems solar cookers are significant due to their much lower cost, high usability potential and wider social impact.

1.3. Potential of solar cooking:

Cooking is one of the main activities of the common people of the developing countries. A major part of the available energy is utilized for cooking purposes only [3]. Cooking alone consume 36 percent of the total primary energy consumption in India [4, 5]. Most of the energy requirement for cooking are met by non-commercial fuels, such as fuel wood; agricultural waste; and animal dung cake in rural areas, and commercial energy sources like kerosene; liquid petroleum gas (LPG); and electric energy in urban areas. The fuel wood requirement is 0 4 ton per person per year in India. Presently due to large scale deforestation and population pressure poor villagers have to spend roughly 8- 10 h a day in search of fuel wood as compared to 1-2 h earlier [4-6]. Also from the survey, it is found that at least 16 million hectares of forest is being destroyed annually due to cutting of fuel wood for cooking purpose which is causing indoor air pollution [5] as well as serious threat to the ecological balance [7]. If animal dung is not used as source of energy for cooking purposes then it can be used as fertilizer and it is equivalent to almost one third of India's fertilizer utilization [4] In urban areas the use of fossil fuel based commercial sources is putting immense pressure on national exchequer in terms of subsidy as their ever-rising demand is met mainly through import. Thus use of new and renewable energy sources can not only meet the growing demand of energy required for cooking purposes but also protect the environment. This has provided the needed motivation for the researchers to work on solar cooking.

To convert renewable energy into heat energy there is a need to develop a cooker which is cheap, portable and reliably efficient. Solar cooker is one of such device which converts solar energy to thermal energy at a temperature appropriate for intended cooking purpose. From the Indian perspective its suitability need not be overemphasized as we know that India is blessed with solar radiation with equitable spatial and temporal distribution [8]. The average solar radiation over India is 5 kWh $m^{-2}day^{-1}$. The maximum solar radiation is received by the dry parts of western Rajasthan. In the month of December, mean global solar radiation is 3.8 $kWhm^{-2}day^{-1}$ at New Delhi, 4.1$kWhm^{-2}day^{-1}$ at Kolkata, 4.4 $kWhm^{-2}$ day^{-1} at Jodhpur and 5 $kWhm^{-2}day^{-1}$ at Kodaikanal. During the period of November to February, i.e.in the winter season, the majority of Indian stations receive radiation between 4.0- 6.3 $kWhm^{-2}day^{-1}$. From March to May, which is summer season, the value increases between 5.0 to 7.5 $kWhm^{-2}day^{-1}$. The annual mean daily solar radiation received at Jodhpur being almost 6.0 $kWhm^{-2}day^{-1}$ [4, 9]. In the North-Eastern India, Tezpur, receives almost 4.39 $kWhm^{-2}day^{-1}$. Similarly at Titabor 4.46 $kWhm^{-2}day^{-1}$, Tocklai 4.586 $kWhm^{-2}day^{-1}$, Karimganj 5.025 $kWhm^{-2}day^{-1}$, Guwahati 4.967 $kWhm^{-2}day^{-1}$, Dibrugarh 4.52 $kWhm^{-2}day^{-1}$, Agartala 5.043 $kWhm^{-2}day^{-1}$, and at Imphal it is 5.127 $kWhm^{-2}day^{-1}$[8]. Therefore solar cooking may be a good replacement of conventional cooking for which an appropriate solar cooker is needed. This is particularly true for remote and rural areas where solar radiation is available at a large scale and there is a lack of assured and sustained other energy supply resources. Even when other conventional sources of energy are available, as in the case of urban areas, environmental and economic benefits dictate the implementation of new alternative energy techniques. In addition to cooking, solar cookers may also be used to pasteurize water, milk and other food items.

A number of solar cooker designs are available in the market but acceptability of solar cooker is limited. There are many factors that affect people's interest to solar cooking in addition to purely economic factors. Among these factors are access to availability of traditional cooking fuels, food preferences, cultural factors, operational ease and technical capabilities of cookers. However to address these issues related to gaining confidence of the people and to motivate them to use solar cookers, there is a need to develop many different solar cooker designs. The design needs to be suited to specific climates, customs and economic conditions. Notwithstanding the developmental efforts it needs to be preceded by a good fundamental understanding of the relationship between key design variables and performance of a solar cooker. Across the globe researchers have developed and fabricated several designs which have been categorized into different types based on most dominant design features.

1.4. Classification of solar cookers:

Solar cookers are classified on two basic factors

i) Based on dominant design factors

ii) Based on dominant mode of heat transfer.

1.4.1. Based on dominant design factors:

Based on the dominant design features they are classified into three categories.

i) Box type (BC), ii) Concentrating type (CC), and iii) Advanced type (AC) .

(i) Box-Type solar cooker (BC):

Sometimes it is also referred to as indirect heating type is shown in Fig1.1. It is considered to be the oldest one. Horace de Saussure (1784) is considered to be the father of the box type solar cooker. It is the most commonly used solar cooker type and is reasonably convenient to use. It essentially consists of a rectangular enclosure insulated from the bottom and sides and having double glass cover on the top. Solar radiation enters through the top and heats up the black-coated absorbing surface lining the rectangular enclosure of the cooker. The unique property of the glass having low transmissivity to long-wave radiation prevents the heat energy from escaping out. The food to be cooked is put in cooking pots (with outer surface coated black) which are placed on the absorber plate. Temperature around 100°C can be obtained in these cookers on sunny days and these are suitable for boiling type of cooking. These cookers are heat retention type. They are slow to heat up, but work well even where there is diffuse radiation, moderate wind driven convective heat, intermittent cloud cover and low ambient temperatures. They are able to keep food at a biologically safe temperature for up to about 3 h past sunset [10]. Reflectors (normally glass mirrors) are commonly used to augment the radiation flux falling on the cooker aperture. A single glass reflector whose inclination can be varied is usually attached to the box type solar cooker to enhance the performance of the cooker [11,12]. The addition of the reflector helps in achieving enclosure temperature which is higher by about 15 to 20°C. As a result the cooking time is reduced. Box type cookers are simple to use and require little tracking attention. As a result they have found the maximum acceptance amongst all the designs developed. Their performance may be enhanced by using more reflectors, which change their operations considerably [11].

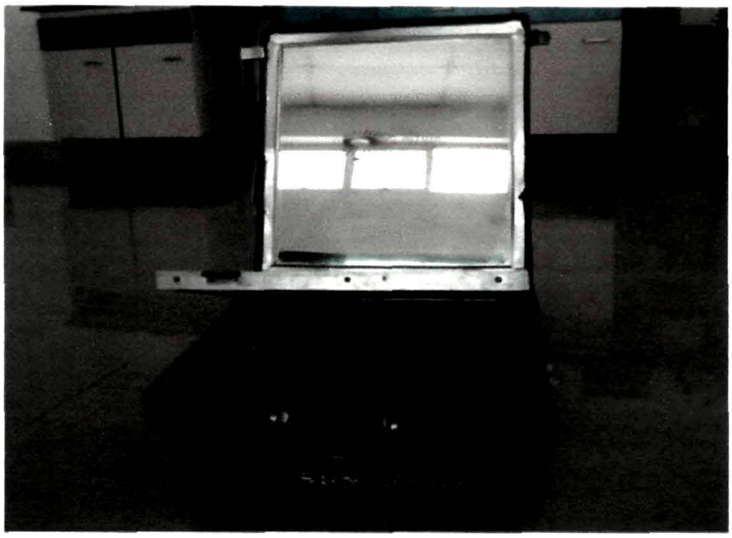

Fig.1.1: Photograph of BC with glass cover and single reflector

Different designs of BC:

Different designs of box type solar cookers are available. These have been developed to improve their performance.

a) Bottom heated BC:

Emed H Amer[13] designed and developed a box type cooker where absorber plate was heated from both top and bottom side(Fig 1.2). Top of the cooker was covered with two glasses through which solar energy flux could reach the absorber plate. The bottom of the cooker was also made transparent by placing one glass cover below the absorber plate. A gap is maintained in between glass cover and absorber plate with a layer of atmospheric air separating them. Two reflectors were placed below the cooker stand in such a position that solar radiation flux reached the bottom of the absorber plate after getting reflected by the two reflectors. The performance of this cooker improved as absorber plate received heat from both sides.

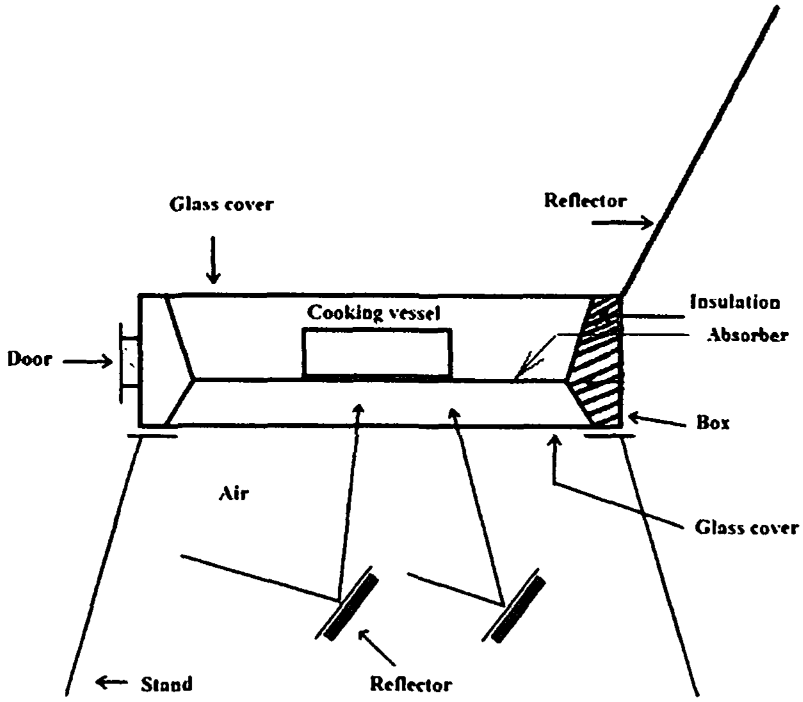

Fig:1.2. Schematic diagram of bottom heated cooker [13]

b) BC with different pot designs:

Gaur *et al.* [14] modified the shape of cooking pot lid used in box type cooker. They used concave shaped lid by replacing plain lid available in conventional pot. This modification was reported to increase the efficiency of solar cookers and reduce the cooking time by 10-13% compared to the time required for conventional cooking pot used in box type solar cooker.

Harmim *et al.*[15] designed a cooking vessel with externally fitted fin which improved heat transfer rate from cooker interior to the food item kept inside the vessel. This reduced the cooking time in comparison to the time taken by conventional cooking vessel

Narasimha Rao *et al.*[16] designed a cooking vessel with central annular cavity. Also they put the vessel on lug provided on the box cooker. By this method they got better performance from the cooker. The same group performed comparative test with conventional pot and observed that pot with central cylindrical cavity placed on lugs gave better performance in terms of temperature rise as well[17].

c) BC with non tracking twin reflector type:

To enhance solar energy collection by the absorber plate, Negi et al., [18] proposed a new design where two plane mirrors on an inclined set up facing E-W direction were employed. The design angle of inclination of the setup where mirrors were fitted was required to be equal to the latitude of the location where cooker is to be used and adjusted seasonally. These two mirrors worked as non-tracking concentrator. It could improve the thermal performance of the BC in terms of increased in stagnation temperature of absorber plate and reduction of cooking time.

d) Advanced box cookers:

An advanced box type cooker was designed and developed by Grupp *et al.*, [19]. The cooking vessel is kept in good thermal contact with absorber plate. The cooking pot was fixed into a hole in the glazing. Single fixed glazing was provided at the top. Three models were developed. In all the models the features mentioned above were the same. In addition to that in one of the modes, one booster mirror with inclined internal reflector was provided. The absorber plate was kept in elevated position. In second design straight internal reflectors were provided and absorber plate was kept at the bottom of the case. In the third one inclined internal reflectors were provided and absorber plate was placed on the bottom of the case.

The proposed systems were reported to show improved heat transfer to the cooking pot. Also one can have easy access to the cooking pot during cooking without disturbing the interior of the cookers.

e) BC with storage:

Mawire *et al* [20] developed a oil pebble bed thermal energy storage system for solar cooker.

Solar energy can be stored in a solar cooker with the help of phase change materials (PCM) as well. Buddhi and Sahoo [21] designed and tested a solar cooker with latent heat storage for cooking food in late evening. In their design, PCM was filled below the absorber plate. In such type of design, the rate of heat transfer from the PCM to cooking pot during the discharging mode of PCM is slow, and more time is required for cooking the evening food.

Sharma *et al.* [22] designed a cooking pot in which a PCM unit surrounded the cooking vessel. In this type of arrangement, the rate of heat transfer between the PCM and the food was higher and cooking was faster. They used commercial grade acetamide (melting point 82 °C) as a latent heat storage material. Cooking of three batches in a day during summer and two batches a day during winter is possible by using acetamide as PCM. From the experimental results it is concluded that the storage of solar energy does not affect the performance of solar cooker for noon cooking and if a PCM having melting point between 105 to 110 °C is used then night cooking is also possible.

Thermo physical properties of some of the PCM have been given in Table-1.1.which can be used as storage material for BC.

Table- 1.1: Thermo physical properties of phase change materials (PCM)[23]

	Melting Temperature (°C)	Latent heat of fusion (kJ/kg)	Thermal conductivity (W/m°C)	Specific heat (KJ/kg°C)		Density (Kg/m^3)	
				Solid	liquid	Solid	liquid
Acetamide	82	263	0.5	1.94	1.94	1159	998
Acetanilide	118.9	222	0.5	2.0	2.0	1210	1020
Erythritol	118.0	339.8	0.326	1.38	2.76	1480	1300
Stearic acid	69.4	199	0.172	1.6	2.2	965	848
Polyethylene glycol 600	20-25	146	-	-	-	-	-
Methyl fumarate	102	242	-	-	-.	-	-

(ii) Concentrating type or direct heating type:

The second category of solar cookers developed is those in which the radiation is redirected and concentrated by a reflecting surface. The cooking pot is placed at the focus of the concentrating surface and is thus directly heated. For this it utilizes multi-faceted mirrors, Fresnel lenses or parabolic concentrator to attain higher temperatures. A parabolic concentrating cooker is shown in Fig. 1.3. Normally they heat up quickly. The heat loss is more. To track the sun directional adjustment of the reflector is required at regular interval. Temperatures well above 200 °C can be achieved in such cookers. Various types of reflecting surfaces have been used. These include glass mirrors, aluminum sheet and aluminum foil. The main disadvantage of with these cookers is that they require continuous attention, as a result of which the operator has to be in the sun most of the time. Another disadvantage is that except for glass, the reflectivity of all other surfaces decrease with the passage of time. However designers have developed a range of configurations that allow new sets of design parameters to be manipulated /controlled. There are also few requirements for maintenance, particularly to retain the quality of optical systems for long periods of time in the presence of dirt, weather, and oxidizing or other corrosive atmospheric components. The combinations of operating problem and cost have restricted the utility of concentrating type cooker [24].

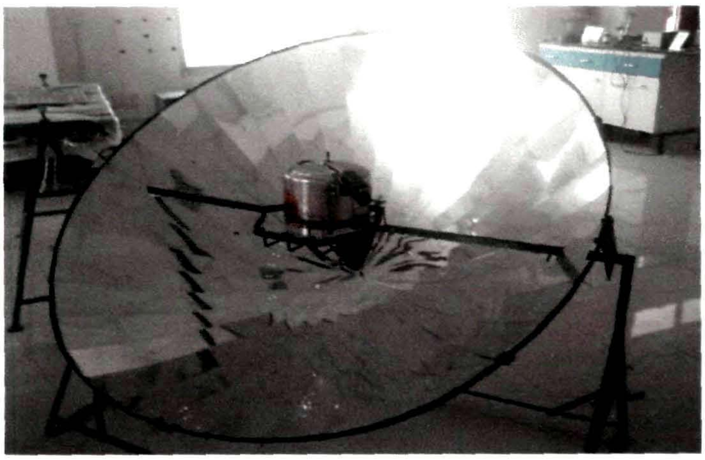

Fig.1.3. Photograph of Concentrating type cooker (CC).

As concentrating cookers are normally designed to utilize beam component of radiation so clearness of the reflecting surface is to be maintained for better performance. [25]. Vapor tight vessels are used in concentrating type cooker to avoid food spillage. Concentrating type cookers are invariably a variant derived from paraboloidal type concentrators.

Different designs of Concentrating type or direct heating type cooker (CC):

Different designs of concentrating cookers are available. These are

a) Paraboloidal CC
b) CC with Fresnel reflector
c) Oven type CC
d) Conical frustum type CC
e) Spherical type CC

a) Paraboloidal concentrator cooker:

Paraboloidal concentrator cooker, shown in Fig. 1.3, is one of the most common design of CC. Its surface is produced by rotating a parabola about its optical axis. The receiver of a paraboloid can be spherical, flat, cavity shape, or spherical segment. The paraboloid suffers from chromatic and spherical aberrations found in optical components. A degraded image is obtained with paraboloid if the object is off-axis. A three dimensional image of the sun of the shape of an ellipsoid is formed by the paraboloid because the reflected rays travel different distances in arriving at the focus [26].

Solar concentrators have some advantages like: Improved thermal efficiency by reducing heat loss area and also reduction in transient effect compared to flat absorber plate used in box type cooker; increased energy delivery temperatures, thus achieving a thermodynamic match between temperature level and task; reduced cost due to replacement of an expensive large receiver by less expensive reflecting or refracting area [26].

Patel *et al.* [27] reported the performance of a German cooker which was paraboloidal concentrator type with aluminum film as reflector material. The spot focus available in case of paraboloidal cooker led to a localized high temperature leading to food burning and accidental burns to the user. The aperture area was 1.45 m^2 and focal length was 0.36 meter. The cooker used cylindrical aluminum pot having 4.5 liters capacity.

Hosny *et al.* [28] reported about paraboloid dish solar cooker. It was constructed from 0.8mm highly polished stainless steel sheet with reflectivity of 0.75. The aperture area was approximately 1 m^2 and focal length was 0.45m. Two receivers were used in this cooker. One was a aluminum pot of 0.2m diameter and 0.09m height for boiling type of cooking and another a tray of size 0.15 x 0.15 m^2 for frying and grilling of food. Tracking was needed every 10 to 15 min interval.

Ozturk *et al.*[29] designed a parabolic cooker (CC) made of steel and Cr-Ni alloy sheet. Cr-Ni alloy sheet was screwed on the structural frame of the CC. The thickness of Cr-Ni sheet was 0.5mm. In the centre of the concentrating reflector a cooking pot 10cm in width and 5cm in depth was welded. The cooking pot was made of galvanized steel sheet of 0.5cm thickness. The outer surface of the cooking pot was painted with matt black. The Cr-Ni alloy sheet acted as reflector to concentrate the sun's rays on the cooking pot. The emissivity of the cooking pot was 0.87 as reported

Al-Soud *et al.* [30] designed and developed a parabolic solar cooker with automatic two axes sun tracking system. A programmable logic controller was used to control the motion of the solar cooker. Introduction of automatic sun tracking system made it useful for developing countries where ambient temperature and intensity of solar radiation is very high.

Badran *et al* [31] designed a portable solar cooker-cum-water heater in which a satellite dish lined with aluminum foil as reflector was used as concentrator. In cooking mode, the cooking pot was placed at the focus of the reflector and in water heating mode a collector was placed at focus of the concentrator. The storage tank was connected with the collector through pipe. Thus water could be heated which could be used for domestic purposes.

b) CC with Fresnel reflector

Sonune *et al.* [32] designed and developed a Fresnel type domestic concentrating cooker. The cooker had an aperture area of 1.5m^2 and focal length of 0.75 m. This cooker was able to provide an adequate temperature required for cooking frying and preparation of chapattis for 4 to 5 persons. This cooker was reported to be suitable for average middle class family.

Patel et al [27] have reported the performance of three different types of concentrating cookers. Out of these two of them namely, Philipines and Chinese, used Fresnel concentrator. The Philipines cooker used Fresnel mirror with aluminum film as reflector material. The aperture area of the cooker was 1.16m^2 and focal length was 0.76 meter. Studies conducted over them showed that Fresnel reflector was more appropriate for cooking applications as the heat gets distributed over a large area on the cooking vessel. The Chinese model also used Fresnel mirror with aluminum film as reflector material. The focal length of this cooker was 0.86 meter and aperture area was 0.96 m^2.

c) Oven type:

Habeebullah *et al.*[33] reported an oven type CC. For collecting the concentrated solar energy to boost the overall cooker efficiency, they designed oven type cooking pot. Better heat transfer could be ensured by heating the pot from bottom and sides similar to conventional CC cookers. The free suspension of the pot prevented spillage of the food which is a common problem in some of the concentrating type cookers. By minimizing the loss of vapor through the cooking pot, it is possible to cook food item with less water and thereby additional saving of energy is possible. Inclusion of insulated pot made it possible to perform cooking operations like frying, roasting, baking etc. also.

Khalifa *et al.* [25] developed a new oven type cooker consisting of a spiral concentrator and insulated hot box with glazed bottom. The spiral concentrator acted as a reflector and insulated hot box was placed at the focus of the reflector. The reflected radiation heats up the pot from its bottom and sides. Thermal performance remains unaffected by wind since the oven is insulated and wind shielded.

d) Conical frustum type:

The conical frustum cooker, designed by Sharaf, E. [34], had a cone with the internal wall covered by a reflective material. The end with large opening received the sun rays while with the small opening end was blocked where the rays reflected from the internal surface get concentrated. The concentration at the focal plane is useful for practical applications like cooking, boiling water etc. In this cooker food and water could be heated from both upper both upper and bottom side. The conical solar cooker was light in weight, easy to manufacture, low price and was suitable for cooking different kind of food.

e) Spherical type:

In this a spherical dish was used. Concentrating mirrors lining its surface convert it to a concentrator. The cooking pot is placed at the focus of the dish.

Malough *et al.* [35] designed, developed and tested a spherical solar cooker with automatic two axes sun tracking system. The cooker was a spherical dish where a total of 256 concentrating mirrors were fixed to collect solar radiation flux by using silicon glue. A pan was fixed at the focus of the dish. By providing automatic sun tracking system it was possible to keep the sun light beam normal to the dish at any time of the day.

(iii) Advanced type or hybrid type cooker:

The third category of solar cooker is the advanced type. This uses a heat transfer fluid to carry thermal energy from the point of collection to the cooking vessel(s). They are suitable for remote energy collection, which is useful for indoor cooking applications, but are comparatively more expensive to produce. The collector of this type of cooker is flat plate type, evacuated tubular type or concentrating type. The advantage of this type cooker is that it yields higher temperature than the box type cooker because of the use of a variety of collectors such as unobstructed concentrating collector, a selectively coated evacuated tubular collector and flat plate collector with booster mirrors. It can, therefore, be used for cooking of large variety of items. In addition to this the cooking area can be at a small distance from the collector and cooking need not be done in the sun. Cooking is also possible in the evening with the inclusion of a storage device.

Different designs of Advanced type solar cooker:

a) AC with FP collector and convective heat transfer

Hussein et al [36] constructed an advanced type solar cooker where heat receiving unit i.e. collector was kept in sun to collect solar radiation flux and transfer the heat using a heat transfer fluid i) to a phase change material(PCM) to store thermal energy as well as ii) to the cooking pot kept inside the kitchen. The collector was flat-plate type and to enhance the solar radiation two plane reflectors were fitted with the collector. By this arrangement, it was possible to cook food during noon, afternoon and evening. The heat storage device helped in keeping food warm at night and early morning also.

Prasanna *et al.* [5] proposed a hybrid solar cooking system where heat was transferred to the kitchen by means of a circulating fluid from the collector. Energy collected from the solar thermal collector was optimized by dynamically varying the flow rate using maximum power point tracking technique. A storage tank was placed in between the collector and receiver. For temperature requirements of less than 100°C flat plate collector could be used and for more than 100°C concentrating collector could be used.

b) AC with ETC Collector and convective heat transfer:

Mahmet Esen [37] designed an advanced type solar cooker where collectors were vacuum tube. Heat pipe containing refrigerants were used as working fluid to carry the heat to cooking chamber from collector. The advantage of using evacuated tube was that it provided high thermal power and temperature without tracking.

c) AC with concentrating collector and radiative heat transfer:

Another advanced type cooker is **Scheffler cooker** without mentioning which discussion on cooker will be incomplete.

Scheffler cooker: The Scheffler solar cooker was invented by Wolfgang Scheffler. Scheffler cooker facilitates cooking in the kitchen. These cookers can supply heat directly to cooking pot or heat can be gathered in a high heat capacity body for cooking later on. The cooker consists of a reflector which is a small lateral section of much larger parabolic concentrator. The reflector is of typical elliptical shape. Sun light falling on this section is reflected to the focus some distance away from the reflector. The tracking mechanism of this cooker is automatic one. Once it is started after adjusting the focus in morning time, the reflector rotates slowly all the day along with the sun with the help of automatic tracking control mechanism. Thereby it keeps its focus on the one spot of the cooking place, i.e. kitchen throughout the day. The axis of rotation of the reflector passes through the centre of the reflector and precisely in north-south direction, which is parallel to earth's axis. For seasonal tracking the reflector rotates at half the solar declination angle with the help of telescopic clamp mechanism [38]. A schematic diagram of Schaffler cooker is shown in fig.1.4.

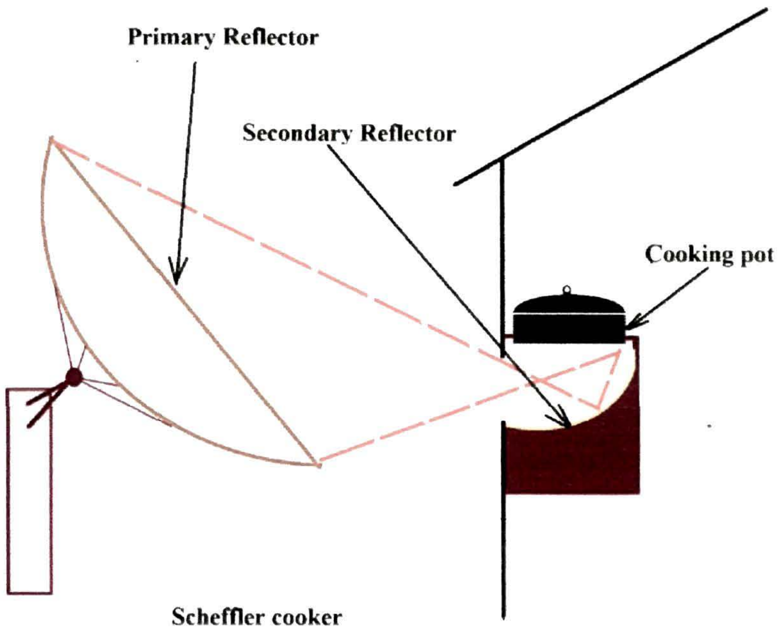

Fig.1.4:Schematic diagram of Scheffler Cooker

1.4.2. Classification based on the dominant mode of heat transfer:

In the present work an attempt has been made to classify the cookers based on the most dominant mode of heat transfer to the cooking pot. Solar cookers, hitherto, have been classified on the basis of the design features.

Type-I : In Box type (BC), the heat is transferred either through absorber plate to pot conductively or through hot air trapped in the cavity convectively. A large portion of the heat is transferred to the cooking pot/surface from the absorber plate by conduction mode as shown in Fig 1.5. So box type or indirect heating type cooker can be called as conduction heating type or simply *conduction type cooker*.

Type-II: As shown in Fig. 1.6 in direct heating type or concentrating type cooker, most of the heat from concentrator to cooking pot/surface is transferred by radiation. So this type of cooker can be named as radiative heating or *radiation type cooker*.

Type-III: In advanced type cooker the heat transfer is taking place to cooking pot/surface from collector fluid is by convection as shown in Fig.1.7. So this type of cooker can be named as convective heating type or *convection type cooker*. Here Scheffler cooker is an exception and may be put under the radiative type.

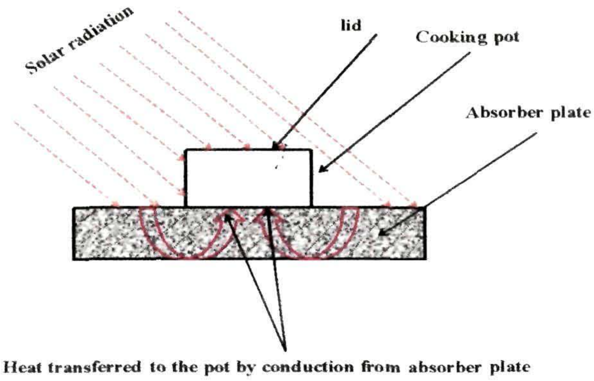

Fig.1.5: Schematic diagram showing heat transfer to cooking pot from absorber plateby conduction mode.

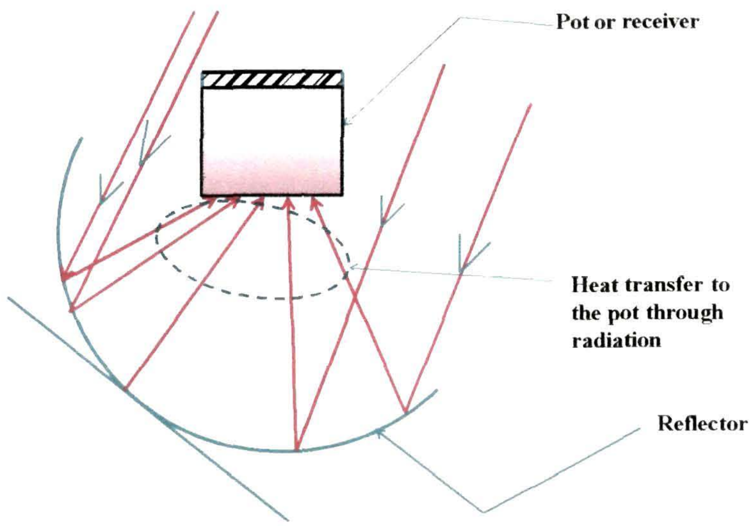

Fig.1.6. Schematic diagram of radiative mode of heat transfer

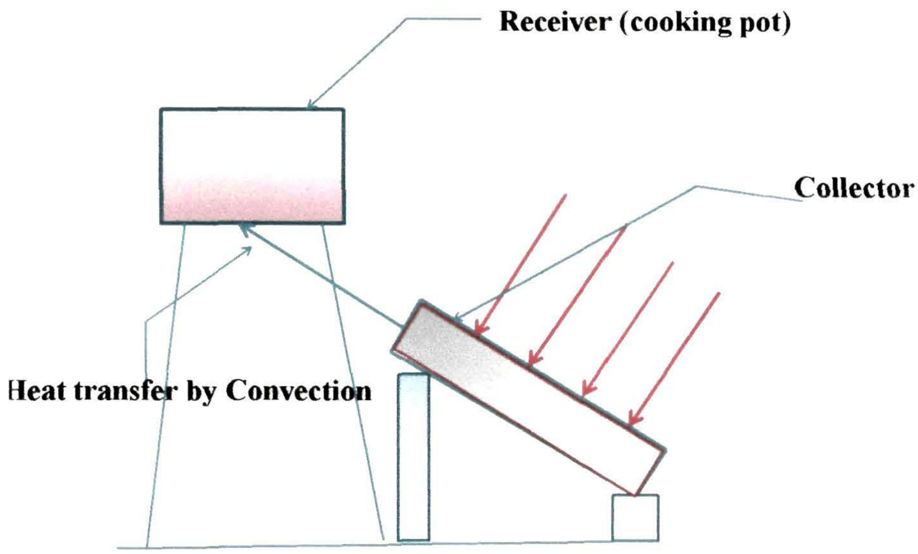

Fig. 1.7: Schematic diagram showing heat transfer to cooking pot by convective mode.

1.5. Acceptability requirements of solar cooker:

For a solar cooking system to be accepted and approved in the most of the households the following objectives are to be satisfied

i) It should be possible to carry out all types of cooking i.e. boiling, roasting, frying etc.
ii) There should be surety of accomplishment of cooking within a pre-assessed time frame.
iii) It should enable cooking to be carried out at any time during a wider cooking time window.
iv) Time taken for cooking must be comparable with the conventional cooking.
v) The cooking should be possible inside the kitchen.

In order to satisfy all the above mentioned objectives an integrated system having the best features of all the three types of cooker may be needed. If needed a hybrid solar cooking system may be proposed wherein solar energy is transferred to kitchen to supplement the conventional cooking fuel [3, 5].

1.6. Need of Thermal Performance Parameter (TPP) and corresponding Test Procedure (TP) for a solar cooker:

TPP is needed to objectively asses the solar cookers capability to fulfill the acceptability requirements,

Thermal efficiency is an established TPP for solar thermal collectors of different types. Different test procedures to determine them and methods to represent them in have been developed in the course of time [39-41].

Any TPP is uniquely defined and has the following objectives:

i) to predict thermal performance of a solar system.

ii) to help the designers in comparing the existing and projecting the future solar collector design performance.

The TPs are developed with an aim to achieve the following.

i) It should have simple and accurate experimental method based on facile data collection process and equipments.

ii) It should provide an absolute value of TPP which should fulfill the above mentioned objectives.

iii) It should be reliable and repeatable.

The TPs may have two different approaches [42]

i) **Comparative test**: The system is tested simultaneously against a standard system having identical size and type. The relative values of the TPPs are used to evaluate the performance. But it is not always possible to have a standard system.

ii) **Absolute test:** The system is tested under uniquely defined conditions to provide an absolute value of TPP. This value may be used to determine the performance for design predictions and for comparison.

Solar cooker is also a type of solar thermal collector. Instantaneous thermal efficiency has unique value as a TPP but may have limited utility in solar cookers because

i) It is temperature dependent.

ii) Cooking is accomplished at above certain temperatures.

iii) Cooking takes time for accomplishment at the temperature of cooking.

Many TPPs and TPs have been developed with an aim to address these issues.

1.7. Review of Literature:

Different designs of solar cookers and their thermal performance parameters with testing methods for their determination have been reported. The TPPs and corresponding TP developed by different workers available in the literature is being presented.

Mullick *et al.* [1987] proposed two TPPs and standard test procedures for their determination for box type solar cookers. The TPPs are *first figure of merit* F_1 *and second figure of merit* F_2. F_1 is determined by conducting no load test and F_2 by conducting sensible heating test of water [43]. Later his group proposed a test method called semi log plot method for determination of F_2 [44]. These TPPs have been used by many researchers to test their BCs [45, 46]

Nahar *et al.* [1993], designed, and developed a community size solar cooker. The performance of the cooker was tested and compared with a single reflector hot box solar cooker in terms of ***temperature-time profile***. Same performance was found in both the cases. No specific thermal performance parameter (TPP) has been proposed here [9].

Beaumont *et al.* [1997], designed and developed a family size low cost cooker. They identified *cooking time of different food items* as the performance parameter [47]. A comparative test procedure was followed by them. Later on other workers also reported the performance in terms of cooking time of different food items [48].

Funk [2000] reported *standard cooking power* (P_s) as performance parameter and developed test procedure for its determination which was termed as international standard. The test was performed on box type cooker (BC) with some assumptions [10]. Performance of each cooker was reported by a unique temperature dependent P_s profile.

Nahar, N.M. [2001] designed and fabricated another hot box type solar cooker (BC) with double reflector and transparent insulation material (TIM). TIM was placed between two glazings. Here *efficiency* was considered as one of the TPP and it was observed that efficiency was more for cooker having TIM than the one without TIM [6].

Amer, E.H.[2003] designed developed a box type solar cooker (BC) which was exposed from both bottom and top side. Solar radiation was allowed to fall with the help of reflector from bottom and top side. The maximum *plate stagnation temperature* which was considered as one of the TPP was measured and compared with conventional box type cooker with one reflector. Their design showed better performance. Another TPP considered was *cooking time*. The cooking time was also compared with conventional cooker and found that the design proposed by them took less time to boil water than the conventional one [16].

In 2003, Nahar, N.M., designed a box type solar cooker (BC) where heat was stored by putting engine oil for evening cooking. In this work *efficiency* was again used as TPP and measured after testing the cooker and found that it improved with system having storage facilities. Efficiency may be assumed to be an absolute TPP as it does not require any standard [4].

El-Sebaii *et al.*, [2005] proposed *utilization efficiency, characteristic boiling time and specific boiling time* as TPPs and for their determination designed a box type cooker (BC) and performed experiments on it by putting one and four pots. They followed international standard proposed by Funk [10] while performing the experiment [49].

Kumar, S. [2005] proposed two TPPs *optical efficiency* and *heat capacity* and developed a TP for their determination for BCs [50].

Nandwani, S.S.[2007] designed developed one box type(BC) hybrid solar food processor where multiple numbers of works could be performed like cooking, heating and pasteurizing of water, distillation of water and drying of food product [3]. The performance parameter of this food processor was *effective thermal efficiency* and it was found in the range of 23-32%. It is identical to the one proposed by Nahar[4].

For CC type, Mullick *et al.* [1991] proposed two TPPs- *optical efficiency factor* and overall *heat loss factor* and developed a test procedure for their determination taking a paraboloidal concentrator cooker. Heating and cooling test of water was performed to determine the two proposed TPPs. From cooling test overall heat loss factor was computed and from heating test optical efficiency factor was determined [51].

Ozturk H. H.[2004] designed a low cost parabolic type solar cooker. Sensible heating test were performed in this cooker. From the test data *energy and exergy efficiency* were calculated to determine cooker performance [29].

Kalbande *et al.*[2008] proposed a test procedure for paraboloidal concentrator cooker. The heating and cooling tests were performed to *measure optical efficiency factor* and *heat loss factor*. From this they estimated thermal efficiency of the cooker and also evaluated approximate time required for cooking. They considered *thermal efficiency* as the performance parameter [52]. Patel et al also proposed *optical efficiency* as performance parameter [27].

Khalifa et al proposed *instantaneous oven efficiency, over all oven efficiency, over all cooker efficiency* as performance parameter [25]. Habeebullah et al also proposed *instantaneous oven efficiency* as performance parameter [33].

Sonune et al proposed *highest achievable temperature* as performance parameter [32].

Sharaf E proposed *short maximum time* as performance parameter[34].

Sardeshpande *et al.*[2011] gave procedure to evaluate the thermal performance of steam generating point focus solar concentrator. Thermodynamics of phase change of water was utilized to measure performance of the cooker. Water was allowed to convert steam at constant pressure and temperature and by measuring quantity of water converted to steam the heat gain by the system was measured. Thus thermal efficiency which is a performance parameter of the system considered here was measured It is reported that thermal efficiency of any point focus concentrator above 100°C can be measured by this method and may be used as a TPP [53] This is essentially an absolute TPP and is applicable to a wide variety of cookers.

Esen, M [2004] designed, developed and fabricated an advanced type cooker (AC) for solar cooking purposes. He identified *cooking time* for different food items as performance parameter [37] The performance in this case may be judged comparatively only

Hosny *et al.* [1998] reported about testing of two cookers Paraboloid dish solar cookers (PDSC) and booster mirror solar box cooker which were designed and developed by them to compare the performance It was tested in winter season in Cairo under same operating conditions The TPPs proposed by them were *optical efficiency, instantaneous thermal efficiency, process thermal efficiency* (η_{pth}) and *characteristic boiling time* (τ_c) From the results they found that PDSC had high rate of cooking, i e η_{pth} was high and τ_c was low [28]

Schwarzer *et al* [2008] presented TPPs and TPs for common cookers based on their basic characteristics For comparing cookers of the same type, efficiency was considered as one of the performance parameter. For comparing different types of cooker, both power and efficiencies were considered to be performance parameter [54] It was perceived that two different types of cooker essentially differ in terms of power delivered which becomes unique if represented with efficiency

Pandey *et al.*[2011] reported *exergy efficiency* as the performance parameter for both box type and parboloid cooker and proposed a testing method for their determination Both cookers were tested by boiling water and cooking rice under identical condition Exergy efficiency of both cookers was computed and comparison was made. The comparison reveals that paraboloid cooker had better exergy efficiency [55]

Several other investigators have designed fabricated and tested box type, concentrator type and even advanced type cooker in their respective places and some of them even compared the performance of different designs of cooker of same categories. They used a range of TPPs some of them the existing ones. These are discussed below:

Escobar *et al.* [1996] designed developed and tested three types of cooker one with vegetable residue as insulator, second one polyurethane residue as insulator and third one also polyurethane residue as insulator. All this three type cookers used double glass cover. The second and third one differs in terms of their shape. In these three cookers, they estimated the performance parameters, such as *first and second figure of merit, thermal resistance of insulator, optical efficiency, average thermal efficiency* etc., and thereby compared the performance of the three types of cooker [56].

Suharta *et al.* [2001] compared the performance of three Indonesian box cooker marked as HS 7534, HS7033, and HS 5521. HS7033, showed the better oven temperature as compared to other two. They also investigated the ratio of *transmittance absorptance product to total heat loss factor* ($\tau\alpha/U_L$) as the parameter to compare performance of the three cookers [57].

Algifri *et al.* [2001] reported about the improvement of the optical performance of the box type solar cooker on its orientation. The performance improvement was more for higher and lower elevation angle respectively during winter than summer. No specific TPPs and TP has been mentioned [58].

1.8: Need of Generalized TPP (GTPP) and Generalized Test procedure (GTP) for solar cookers:

After going through the open literature, it is observed that for each type of cooker there are many and different performance parameters. Mullick *et al.* [43, 51] proposed separate sets of TPP and the corresponding test procedure for box-type (BC) and concentrating type cookers (CC) respectively. Funk [10] proposed a TPP and corresponding test procedure, basically for BC, and termed that as standard cooking power and International standard test procedure respectively. Some other TPPs and corresponding test procedures were proposed by Nahar *et al.* [4] for BC and Khalifa *et*

Khalifa *et al.* [25] for CC. Rathore *et al.* [59] as well as Pandey *et al.*[55] compared the performance of box-type and CC in terms energy and/or exergy efficiency. All these TPPs and test procedures have been claimed and reported for only one of these three types of cookers with the majority catering to indirect or Box type.

Solar cookers, like any other solar device, inherently need a storage system, generally integrated, to address the problem of spoilage of food due to small unpredictable and intermittent reduction/interruption in the radiation. Buddhi *et al.* [21] developed a BC with latent heat storage system. In the absence of any TPP and test procedure for such designs the thermal performance of latent heat storage system was evaluated through comparative analysis with an identical cooker without any storage system as the bench mark. Sharma *et al.* [22] designed, developed and evaluated the performance of a latent heat storage unit for a solar cooker separately. The TPPs, hitherto developed, have not been developed to reflect this aspect of improvement in the design features. The results of comparative analysis cannot be duplicated and/or repeated. Also the performance parameter of a separately developed and tested heat storage unit do not ensure a proportionate predictable change in the performance of an integrated system. TPP(s) must have absolute value which is dependent only on design parameters and independent of operational and climatic variables. It must also provide a value which is inclusive/holistic i.e. which reflect performance of the integrated system.

For locations with low annual mean solar radiation some additions/modifications in the cookers optical system is required to maintain the radiation flux above a required minimum level. Amer, E.H.,[13] proposed a double exposure solar cooker and carried out theoretical and experimental assessment of its performance in terms of absorber plate temperature and cooking time taking conventional box type cooker as the bench mark. Thus he followed a comparative test procedure. Grupp *et al.* [19] has worked on a new design of box-type solar cooker to enhance the cooker's thermal performance by improving design to increase heat transfer rate from absorber to the pot. Tiwari *et al.* [7] designed solar cooker to minimize the heat loss during opening of the cooker cover. The performance of a box type cooker having externally fitted fin on cooking vessel to improve heat transfer rate to the food from cooker interior was investigated by Harmim *et al.*[15].

Most of these improvements may not get fully reflected in the values of existing TPP(s) because of the basic considerations in their development and highly design specific test procedure(s).

1.9. Origin of the present work and objectives:

As stated above it is difficult to compare the performance of two cookers of the same type by different workers if small improvements in design and/or new features are incorporated. Also after going through the available literature, it is found that it is very difficult to compare the cookers which are not of the same type i.e. any two out of the three types, employing the existing Thermal Performance Parameters (TPPs) and Test procedures (TPs). So it is needed to find out some TPPs and test procedure which can help different researchers to compare the thermal performance of cookers of same type of different size and/or additional features(intra-cooker comparison) and also two cookers of different type (inter-cooker comparison) This calls for making an attempt to develop generalized TPPs and test procedure applicable to all the existing types of cookers and their improvised variants

More over these parameters cannot provide all the information regarding achievable temperature, rate of cooking, and heat storage rate of supply of stored heat Each existing TPPs were determined using corresponding test procedures which are non-identical. So, conclusions drawn from these cannot be compared Each TPP has been proposed for only one type of cooker and hence enables intra-cooker comparison. But question is whether it can be extended to inter-cooker thermal performance comparison and whether it can be used independently by different researchers to provide comparable results Similarly the test procedures have been designed keeping only one type of cooker in mind. So they cannot be used for other or hybrid designs.

Some of the workers have proposed some performance parameters and test procedure for their determination, by which performance of both BC and CC can be compared But these parameters do not seem to fulfill the criterion of uniqueness, absoluteness and holistic/inclusiveness.

The present thesis attempts to sort out the above problem associated with solar cookers. The main object of the thesis is to facilitate in some design improvement so as to make solar cooker more user-friendly and hence popular However the specific objectives are

1 To study the performance parameters and test procedures developed for the cookers
2 To evaluate the applicability of the thermal performance parameters and to correlate them through design/operational parameters
3 To attempt to generalize thermal performance parameters (TPPs) for cookers
4 To attempt to develop a common test-procedure to determine TPPs.
5 To attempt to propose an improved design of a cooker through incorporation of new features

1.10. Summary of the present work:

This thesis aims to develop a Generalized Thermal Performance Parameter and corresponding test procedure analyzing different issues in detail and thus providing the rationale

It proposes some performance parameters to correlate and analyze the existing TPPs for cookers of indirect heating type (i) and direct heating type (ii) represented basically by common Box type cooker (BC) and Paraboloid concentrating cooker (PCC) A generic approach has been adopted to develop, propose and analyze new set of TPPs for one type of cooker It is endeavoured to extend it to other cookers and complement that with a common test procedure The main objective of the work is to develop the TPP which is cooker-type independent, responsive to new features, holistic/inclusive and unique, in addition to having a simple absolute and generalized test procedure The report consists of seven chapters and two appendices

Chapter I: It introduces the theme of the thesis including information about different types of cookers and their special features A detailed literature survey with regard to cooker specific TPPs and test procedures for their determination has been done with a view to provide rationale of the work and to set the objectives. A new basis to classify the cookers has also been presented in this chapter.

Chapter II: This chapter aims to correlate the existing TPPs. For this a set of performance parameters named as Objective Parameters (OPs) have been proposed. These are – i) Maximum achievable temperature, ii) Reference time, and iii) Heat retention duration. Each OP has been carefully defined and methods for their experimental determination have been outlined. The existing TPPs, generally cooker specific, as reported by different workers have been correlated through the proposed OPs. This chapter provides an insight into the existing TPPs for BC, their commonalities and strengths. It is concluded that the TPPs are not able to predict all the OPs and hence it is difficult to correlate them. Thus, this chapter provides a sound basis and understanding of the course to be adopted to develop generalized TPP(s).

Chapter III: PCC has more constraints than BC in terms of cooking pot placement and tracking requirements. So attempts have been made to develop TPP(s) for PCC from the basic HWB equation in this chapter. Two parameters considered to be more basic, simple and holistic TPPs for PCCs have been proposed. For their determination a generic and simple test procedure has been employed. It may be noted here that it is possible to accurately measure temperature of a standard fluid kept in a standard pot at the focus of a PCC. Equations for expressing OPs in terms of proposed TPPs have been derived. The test procedure and the TPPs have been validated through experimentations carried out under standard operational and climatic conditions OPs have been determined for PCC from the TPP values and are found to conform well to the definition of the OPs. It has been concluded that an attempt may be made to have identical TPPs and test procedure employable to other cookers as well.

Chapter IV is dedicated to examine the employability of the two TPPs proposed earlier for PCC, to BC as well. An attempt has been made to develop a common test procedure to determine them. A new parameter termed as Cooker Opto-thermal Ratio (COR) has been defined. The test procedure for BC and PCC are discussed here to evaluate COR from the two TPPs. Inter-cooker comparison is possible from this COR. So it can be considered as first step towards generalization. To carry out the test some standard climatic and operational conditions/norms have been proposed.

Chapter V explores the possibility of generalization of the TPPs and test procedures for the cookers of all the three types. Here basis for selection of TPPs for both BC and PCC are discussed. Consequently the possibility of using the TPPs proposed earlier for BC and PCC is investigated and discussed. The advanced type cooker has a heat transfer fluid to transfer the heat from the collector to the cooking chamber. The design, fabrication and detailed analysis of such a cooker is beyond the scope of the thesis. However by considering the basic design of such a cooker and through detailed qualitative analysis of the same the possibility of use of existing and proposed TPPs has been explored for advanced type cookers including other cookers. A similar approach has been taken for generalizing the test procedure as well. For generalization the parameters needed for determining TPPs and conditions set for carrying out the test must be same for all types of cookers.

Chapter VI: In this chapter a box type cooker with a new design feature is proposed. After that the cooker is evaluated using the proposed generalized TPPs and the corresponding test procedure. The conventional cooker (without design changes) is also evaluated using generalized TPPs and the test procedure. The results have been compared and analyzed to assess the efficacy of the proposal. It is found that the proposal provides an enabling tool to conclude about the impact (positive or negative) of design changes.

Chapter VII: This chapter concludes about the strengths and discusses about the scope of improvement in the proposed TPPs and the test procedure in carrying out inter-cooker and intra-cooker comparison. Some suggestions about the possible design changes in the cookers have been made. Some of them are expected to show improvement in the TPP values. This work attempts to provide an option in the form of TPP values as a measure to denote the cooker's thermal performance.

Appendix- I, discusses about the possibility and merits of using photo catalysts in the case of box type cookers.

In **Appendix-II**, the possibility of using plastic cover in place of glass cover is discussed through numerical simulation studies of heat transfer through the cover.

Appendix-III includes the details of existing thermal performance parameters for concentrating cookers and test procedure for their determination.

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Chapter -2

Identification of objective parameters to correlate and analyze the scope of applicability/robustness of existing thermal performance parameters

Chapter 2

Identification of objective parameters to correlate and analyze the scope of applicability of existing thermal performance parameters

A thermal performance parameters(TPPs) aims (i) to provide a parameter, absolute value of which makes rating of the system possible (ii) to enable the assessment of impact of design modifications and improvements and (iii) to facilitate performance comparison of inter and intra-system(cooker) designs. The parameters themselves must have the following characteristics: (i) They must be robust and hence independent of geographic location, meteorological, operational parameters; and personal preferences (ii) They must be sensitive to design modifications and improvements. (iii) It should be possible to determine them with reasonable degree of accuracy through a simple test procedure. (iv) It should be possible to replicate the TPP values precisely under the conditions laid out for the test procedure

A number of TPPs and TPs exist and a few new ones are being projected. But it is needed to have identical conclusions from them finally to facilitate the basic requirements for development of a solar cooker. Prior to this there is a need to develop a mechanism. This chapter attempts to do that by identifying some objective parameters (OPs).

2.1. Introduction

As discussed in Chapter-1, there has been a considerable interest in the design, development and testing of various types of solar cookers like box type [1], côncentrator type [2, 3] and advanced type [4] around the globe. Many designs of each type have been proposed. The need to evaluate a cooker and compare different designs calls for testing procedures and thermal performance parameters (TPPs) which represent their respective thermal performance. The work aimed at addressing these concerns has resulted in many useful test procedures and TPPs. These parameters must be independent of geographical, climatic, operational and other social variables such as food habit of a society and judgment of a person. Many of the existing TPPs are largely independent of aforementioned variables. Initially this chapter aims at reviewing the test procedures and TPPs as well as tries to find the commonality and the most useful features of these with special reference to box-type cookers. For CC this will be discussed in the following Chapter-3. An attempt has been made to establish a linkage between the TPPs proposed by different workers. The linkages enable comparative assessment of different TPPs. The TPPs of various designs of box-type cookers have also been reviewed in the section 2.3.

The existing TPPs which have been hitherto adopted by researchers are – utilizable efficiency, specific time, characteristic time [5], figures of merit[1], cooking power[6] standard cooking power[7], thermal efficiency, effective thermal efficiency [8], optical efficiency factor ($F'\eta_o$) and heat loss factor ($F'U_L$)[2,3], useful thermal power[6], etc. Most of these TPPs are applicable to cookers of a specific type. Initially only box type cooker is considered. Some of these TPPs which are applicable specifically to box-type cooker evaluate performance of these cookers based on the data of respective non-identical test procedures. These TPPs are able to predict the relative performance of the cooker and hence make it possible to grade them. But it is still difficult to correlate the performance of two cookers if their performance is reported in terms of two different TPPs. Hence, to identify a common link between these parameters and to analyze them with a view to assess the TPPs there is a need of development of common derivatives from these parameters. Three objective parameters

(OPs) have been identified in the present work. They have been defined carefully and attempt has been made to derive them from existing TPPs. These are

(i) *Maximum achievable fluid temperature (MAT),* T_{fx}
(ii) *Reference time (RT),* τ_r
(iii) *Heat retention duration (*HRD), τ_{hr}

(i) ***Maximum achievable fluid temperature (MAT),*** T_{fx}: It characterizes the highest achievable temperature of the standard load in the form of a standard fluid in the cooking pot. Under standard conditions it will depend upon the design of the cooker. The standard load is normally distilled water which cannot be used above 100 °C. Hence MAT is predictable for most of the cookers. It may be noted that maximum achievable fluid temperature (T_{fx}) or maximum achievable plate temperature (T_{ps}) may be determined based on the temperature recorded during the experimentation. The useful heat collected by a solar collector is shown as

$$\dot{Q}''_u = S - U_L\left(T_{ps} - T_a\right) \tag{2.1a}$$

If average plate temperature is measured at steady state then putting $\dot{Q}''_u = 0$ and dividing the equation by average irradiance gives

$$0 = \eta_0 - \frac{U_L\left(T_{ps} - \overline{T}_a\right)}{\overline{G}_T}$$

$$\frac{\eta_0}{U_L} = \frac{\left(T_{ps} - \overline{T}_a\right)}{\overline{G}_T} \tag{2.1b}$$

If however fluid temperature is measured at steady state then

$$0 = F'\eta_0 - F'U_L\frac{\left(T_{fx} - T_a\right)}{\overline{G}_T}$$

$$\frac{\eta_0}{U_L} = \frac{\left(T_{fx} - T_a\right)}{\overline{G}_T} \tag{2.2}$$

The second value will be slightly lower and hence T_{ps} will be higher than T_{fx}. But T_{fx} is taken as OP because plate is not an integral component of a concentrating cooker.

For a user the MAT facilitates the selection of the type of cooking (boiling type, frying, roasting).

(ii) Reference time (RT), τ_r: It is the time required for a standard load to reach a reference cooking temperature (95°C in the present work) from an initial temperature (30°C). It characterizes rate of heat supply to the food being cooked. It helps the user in identifying the load and number of meals which a cooker can provide in a day. The basis of selection of these values is that the highest temperature should remain just below the boiling temperature of working fluid (water in this case) and the initial temperature should be higher than but close to the ambient. Some non-linearity in the temperature time profile may be ignored. This helps in having a realistic view regarding the expected cooking time.

(iii) Heat retention duration, (HRD), τ_{hr}: It is the duration for which temperature of the load between two reference temperatures (95° to 85°C) is maintained under sudden uncontrolled reduction in clearness and radiation. HRD is the time of cooling of the standard load from a predetermined temperature of 95 to 85 °C. This characterizes the heat storage capacity in terms of duration of heat retention between the temperature ranges. This gives an idea about the probability of spoilage of food under adverse weather conditions, for example if the weather intermittently becomes cloudy for small durations.

The upper limit of τ_{hr} *has* been selected to be 95°C, i.e. below the boiling temperature to maintain the linearity of dependence of heat loss on temperature. As a result temperature and time also have linear relationship. However the lower limit of the reference temperature needs to be properly defined since cooking should continue even during small interruptions in radiations and should be above the pasteurization temperature of 69°C as well [8]. For this the minimum temperature needed for cooking to take place is to be identified for a given food grain. Rice is taken as the sample food grain because it is widely used in developing world. Cooking of rice is characterized in terms of reactions leading to absorption of water and the gelatinization of the starch

(90% in rice). The gelatinization temperature (GT) which is considered to be the cooking temperature is the temperature at which starch granules irreversibly lose their crystalline order during cooking and is the most important cooking quality of rice grains [9]. Gelatinization temperature of different varieties of rice varies from 70 to 82.5°C [10]. Accordingly 85 °C has been taken as the lower reference temperature. The upper limit is assumed to be 95 °C for defining HRD. It is justified because it is only 10°C higher than the gelatinization/reference temperature. The time difference between these values is measurable and spaced to reflect the variations. Also it is sufficient and desirable to keep the temperature of cooking between these two values. It is to be noted that energy consumed in cooking rice, potatoes or green vegetable is only 0.06 to 0.10 kWh/ kg at cooking temperatures of 82 – 88 °C and the cooking time at these temperatures is 30-45 min [11]. Also the lower limit is above pasteurization temperature of 69°C and duration of 15 min at this temperature is sufficient for completion of pasteurization. Rice cooking at 100 °C is basically a visible / audible reference for assumed surety of accomplishment of cooking by common person.

Some of these OPs are derivable from the existing TPPs. The basis of selection of the OPs has been the – applicability, simplicity and need of the prospective users, manufacturers and researchers at different geographic locations with different climatic and operational conditions. For a user the first objective parameter, as stated earlier, facilitates the selection of the type of cooking (boiling type, frying, roasting). The second one helps the user in identifying the load and number of meals which a cooker can provide in a day. The third one gives an idea about the probability of spoilage of food under adverse weather conditions, for example if the weather suddenly becomes cloudy. For manufacturers and researchers these OPs are quantities which are measurable or which can be easily found out. These may be used to determine TPPs which are represented such that they are the material and design-dependent but geographic location, climate, and operational variable independent. It must be noted that the TPPs are quite complex for a common user but are useful tool for researchers and manufacturers. OPs, however, may be simple for a common user but highly dependent on external variables and hence are not of direct use for researchers. This concern led Mullick et al [1] to define an empirical time constant in terms of the two figures of merit. It must be noted that Mullick et al [1] have given TPPs in terms of figures of merit. Later they used these TPPs to derive an expression for empirical time constant[1] (a kind of objective parameter), probably to give an idea about the cooker's performance to a general user. Hence at present it is aimed to use TPPs in simple relations to derive objective parameters the value of which is valid for a specific location, climate and operational condition. It is also to be investigated if it is possible to do so by using the existing TPPs.

Some of the features of TPPs and OPs are listed in Table 2.1.

Table 2.1: Characteristics of TPPs and OPs:

Sl.No.	TPPs	OPs
1	Design dependent	Design dependent
2	Independent of climatic parameters	Vary with climatic parameters
3	Uniquely defined hence determination is cumbersome	Determined easily through direct measurement
4	Tools for designer	Tools for general users
5.	Need a carefully designed test procedure	Need simple temperature-time measurement

[1] Determination of this time constant calls for measurements under defined (or standard) climatic conditions i.e. it may again be one of the derived TPPs or an objective parameter.

2.2. Distinctive features of different Types of Solar Cookers:

As discussed in section 1.4 basically there are three types of solar cookers. For each one of them different performance parameters has been used by researchers[2]. The distinctive design and operational features which have differential influence on objective parameters, of the different types of cookers and their variants are described below.

In ***box type (BC)*** solar cooker, the temperature of around 100^{0}C is achieved. This range of temperature is suitable for cooking by boiling. In spite of having desired features, such type of cookers may either fail to cook or take longer time to cook a full load of food because of its inability to reach desirable temperature or to transfer heat to the content of pot at a fast rate in a given climate. These cookers cannot be used in partial cloudy days or in late evening unless the system has solar energy storage device [12]. So it can be made popular by introducing storage material which can store solar energy during day time when it is in excess of the load and use it whenever required i.e. for late evening cooking etc [13]. In one such design, phase change material (PCM) has been used to store the solar energy. Two or three reflectors have been introduced in the cooker [14]. To store solar energy in box type solar cooker, engine oil has also been used in between absorber plate and insulation [15]. Box type solar cooker with two reflectors and Transparent Insulation Material (TIM) inserted in between two glazing made it possible to cook two meals in a day in extremely cold winter [16]. To reduce the time required to preheat the cooker for cooking second batch of food in box type solar cooker a new design is introduced. Here base of the cooker is used as the lid [17]. Thus efficiency, the TPP used here, of the cooker increased over conventional box type cooker. Another type of box cooker is available where bottom insulation is replaced by glass cover [18]. Some of the TPPs used for determining the performance of BC are: first figure of merit (F_1), second figure of merit (F_2), standard cooking power (P_s), thermal efficiency (η), utilizable efficiency (η_u), specific time (t_s), characteristic time (t_c) etc.

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[2] However OPs are common parameters for all types these may be derived from the any TPP used to represent a cooker's performance.

Concentrating type or ***direct heating (CC)*** type cookers utilize multifaceted mirrors, Fresnel lenses, or parabolic concentrator to attain higher temperatures. Typically, they heat up quickly and to higher temperature (~150°C) but they do not have well insulated pot and require directional adjustment to track the sun. As concentrating cookers primarily utilize direct beam radiation, so cleanliness of the reflector is very much essential. It is very difficult to control some of the events which reduce the cleanliness of the reflector and thereby affect the performance of the cooker. A Fresnel type domestic concentrating cooker designed and developed [19]. Another variant of concentrating type is a ***conical solar cooker*** [20] which is easy to manufacture and occupies less space. Different time based parameters have invariably been used to depict performance of such cookers. Some of the TPPs used for CCs are: Optical efficiency factor ($F'\eta_0$) and Heat loss factor ($F'U_L$), specific time etc.

The ***Advanced type(AC)*** cooker use a convective or radiative mechanism to transfer energy from the point of collection to the cooking vessel(s) away from the collector. Thus they are suitable for indoor cooking applications, but are comparatively more expensive to produce. The useful thermal power is much higher in this type of cooker. Normally a heat transfer fluid is used to transfer the sensible heat [21]. Another such cooker consists of vacuum – tube collector with heat pipes containing different refrigerants, where no tracking is required [4]. Another advanced type of cooker is the indoor focusing hybrid cooker with a thermal storage block [22] which is similar to the Scheffler solar cooker. But in Scheffler design (discussed in Chapter 1), usually thermal storage block is not available. The variables to be considered in developing the TPPs of this type of cookers will be design, operational and meteorological variables etc. No work referring to a performance parameter for these cookers has been found.

Table 2.2: Solar cookers with specific design features, conventional classification and mode of heat transfer to the pot.

Sl. No.	Type/Name	Conventional classification	Collector	Pot	Mode of heat transfer	Special features
1	A new solar cookers, Tiwari *et al*(1986).	BC	A thin aluminum blackened sheet with one reflector. Base is converted to lid to minimize heat loss	4 pot	Conduction, convection	Cooking time for second batch of meal is reduced due to conversion of base of the cooker as lid [17].
2	Solar cooker with PCM as storage media, Domanski *et al*(1995),	BC	Absorber plate and PCM(stearic acid)	Cylindrical vessel with PCM storage facilities(stearic acid)	Conduction, convection	Off sun shine cooking and indoor cooking possible. Efficiency more than the steam and heat pipe solar cooker [23].
3	Solar cooker with latent heat storage Buddhi et al(1997)	BC	Absorber plate with PCM as latent heat storage below the absorber plate	A cylindrical container welded with the absorber plate.	Conduction, convection	PCM used for heat storage to make the cooker suitable for multiple climatic conditions [24].
4	Hot box solar cooker, Mohamad *et al*(1998)	BC	Steel sheet absorber plate, Painted black	1-2 pot	Conduction, convection	Simple in design with one booster mirror [25]

5	Sudanese solar box cooker Mohamad Ali *et al*(2000)	BC	Aluminum plain sheet painted black with internal and external reflector	3 pots	Conduction, convection	With two internal and one external reflector with inclined cover, showed better thermal performance [26]
6	Double exposure solar cooker Amer, E H (2003)	BC	Absorber is exposed to solar radiation from two sides	4 pot	Conduction, convection	As absorber is exposed to solar radiation from top and bottom, so cooking time is reduced [18]
7	Solar cooker with Latent heat storage unit for evening cooking Buddhi *et al* (2003)	BC	Absorber plate and fin welded with inner wall of the PCM container	Cylindrical pot with storage unit for PCM	Conduction, convection	PCM having high melting point and higher latent heat of fusion were used for cooking at late evening [14]
8	Box type solar cooker with PCM as transparent Insulation Murty *et al.* (2003)	BC	Absorber plate with PCM as transparent insulation	Aluminium pot	Conduction, convection	PCM is filled in the space available between two glasses of the glass cover PCM used here has good transmittance and insulating property It reduces heat loss at lower temperature from the cooker and also supply heat to the item to be cooked [27]

9	Box type solar cooker employing non tracking concentrator Negi *et al*(2005),	BC	Absorber plate with double reflector	direct contact with absorber plate	Conduction, convection	Improved heat collection Less cooking time Efficient cooking [28]
10	Cooking vessel with central annular cavity Narasimha Rao et al(2005)	BC	Absorber plate, lug	Pot with central annular cavity	Conduction, convection	Hot air circulates through the annular cavity and there by heats up the food material away from the pot wall and thus reduces cooking time [29]
11	Hybrid solar food processor, Nandwani (2007)	BC	Electric black plate as an absorbing surface with one reflector	1 pot	Conduction and electric power	Four-in-one device can be used for cooking drying, water pasteurizing and distillation using solar and electrical energy [8]
12	New concentrating type solar cooker Khalifa *et al*(1987)	CC	Solar energy is concentrated through spiral concentrator	Pot is covered with glass and placed at the focus of the reflector/oven receiver	Radiation	Short cooking time Eliminates spillage problem No condensation problem Potential to reach 180°C is high [30]
13	Concentrating solar cooker with oven receiver Habeebullah et al(1995)	CC	Parabolic concentrator	Oven type receiver /glass sided oven	Radiation	Efficient and independent of wind speed Cooking at high temp is possible with oven receiver [31]

14	Philippine Chinese IME Model Patel *et al* (2000)	CC	Fresnel concentrator, Paraboloidal concentrator	One pot	Radiation	Fresnel reflector is more appropriate for cooking as heat is distributed over a large area over cooking vessel Point focus is available in IME cooker which may burn food item and injury to the user [32]
15	Conical solar cooker Sharaf E (2002)	CC	Single frustum cone	One pot	Convection	Cooking time is less [20]
16	Domestic concentrating cooker Sonune *et al*(2003)	CC	Fresnel reflector	One pot	Radiation	A Fresnel type concentrating cooker It provides high temperature which is sufficient for cooking, frying, preparation of chapattis [19]
17	Split system solar cooker Khalifa *et al*(1986)	AC	Flat plate collector	Cooking chamber inside, transferring heat through heat pipes	Convection	Flat-plate collector is kept outside and cooking chamber is inside the kitchen Tracking is not required It is wind resistant [33]
18	Flat-plate collector solar cooker with	AC	Flat plate collector with coconut oil as	Cooking pots are immersed in oil	Convection	Absorber plate is covered with maxorb foil instead

	short term storage Singh, H *et al* (1996)		heat transfer fluid	bath which is used as heat storage medium		of black paint Coconut oil is used as heat transfer fluid Cooking pot is immersed in oil bath for good heat transfer between working fluid and cooking pot [34]
19	Evacuated tube solar collector Sharma *et al* (2005)	AC	Water and PCM	Cylindrical cooking vessel with PCM storage unit	Convection	Two meals can be cooked (noon and evening) by this cooker [35]
20	SK-14 parabolic solar cooker for off –place cooking Murthy *et al.* (2006)	AC	Heat transfer fluid to transfer heat to PCM	Cylindrical pot surrounded by PCM	Radiation	Parabolic solar cooker is used to heat the heat transfer fluid Heat energy is retained for longer period of time in this cooker [36]
21	Solar cooker with auxiliary heating Hussain et al(1997)	Hybrid, BC	Absorber plate	pot	Conduction	Performance is better Cooking is possible in partial cloudy day also [37]
22	Electrical backup for solar cooker Chaudhuri et al(1999)	Hybrid BC	Flat absorber plate	Pot in contact with absorber plate	Conduction	Cooking is possible in partial cloudy days with the help of auxiliary heating device [38]

2.3. Existing Thermal Performance parameters and the Test Procedures for box type solar cooker

A large fraction of the cooking load in boiling type cooking is water As a result sensible heating up to the cooking temperature requires almost 4186J/kg-K Khalifa et al[5] proposed the performance parameters like utilizable efficiency (η_u), characteristic time (t_c) and specific time (t_s) etc They determined *utilizable efficiency* to grade the cookers TPPs in terms of two figures of merit (F_1 and F_2) proposed by Mullick et al [1] have been adopted by Bureau of Indian standards [39] It enables prediction of sensible heating time of the water in the cooking pot Additionally, for calculation of optical efficiency factor $F'\eta_0$ and heat capacity (MC) ', Kumar et al [40] used the linear regression analysis of experimental data of F_2 for different loads of water Thus, to predict the thermal performance of solar cooker, $F'\eta_0$ and (MC)' may be considered as essential parameters Funk [7] discussed about international standard procedure for testing of solar cookers and in that context calculated standard cooking power (P_s) which may be helpful in comparison of performance of different other types of solar cookers as well Nahar [15] used efficiency as a TPP for box type solar cooker Some of these parameters used by different workers and their test procedures are discussed below

Overall utilizable efficiency, as discussed by Khalifa et al [5] for box type solar cooker, is calculated by using the following formula

$$\eta_u = Q_F/Q_{in} \qquad (2\ 3)$$

where Q_F is the useful heat stored in the food for a temperature rise of ΔT For relatively constant direct normal radiation G_{NR}, collector area A_{ca}, and cooking time Δt, solar input Q_{in}, can be expressed as

$$Q_{in}=G_{NR}A_{ca}\Delta t \qquad (2\ 4)$$

The specific time (t_s) required to heat mass of water M_1, to boiling is expressed as

$$t_s=\Delta t A_{ca}/M_1 \qquad (2\ 5)$$

Alternatively,

$$t_c = t_s \overline{G} / \overline{G}_{NR} \tag{2.6}$$

where t_c is the characteristic time and G_{NR} is reference direct normal radiation and is taken to be 900W/m^2 and $\overline{G}$ is average solar radiation.

In the standard thermal test procedure proposed by Mullick et al [1] for box type solar cookers, two figures of merit F_1 and F_2 are determined by conducting the no load stagnation temperature test and sensible heating test of known mass of water respectively. F_1 is obtained from the no load test by using the expression:

$$F_1 = \frac{\left(T_{ps} - \overline{T}_a\right)}{\overline{G}} \tag{2.7}$$

where F_1 is first figure of merit, T_{ps} is maximum plate surface temperature $\overline{T}_a$ is average ambient temperature and $\overline{G}$ is average solar irradiance on horizontal aperture.

The second figure of merit F_2 is obtained from the full load water heating test:

$$F_2 = F'\eta_0 C_R = \frac{F_1 (M_1 C_w)}{A\tau} \ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \overline{T}_a}{\overline{G}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \overline{T}_a}{\overline{G}}\right)}\right] \tag{2.8}$$

where F_2 is second figure of merit, F' is heat exchange efficiency factor, η_o is optical efficiency, C_R is heat capacity ratio, F_1 is first figure of merit, (M_1C_w) is product of the mass of water and its specific heat capacity, A is absorber area, τ is time interval, T_{w1} is the initial temperature of water, and T_{w2} is the final temperature of water.

From the above equation (2.8), it is seen that F_2 is more or less independent of climatic variable. The expression for empirical time constant for sensible heating using F_1 and F_2 is as follows

$$\tau_o = \frac{F_1(M_1 C_w)}{AF_2} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \bar{T}_a}{\bar{G}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \bar{T}_a}{\bar{G}}\right)} \right] \tag{2 9}$$

where τ_o is the time constant and other symbols are same as in equation (2 8)

To estimate the first figure of merit (F_1) and second Figure of merit (F_2), it is required to measure the intensity of solar radiation falling at horizontal aperture of the cooker, ambient temperature, wind speed, initial water temperature, final water temperature etc It is recommended that experiment should be done within ± 1 30 hrs of the solar noon with the intensity of solar radiation above or equal to 500 W/m^2 Initial temperature of water should be higher than the ambient temperature and the final temperature of water should be lower than the boiling point It may be 90 or 95 °C to avoid error in reading from the experimental curve as the curve flattens at higher temperature i e around 100 °C The sensible heating test is to be conducted at full load as suggested by the supplier [1]

Mullick *et al.* [41] found that, F_2 increases, with increase in number of pots, if load is kept constant and equally distributed This is due to an improvement in the heat exchange efficiency factor (F′) with number of pots They also determined that F_2 increases with increase in load, if number of pot is kept constant and the load is equally distributed This is because of an improvement in heat capacity ratio C_R, as mass of water in the pots increases They suggested that F_2 should be determined at full load and with all the four standard pots since the value is lower with lower load and lesser number of pots

To study the effect of increasing number of pots on F_2 it is suggested that load should be kept constant irrespective of number of pots and should be 1kg of water [41] Test should be conducted for one, two, and four pots To study the effect of load on F_2, recommended test load is 1 0, 1 5, 2 0, 2 5kg of water which should be divided equally in the four pots [41]

Funk [7] discussed two types of test variables. They are mainly uncontrolled (weather) variables and controlled (cooker) variables. Wind, ambient temperature, pot contents temperature, insolation and solar altitude and azimuth are the uncontrolled variables while loading, tracking, temperature sensing are the controlled variables. From Funk's definition, cooking power may be expressed as

$$P = \frac{M_1 C_w dT_w}{dt} \tag{2.10}$$

where P is the cooking power, M_1 is the mass of water, C_w is specific heat of water, dT_w is temperature difference of water and dt is time interval.

Funk [7] also introduced the term standard cooking power which can be expressed as.

$$P_s = \frac{700 M_1 C_w \Delta T}{600 \overline{G}} \tag{2.11}$$

where P_s is standard cooking power, ΔT is temperature difference and $\overline{G}$ is average solar radiation, 700 is the standard solar irradiance in W/m^2 for normalization, and 600 is the time interval in seconds.

To find the cooking power and standard cooking power the parameters to be measured are wind speed, ambient temperature, water temperature, solar radiation, intercept area of the cooker etc. During the experimentation the wind speed should be less than 1 m/s. If wind speed is 2.5 m/s for more than 10 min then test should be stopped. Ambient temperature should be in the range of 20-35°C. Water temperature of the pot should be recorded in between 40 – 90°C. Solar radiation during the experimentation should be in the range of 450-1100 W/m^2. The suggested load is 7 kg of water/m^2 intercept area of cooker and should be distributed in the pots equally. For box type solar cooker zenith angle tracking is not required if the duration of test is less than two hours. To calculate standard cooking power the reference solar radiation should be 700 W/m^2 [7]. Hence all the results are multiplied by a proportional factor to get normalized result.

Patil *et al.* [42] proposed the following analytical method for calculation of standard cooking time (τ) from standard cooking power

$$\tau = \frac{M_1 C_w}{C_3 N} \ln \frac{P_s(T_{w1})}{P_s(T_{w2})} \tag{2 12}$$

where τ is time interval, M_l is mass of water, C_w is specific heat of water, P_s is standard cooking power, T_{wl} is initial temperature of water, T_{w2} final temperature of water, N is number of pots, C_3 is coefficient

Nahar [15, 16], proposed the method of calculation of efficiency (η) of the solar cooker by the following relation

$$\eta = \frac{(M_1 C_w + M_u C_u)(T_{w2} - T_{w1})}{CA\int_0^{\tau} \overline{G}\,dt} \tag{2 13}$$

where η is Efficiency of the solar cooker, M_l is mass of water, Kg, M_u is mass of cooking utensil, kg, C_u is specific heat of cooking utensil in J/kg/°C, T_{wl} is initial temperature of water in °C, T_{w2} is Final temperature of water °C, C is concentration ratio, A is Absorber are in m^2, τ is time interval, sec, $\overline{G}$ is solar irradiance on horizontal surface in W/m^2

To estimate the efficiency of the reported cooker, load should be 1 kg of water and it is to be equally distributed into four pots of the cooker The cooker should be placed for cooking ±1 0 h of local noon time Rise in water temperature and time required to reach the water temperature to boiling point is to be measured [15]

These parameters along with the range of value(s) reported by respective authors are shown in Table-2 3

Table-2.3: Thermal performance parameters, expressions and range of values for box- type Cookers.

Reference	Parameters	Expression for performance parameter	Range of values
Mullick et al [1]	(i) F_1	$\frac{T_{ps} - \overline{T}_a}{\overline{G}}$	0.12- 0.16 $m^2\,^0C$ / W
	(ii) F_2	$F'\eta_0 C_R = \frac{F_1(M_1 C_w)}{A\tau} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \overline{T}_a}{\overline{G}}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \overline{T}_a}{\overline{G}}\right)} \right]$	0.254 – 0.490
Funk PA [7]	(i)P_s	$\frac{700 M_1 C_w \Delta T}{600 \overline{G}}$	348.83333 Watt at $\Delta T=50^0C$
El Sebaii et al [43]	(i)η_u	$M_1 C_w \Delta T / \overline{G}\, A_p \Delta t$	Details not available
Khalifa *et al* [5]	(i) η_u	Q_F/Q_{in}	7.4% – 29.6%
	(ii)t_s	$\Delta t A_c/M_1$	Details not Available
	(iii)t_c	$t_s \overline{G} / G_{NR}$	20.1- 66.7min-m^2/kg
Nahar, N.M. [15]	η	$\frac{(M C_w + M_1 C_u)(T_{w2} - T_{w1})}{CA\int_0^\tau \overline{G} dt}$	27.5%
Nandwani S S [8]	η	$\frac{(M C_w + M_1 C_u)(T_{w2} - T_{w1})}{A_p\int_0^\tau \overline{G} dt + P_E\int_0^\tau dt_E}$	22 8%*

- Includes electrical heating as well.

2.4. Correlating Performance parameters for box type cookers:

This section explores the possibility of determination of the three OPs from the TPPs for BCs. The values of the variables used for the purpose are given in Table-2.4

The objective parameter T_{fx} is calculated from different thermal performance parameters by using the relations given in the Table-2.5. By knowing the value of T_{fx}, decision can be taken with regard to the type of cooking the cooker is suitable. T_{fx} has direct relation with F_I and has been depicted in Fig-2.1. T_{fx} increases with increase in F_I. It shows that cookers with high F_I will show better performance. The other OPs τ_r and τ_{hr} are determined for standard load, so they cannot be calculated from F_I.

Table-2.4: Values of the variables considered in calculations.

Variable	Value	Variable	Value
A	0.160m^2	M_l	1 kg
A_c	0.245m^2	M_u	176.342 gm
A_p	0.245 m^2	N	4
C	1.732	T_a	30^{0}C
C_u	0.9J/gm/K	T_{w2}	95^{0}C
C_v	4140.556J/Kg/K	ΔT	50^{0}C
T_{w1}	30^{0}C	η	27.5%
C_w	4186 J/kg/K	τ	600 sec.
C_1	23.425	F_I	0.12 m^{2}K/W
C_2	18.77	$\overline{G}$	700 W/m^2
C_3	0.31775	G_{NR}	900W/m^2

Table-2.5: Expressions for objective parameters derivable from performance parameter with some estimated values

Reference (1)	Performance Parameter (2)	Reported range of Parameters (3)	Objective parameter (4)	Equation for objective parameter (5)	Estimated range of objective parameters using column (3). (6)
1. Mullick *et al.*[1]	F_1	F_1=0.12-0.16	T_{fx}	$F_1\bar{G}+\bar{T}_a$	114^0C-142^0C
			τ_r	Cannot be expressed	-
			τ_{hr}	Cannot be expressed	-
Mullick *et al.*[1]	F_2	F_2=0.254–0.490	T_{fx}	Cannot be expressed	-
			τ_r	$\frac{F_1(M_1C_w)}{A\tau}\ln\left[\frac{1-\frac{1}{F_1}\left(\frac{T_{w1}-\bar{T}_a}{\bar{G}}\right)}{1-\frac{1}{F_1}\left(\frac{T_{w2}-\bar{T}_a}{\bar{G}}\right)}\right]$	3.332-1.727 hrs
			τ_{hr}	Cannot be expressed	-
3. Patil et al[42]	P_s	T_{w2}=60-95^0C	T_{fx}	Cannot be expressed	-

			τ_r	$\frac{M_1 C_w}{C_3 N}\ln\frac{P_s(T_{w1})}{P_s(T_{w2})}$	0.447–1.669 hrs.
			τ_{hr}	Cannot be expressed	-
4.Khalifa *et al.*[5]	t_c	η=7.4-29.6%	T_{fx}	Cannot be expressed	-
	t_s	t_s= 25.843 - 85.757 min-m^2/kg (0.431- 1.429 hrs-m^2/kg).	τ_r	$(M_1 t_s)/A_c$	1.758-5.834 hrs
			τ_{hr}	Cannot be expressed	-
5.Nahar[15]	η	η=27.5%	T_{fx}	Cannot be expressed	-
			τ_r	$\frac{(M_1 C_w + NM_u C_u)(T_{w2} - T_{w1})}{CA\overline{G}\eta}$	1.631 hrs
			τ_{hr}	Cannot be expressed	-

6 Nandwani, S S [8]	η	η=22 8%	T_{fx}	Cannot be expressed (as some amount of electrical energy was also used)	-
			τ_r	Cannot be expressed (as some amount of electrical energy was also used)	-
			τ_{hr}	Cannot be expressed (as some amount of electrical energy was also used)	-

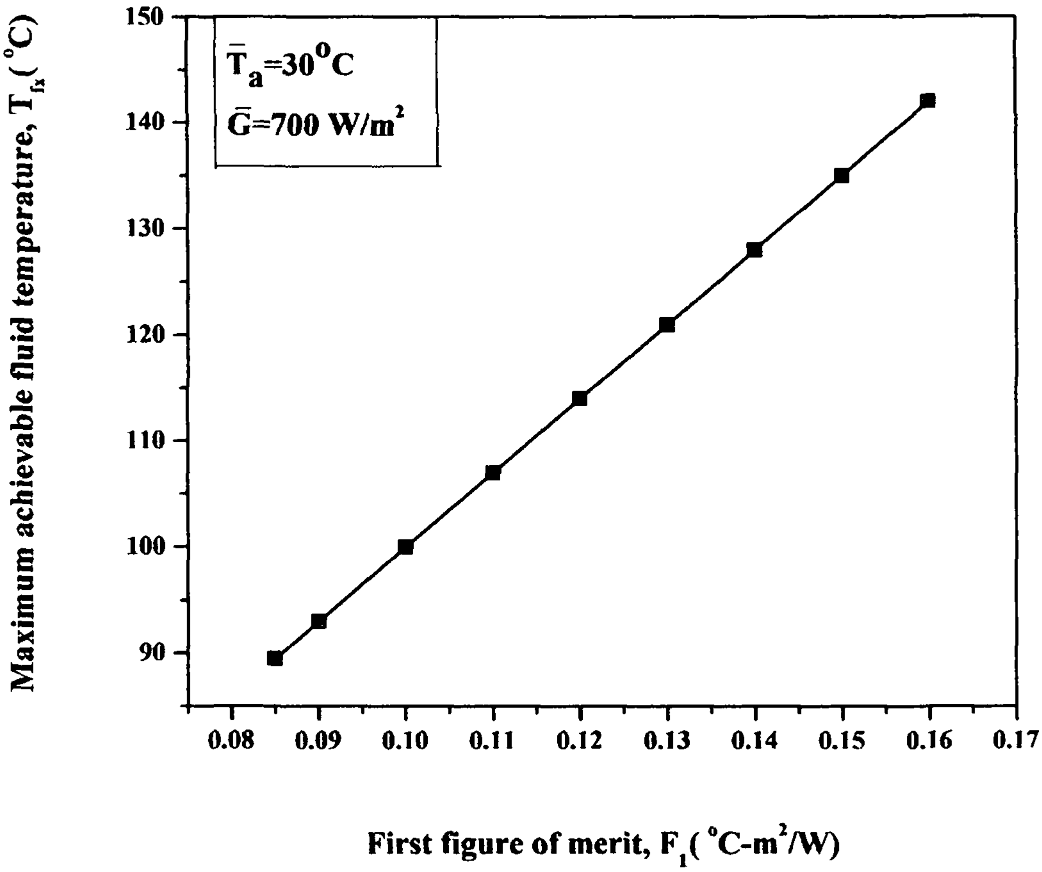

Fig.2.1: Absorber plate surface temperature, T_{fx} vs. F_1 graph.

The objective parameter, τ_r, i.e the time taken to reach the reference cooking temperature T_{w2} of 95°C from the initial temperature T_{w1} of 30 °C of the content of the cooker pot, is calculated by using the relation given in the Table-2.5 [1]. It is found that τ_r(RT) has inverse relationship with second figure of merit F_2, if other variables are considered to be constant. τ_r decreases with increase in F_2. So this objective parameter can provide information about the cooking rate of the cooker which can eventually give the idea about the number of meals that can be cooked in a day. The behaviour of τ_r with increase in F_2 is shown in Fig-2.2. As expected there is a non-linear drop in the value of τ_r. For higher value of F_2 the decrease in RT decreases. This is because of non-linear heat losses of higher temperature. T_{fx} and τ_{hr} cannot be calculated from F_2.

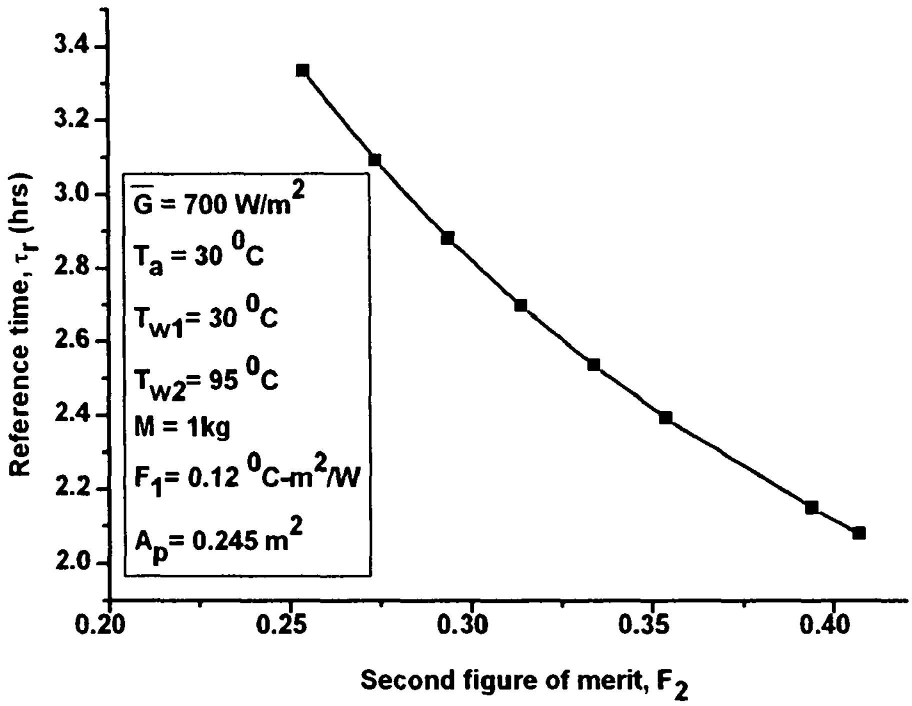

Fig.2.2: Reference Time, τ_r, vs. Second figure of merit,F_2 curve.

The objective parameter τ_r can also be calculated from standard cooking power (P_s) as given in the Table-2.5[42]. From the relation it is seen that τ_r increases with decrease in power (P_s). This is probably due to the fact that at higher temperature heat loss from the system to surrounding increases and also heat transfer process to the cooking pot slows down due to small temperature difference between the load and the heat source. The non- linearity in P_s appears to be a little more than F_2. Fig-2.3 shows the relationship between τ_r and P_s. The other two objective parameter T_{fx} and τ_{hr} cannot be calculated from P_s as it does not provide sufficient information about these two parameters.

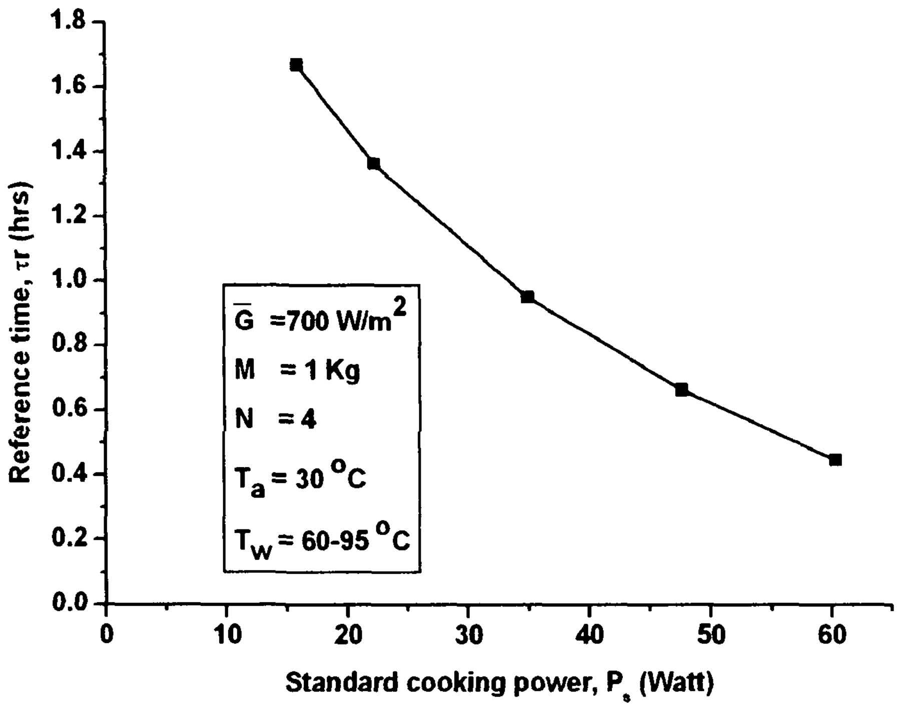

Fig.2.3: Reference Time, τ_r vs. Standard cooking power, P_s curve.

The standard cooking power can be represented as a function of (T_w-T_a) and number of pots (N) for the cookers on the basis of regression analysis of experimental data [42] standardized for solar irradiance (G) of 700 W/m^2. It is of the form

$$P_s = [C_1+C_2N-C_3 (T_w-T_a) N] \tag{2.14}$$

where P_s is the Standard cooking power, Watt, C_1, C_2, C_3 were Coefficients, N is the Number of pots, T_a is the Ambient air temperature.°C, T_w is the water temperature °C. Here the coefficients C_1, C_2 and C_3 are estimated for each cooker.

Time (τ_r) taken for sensible heating of water from $T_{w1}$to T_{w2} can now be derived from equation (2.12). It can predict the time for sensible heating with variation in N also. From theoretical calculation it is seen that up to 89^{0}C the time required for sensible heating of a given load of water decreases with increase in number of pots. This may be because standard cooking power increases with increase in number of pots. Then from 90^{0}C onwards, standard cooking power and sensible heating time of water decreases with increase in number of pots This may be due to increase in temperature difference beyond certain limit (here 60^{0}C) which causes slowing down of heat transfer rate to the content of the cooking pot and increases heat loss from the cooker interior to outside by different mode.

The objective parameter τ_r can also be calculated from efficiency of the cooker [15] as given in the Table-2.5. τ_r decreases asymptotically with increase in efficiency. The interdependence of these two parameters is shown in Fig-2.4. The increased non-linearity

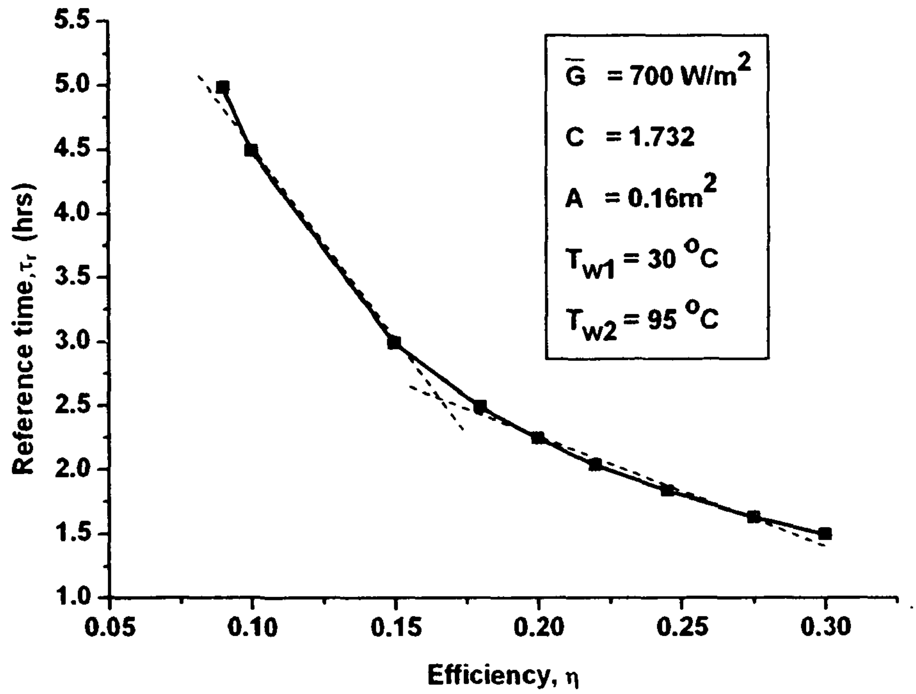

Fig.2.4: Reference Time, τ_r vs. efficiency, η curve.

limits its utility within narrow ranges of variations in the efficiency only. We may use two different ranges to determine τ_r based on the slopes as shown in fig.2.4. Small change in τ_r in the higher efficiency ranges limits the utility of this TPP.

Fig.2.5 shows the relationship between τ_r and specific time (t_s). The graph clearly indicates that if specific time increases then time required for reaching reference cooking temperature also increases. Lower the value of τ_r, higher the number of meal that can be cooked. τ_r, which is an objective parameter is also a user-friendly parameter as this parameter helps the users in selecting their requirement. But performance parameter t_s provide this information to the user indirectly.

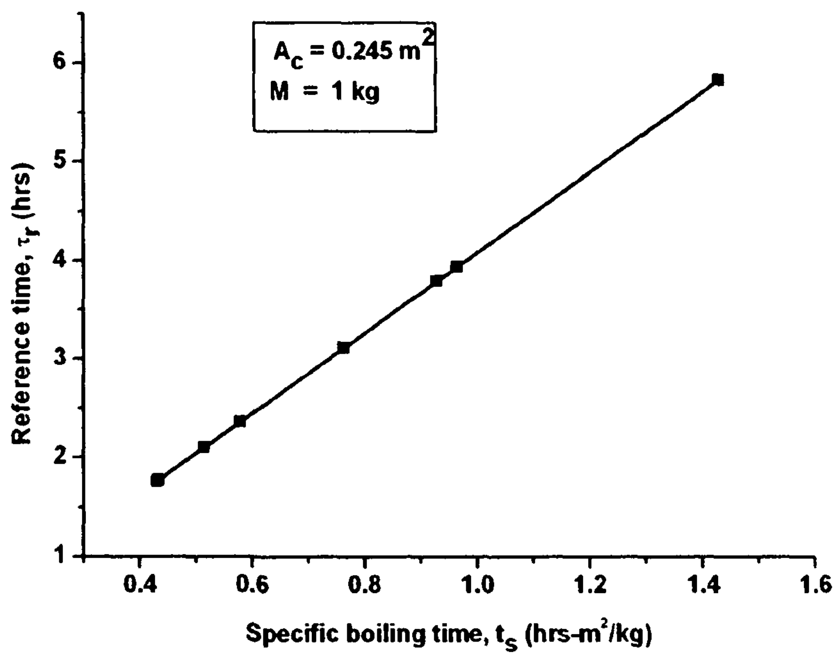

Fig.2.5. Reference Time, τ_r vs. specific boiling time, t_s curve.

By knowing the time(τ_r) from different performance parameters like F_2, standard cooking power (P_s), specific time (t_s) etc. the user can select the cooker according to their requirement i.e. whether they are going to use the cooker for cooking single meal or double meal. It is very difficult from users' point of view to grade the cooker if different performance parameters are supplied for different cookers of same type (i.e. box type).

By knowing the time(τ_r) of different types of box type cooker specific to location and climate, comparison can be made among these cookers. So this objective parameter (τ_r) can help in providing information about the quality of the cooker. Efficiency is dependent on ambient temperature (T_a) so it may vary from place to place. The other two objective parameter T_{fx} and τ_{hr} cannot be determined from efficiency of the cooker.

2.5. Conclusions:

From the study it is concluded that objective parameters can provide all the necessary information related to cooking of a cooker, on the basis of which cooker suitable for a particular climate and geographic location may be selected. But determination of these requires performance parameter which is independent of external factors. Most of the existing performance parameters are largely climate independent and can provide the information about the gradable performance value of the cookers.

It has been shown that it is possible to calculate only some of the objective parameters from available performance parameters. None of these performance parameters is capable of predicting the value of heat retention time (τ_{hr}).

The performance parameter F_1 and F_2 are design dependent parameters. So if the values of F_1 and F_2 are close to higher limit of their respective ranges then the cooker will perform well. But in reality that may not be possible because the cooking activity is dependent on intensity of radiation and some other parameters like velocity of wind, duration of sun shine, presence of clouds etc. These factors are not taken care of by these TPPs as they are not able to predict HRD, τ_{hr}. So depending on the role of these parameter the cooker having better F_1, F_2 may not be able to solve the purpose/aspiration of the buyer of a locality having these types of constraints. Researchers are also not considering this aspect while grading the cookers. So users are in dilemma in selecting cookers suitable for their location. Similarly, in measuring P_s maximum temperature difference is considered to be 50°C and having this difference the P_s is considered to be suitable for cooking purpose. But lower and upper limit of temperature range is not set for estimation of P_s. So the cooker having good cooking power may not even be able to cook.

Thus, in spite of being very stable the existing parameters do not seem to predict every aspect of solar cooker.

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Chapter -3

Evolution of a generic test procedure for determination of proposed thermal performance parameters for paraboloid concentrator cooker and their correlation with objective parameters.

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Evolution of a generic test procedure for determination of proposed thermal performance parameters for paraboloid concentrator cooker and their correlation with objective parameters.

A concentrating cooker system appears to have more degrees of freedom as its cooking pot and collectors are two different and independent components which may be independently designed. On the contrary the dominant mode of heat transfer from the collector to the pot is radiation. It puts additional constraint because unlike other modes of heat transfer it depends on direction as well. Also this is an open system and all its measureable parameters are susceptible to variation with minimal fluctuation in climatic parameters. With the aim of the thesis being development of a generalized performance parameter which is absolute, holistic, and robust with an associated test procedure it is pertinent to consider a concentrating cooker system like PCC, initially. Performance of other cookers may be represented in terms of those TPPs as special cases.

This chapter deals with the development of such a generic test procedure for determination of identified TPPs for PCCs. It is endeavored to evolve and build-up the generalized TPPs and test procedure for different cooker designs on this foundation.

3.1. Introduction:

To enhance the performance and utility and to decrease the cost of solar cookers, different designs of concentrator type cooker have been proposed [1]. The performance of each design has been represented in terms of one of the TPPs based on the respective test procedure. The details of some of them with the values of TPPs reported by respective workers are being presented here.

A CC with spiral reflector and insulated oven receiver have designed and developed by Khalifa *et al.* [1987]. The cooking pot was heated from both side and bottom. The thermal performance parameter proposed used was instantaneous oven efficiency, overall oven efficiency and overall cooker efficiency. The oven efficiency and cooker efficiency were reported to be 68.3% and 33.1% respectively [2]. The details are given in Appendix-III.

Cooking in concentrating cooker (CC) is done in cooking pot which is normally exposed to outer environment. Insulated pots can be used in place of bare pot to boost the overall cooker efficiency. Oven type receiver, proposed by Habeebullah *et al.*[1995], had an insulated cooking pot to enhance the performance of the CC. The instantaneous efficiencies for the oven receiver were well above 50% irrespective of wind speed. Similarly the overall efficiency of insulated receiver and bare receiver at wind speed of 2.5 m/s were 55.11% and 36.95% respectively [3].

Another variant of CC available is paraboloid dish solar cooker [4]. The cooker developed by Hosny *et al* consisted of paraboloid dish reflector made of highly polished stainless steel sheet with reflectivity of 0.75, a wind shield and a tracking system. Two receivers were used in this cooker. One was aluminium cooking pot for water heating test and other one was cooking tray for frying and grilling test. The PPs proposed to evaluate the performance of the cooker were optical efficiency, instantaneous thermal efficiency, process thermal efficiency, characteristic boiling time etc. The process thermal efficiency and characteristic boiling time were 15.52% and 33.04 min/kg respectively, as reported by them. The effect of some parameters such as wind clouds and load on performance of the cooker was studied. It was found that process thermal efficiency decreased with increase in load, wind speed, and cloudiness duration.

The TPPs considered for PCC by Mullick *et al* [5] were optical efficiency factor, and over all heat loss factor. On the basis if the heating and cooling tests on water they could predict the values of the optical efficiency factor to be 0.4 and over all heat loss factor of 17.6 W/m^2K. This work provides one of the most stable parameters. The details of the test procedure are discussed in Appendix-III.

Three different types of CCs were available as reported by Patel et al [6]. The optical efficiency, one of the performance parameter of these three types of cooker, varied from 35-42% as reported. For one parabolic cooker it was 35%, and for two Fresnel type cooker designs it was reported to be 39% and 42%. The details are given in Appendix-III. Performance of another Fresnel concentrating cooker [7] was determined through different types of tests. The tests were stagnation test, water heating test and cooking test, as reported. The stagnation test gave the highest achievable temperature and the water heating test gave the time required to reach some predetermined temperature.

Another design variant of the CC, a conical frustum cooker, was reported by Sharaf, E[8]. It was a cone type cooker with reflecting internal wall. The performance parameter proposed here was short maximum time for cooking. The short maximum time to boil 0.3 kg of corn oil was 0.25 hr as reported.

A simply designed and low cost parabolic solar cooker was fabricated and tested [9]. The performance parameter proposed here were energy efficiency and exergy efficiency. The cooking pot in this type of cooker is placed at the centre/focus of the reflector which is a line focusing type. The energy efficiency was found in the rage of 2.8-15.7%. Exergy efficiency was in the range of 0.4-1.25%. Energy output was in between 20.9 and 78.1 W while the exergy output was in the range of 2.9-6.6 W. Thus this TPP was dependent on temperature of operation.

Most of the aforementioned TPPs are largely having the desirable features but are too design specific of a particular CC and facilitate determination of a few OPs only. This chapter tries to evolve an approach to develop TPPs and test procedure for CCs with special reference to PCC. Paraboloid concentrator cooker is one of the many types developed so far with the objective of getting improved performance and capability to carry out multiple number and types of cooking. Concentrator type solar cooker can provide enough power to carry out cooking at a faster rate and at high temperature compared to box type cooker [10]. So it is not only suitable for different types of cooking, i.e. boiling type, frying, roasting etc. but also for preparing multiple meals.

Objective parameters (OPs), which enable determination of usability of a cooker, have been identified in Chapter-II for box type solar cookers. These are (i) Maximum achievable fluid temperature (T_{fx}), (ii) Reference time (τ_r), and (iii) Heat retention duration (τ_{hr}). The details of the parameters have been discussed in Chapter-II. An attempt has been made to use these OPs for parabolic concentrator cookers and develop correlations linking the existing and proposed TPPs with OPs. It is given in Table 3.1. From the Table 3.1 it is seen that no OPs can be correlated with the existing TPPs. The proposed test procedure and TPPs enable determination of all the three OPs. It is discussed in detail in Section 3. 3.

Table- 3.1: Correlation between existing TPPs and OPs for PCC

Reference	PP	Reported range of PP	OP	Equation for OP
Mullick et al.[5]	$F'\eta_o$,	0.447-0.454	T_{fx} τ_r τ_{hr}	Cannot be expressed
	$F'U_L$	17.2 $W/m^{2o}C$		
Khalifa et al[2]	η_c	33.1% (Water) 18.6-29.6% (olive oil)	T_{fx} τ_r τ_{hr}	Cannot be expressed
	η_o	68.3% (Water) 38.4-61.0 (olive oil)	T_{fx} τ_r τ_{hr}	Cannot be expressed
Patel et al[6]	η_{th}	35-42%	T_{fx} τ_r τ_{hr}	Cannot be expressed
Habeebullah et al[3]	t_s	24.26-30.952	T_{fx} τ_r τ_{hr}	Cannot be expressed
	$\eta_{o,rec}$	54.31-56.11%	T_{fx} τ_r τ_{hr}	Cannot be expressed

Hosny et al.[4]	t_c	33.0-36.5	T_{fx} τ_r τ_{hr}	Cannot be expressed
	η_p	5.41-17%	T_{fx} τ_r τ_{hr}	Cannot be expressed
Sonune et al[7]	T_{px}	255° C	T_{fx} τ_r τ_{hr}	Cannot be expressed
Ozturk et al.[9]	η	2.8-15.7%	T_{fx} τ_r τ_{hr}	Cannot be expressed
	Ψ	0.41-1.25	T_{fx} τ_r τ_{hr}	Cannot be expressed
Sharaf E[8]	$\tau_{max(hr)}$	0.25-3.5	T_{fx} τ_r τ_{hr}	Cannot be expressed

3.2. Proposed thermal performance parameters and Test procedure for their determination:

3.2.1 Theory:

The energy balance considerations, similar to flat plate collectors, are applied to describe the performance of concentrator cookers. The complication occurs in the calculation of thermal losses due to the following reasons:

i. Receiver shapes are widely variable and the radiation intensity at the receiver/pot is not uniform
ii. The temperature being high, edge losses and conduction effects are significant

Thus it is not possible to give a general analysis for the estimation of thermal losses of concentrating cooker. Each receiver has to be analyzed separately. However from basic knowledge of flat plate collector one can derive the expression for collection efficiency or thermal efficiency in terms of fluid temperature, ambient temperature and solar intensity [11]. Rate of gain of energy is the difference between the solar energy absorbed and thermal energy lost and is given by

$$\dot{Q}_u = \dot{Q}_{in} - \dot{Q}_L$$
$$= S - U_L\left(T_{pm} - T_a\right) \quad (3.1)$$

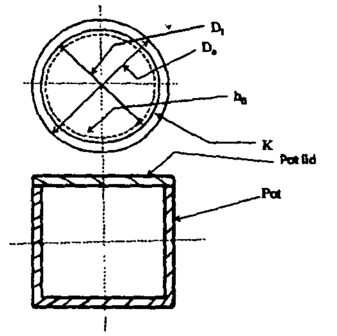
where $\dot{Q}_u, \dot{Q}_{in}, \dot{Q}_L$ are gain in energy, energy absorbed and energy lost respectively. S is the absorbed radiation per unit area of unshaded aperture falling normally and is given as $\overline{G}_b \rho(\gamma\tau\alpha)_n K_{\gamma\tau\alpha}$. Here $\overline{G}_b$ is the beam component of the incident radiation, ρ is the specular reflectance of the concentrator, γ is intercept factor, α is absoptance of the absorber, τ is transmittance of the transparent cover (if any), and $K_{\gamma\alpha\tau}$ is an incidence angle modifier. Here γ, ρ, α, and τ are the functions of angle of incidence of radiation on the aperture. γ and $K_{\gamma\alpha\tau}$ are taken approximately equal to unity in the present case. U_L is the heat loss coefficient from pot to ambient; T_{pm} is the mean temperature of the bottom of the pot and T_a is the ambient temperature.

The useful energy gain in terms of the absorbed solar radiation per unit collector's aperture area is

$$\dot{Q}_u'' = \frac{\dot{Q}_u}{A_c} = S - \frac{A_t U_L}{A_c}\left(T_{pm} - T_a\right) \quad (3.2)$$

where A_c is the aperture area and A_t is the heat loss area of the pot of a given shape/cross section.

In steady state condition the useful energy gain per unit area in terms of the energy transfer to the fluid/ water at local fluid temperature T_{wm} in the pot, is given in equation (3.3) and shown in Fig.3.1 (a). Fig.3.1 (b) shows the position of the pot with respect to the collector.



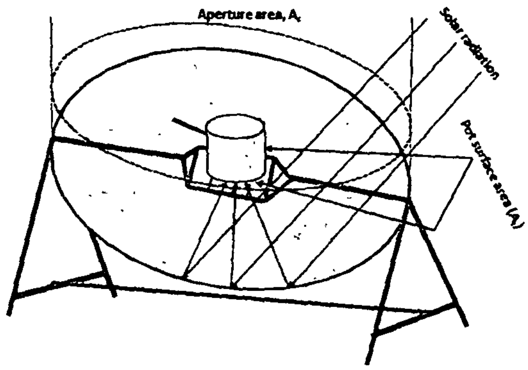


Fig.3.1 (a).Sectional view of a pot of circular cross-section.

Fig.3.1 (b). Schematic drawing of a PCC showing position of the pot and collector.

$$\dot{Q}_u'' = \frac{A_t/A_c\left(T_{pm} - T_{wm}\right)}{\dfrac{D_0}{h_{fi}D_i} + \left(\dfrac{D_0}{2K}\ln\dfrac{D_0}{D_i}\right)} \tag{3.3}$$

Elimination of T_{pm} from the above equations (3.2) and (3.3) gives the rate of useful energy per unit area as

$$\dot{Q}_u'' = F'\frac{A_c}{A_c}\left[S - \frac{A_t}{A_c}U_L\left(T_{wm} - T_a\right)\right] \tag{3.4}$$

F′ is collector efficiency factor and is defined below. Other parameters are same as given above.

Collector Efficiency Factor F′

The collector efficiency factor F′ is defined as the ratio of actual useful heat collection rate to the useful heat collection rate when the collector absorbing surface (T_{pm}) is at the local fluid temperature (T_{wm}), i.e.

$$F' = \frac{\dot{Q}_{u\,seful}}{\dot{Q}_u \mid_{T_{pm}=T_{wm}}} = \frac{\dot{Q}_{useful}}{A_c\left[\dot{Q}_{ab} - U_L(T_{wm} - T_a)\right]} \tag{3.5}$$

A general expression for F′ can be obtained with the following simplifying assumptions:

i. The incident solar radiation is absorbed only by the absorbing surface.
ii. The bottom surface of the plate (absent in CC) is perfectly insulated and the heat loss occurs only from the top surface of the plate.
iii. The pot is kept onto the plate (absent in CC) and the contact has a poor thermal conductivity
iv. Thermal inertia effect can be neglected i.e. steady state analysis is valid.

Thus

$$F' = \frac{Heat\ transfer\ resistance\ from\ absorbing\ surface\ to\ the\ ambient}{Heat\ transfer\ resistance\ form\ fluid\ to\ ambient} \tag{3.6}$$

The collector efficiency factor, F′ is essentially a parameter dependent on design. F′ increases with increase in material thickness and the thermal conductivity. Increasing the overall loss coefficient decreases F′ while an increase in the fluid to pot heat transfer coefficient increases it. From figure (1) F' can be defined as:

$$F' = \frac{\dfrac{1}{U_L}}{\dfrac{1}{U_L} + \dfrac{D_0}{h_{fi}D_i} + \dfrac{D_0}{2K}\ln\dfrac{D_0}{D_i}} \tag{3.7}$$

in which, U_L is the heat transfer coefficient from pot to ambient; D_i and D_o are the inside and outside diameter of the pot, h_{fi} is the heat transfer coefficient from fluid to inner wall of the pot and K the thermal conductivity of the pot.

Now from equation (3.4)

$$\dot{Q}_u'' = F'\left[S - \frac{U_L}{C}(T_{wm} - T_a)\right] \quad (3.8)$$

where C = concentration ration= A_c/A_t

$$= F'\left[\eta_0 \overline{G}_b - \frac{U_L}{C}(T_{wm} - T_a)\right] \quad (3.9)$$

where $\eta_0 = \frac{S}{\overline{G}_b}$

Now dividing the equation by mean beam irradiance $\overline{G}_b$

$$\frac{\dot{Q}_u''}{\overline{G}_b} = \left[F'\eta_0 - \frac{F'U_L}{C}\left(\frac{(T_{wm} - T_a)}{\overline{G}_b}\right)\right] \quad (3.10)$$

3.2.2 Identification of TPPs for CC/PCC:

Parameters that play crucial role in determining the thermal performance of such type of solar cookers are - optical efficiency factor ($F'\eta_o$) [12], heat loss factor ($F'U_L$) [13] and concentration ratio(C). These parameters are quite useful thermal performance parameters (TPPs). The optical efficiency factor ($F'\eta_o$) identifies the upper limit of performance and is basically dependent on geometry of the concentrator, surface precision of reflector, reflectance of surface, absorptance of the cooking pot, accuracy of tracking etc. [13-16]. It is also influenced by variation in F', incident angle modifier [5] and presence of diffuse component of solar radiation to some extent but these are either averaged out and/or have negligible influence. The heat loss factor ($F'U_L$) depends on design parameter and operational conditions such that it increases with rise in pot water temperature and wind velocity [10]. Increase or decrease in the value of $F'U_L$ is largely and directly dependent on the speed of wind [2, 3, 5, 15,]. It is also affected by loss of vapor and hence it requires a vapor tight pot for better performance. The tilt of the reflector aperture also has an effect on the value of $F'U_L$ [15]. As noted earlier to qualify to be TPP the parameters must be independent of climatic parameters and must be inclusive in terms of different components of cookers. Concentration ratio is the ratio of collector aperture area to absorber area. It is the factor by which radiation flux on the energy- absorbing surface is increased. Concentration ratio can vary over several orders of magnitude. With this wide range of designs, it is difficult to develop general performance parameters applicable to all concentrators [17].

As discussed earlier some of the thermal performance parameters (TPPs) reported by different workers for CC/PCC are optical efficiency of the concentrating surface ($F'\eta_o$)[13], heat loss factor from the pot($F'U_L$) [5, 15], cooking time [3, 13], effective cooking power[16, 18], standard cooking power (P_s) [12 18], specific boiling time(t_s) [2]etc. To determine the TPPs there is a need to follow a test procedure which is simple, less time consuming, single step and less constrained.

It may be noted that the concentration ratio influences the thermal performance of the PCC as the radiative heat transfer from the cooking pot is partially governed by this. In the present work the two TPPs, $F'\eta o$ and $F'U_L/C$ are proposed. The test procedure is single step based on heating of a standard load. The proposed test procedure needs experimental recording of certain variables at regular interval. For this, water is heated in the cooking pot by keeping it at the focus of the PCC. T_w, T_a and G_b are recorded at regular interval. The rate of useful heat gain per unit area by water can be estimated from the equation (3.9)

The two thermal performance parameters $F'\eta_0$ and $F'U_L/C$ being proposed are identical to those considered by Mullick *et al.* [5], but are more holistic in nature and are determined using a different test procedure. The test procedure is single step based on heating of a standard load. The overall procedure takes less time and provides identical accuracy with absolute error less than ±7%. Here the error, as given later in Table-3.3, indicates the deviation in the theoretical values of Objective Parameters (OPs) predicted using their correlation with TPP of the cooker from the experimentally measured values.

Here the second TPP consists of C in the denominator which enables characterization of the reflecting surface as well which might play an active role in enhancing the radiative component of the heat transfer process. This is also in tune with the objective of the thesis enumerated in section 1.9 and has following additional justification

i) A single parameter takes into account both pot and reflector system.

ii) The concentrating system affects both radiative and convective losses from the pot in addition to its envisaged function as radiation augmentor.

Hence the proposed parameter seems to be more holistic in characterizing the cooker. Experimental determination of these parameters is possible by the method which is discussed next.

In this method an exponential curve is fitted through the points of the temperature, T_w versus time, t graph which may be an equation of the form similar to

$$T_w = T_{w0} + Ae^{-t/t_0} \tag{3.11}$$

where T_{wo} is the initial value of the T_w, A is a constant (°C), t_o is the decay constant in min and t is the time in min. The equation of the curve is used to determine statistically corrected value of the rate of the temperature rise at different time intervals by using the equation (3.11). This data is used to plot $\dot{Q}''/\overline{G}_b$ versus $(T_{wm} - \overline{T}_a)/\overline{G}_b$. The experimental test procedure followed to determine the two thermal performance parameter is outlined in the following section.

3.2.3. The Proposed Test Procedure:

a) Instrumentation:

To forecast performance of solar cookers, accurate solar irradiation data is required. Measurement of both beam and total solar radiation is required. Pyrheliometer and Pyranometer are the two basic instruments by which these solar radiation components can be measured.

(i) **Pyreheliometer:** It is an instrument which measures beam radiation. In this instrument the sensor disc is located at the base of a tube whose axis is associated with the direction of the sun's rays to block the diffuse radiation. Pyrheliometer follows the sun to measure only direct sun rays and avoid diffuse part. In practice an electrically driven equatorial mount is attached with the instrument to track the sun. The diffuse component is avoided by installing a collimator tube over the sensor with a circular cone angle of 5°. Problems with pyreheliometer measurement are several fold; the aperture angle, the circum solar contributions and imprecision in tracking mechanism. The first two problems are almost impossible to eliminate because of the inability to define the solar disc precisely and the finite dimensions of the instruments components. Three different types of pyre heliometers are widely use to measure the beam radiation. The instrument used in the experimentation was a Recording Pyreheliometer. The calibration constant was 6.58μV/W/m^2 or 4.59mV/cal/cm^2/min. The error of this instrument is 0.1%. The photograph is as shown below. The manufacturer of the Recording pyreheliometer is National Instruments Ltd. Calcutta, India.

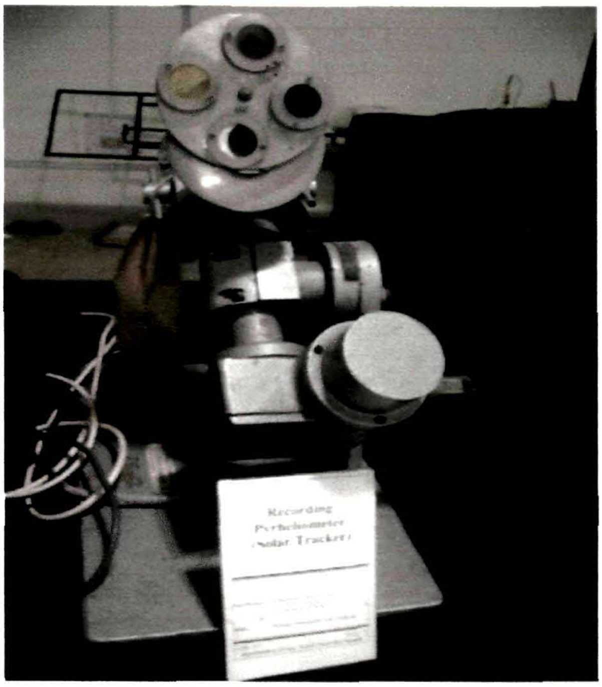


Fig.3.2. Photograph of Recording Pyreheliometer

(ii) **Pyranometer:** A pyranometer is an instrument for measuring total hemispherical solar radiation (beam plus diffuse) radiation usually on a horizontal surface. If shaded from the beam radiation by a shade ring or disc, a pyranometer measures diffuse radiation. In most pyranometers, the sun's radiation is allowed to fall on a black surface to which the hot junctions of a thermopile are attached. The cold junctions of the thermopile are located in such a way that they do not receive the radiation. As a result an e.m.f. proportional to the solar radiation is generated. This e.m.f. which is usually in the range of 0 to 10 mV can be read, recorded or integrated over a period of time with regular calibration of about ±2% can be obtained. The calibration factor of the instrument used in the experiments was $7.56\mu V/W/m^2$ or $5.27 mV/cal/cm^2/min$. The manufacturer of the pyranometer used is National Instruments Ltd. Calcutta, India.

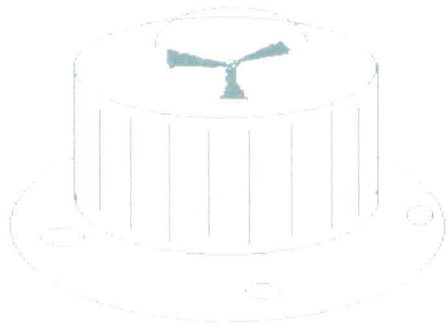


Fig.3.3. Schematic diagram of Pyranometer

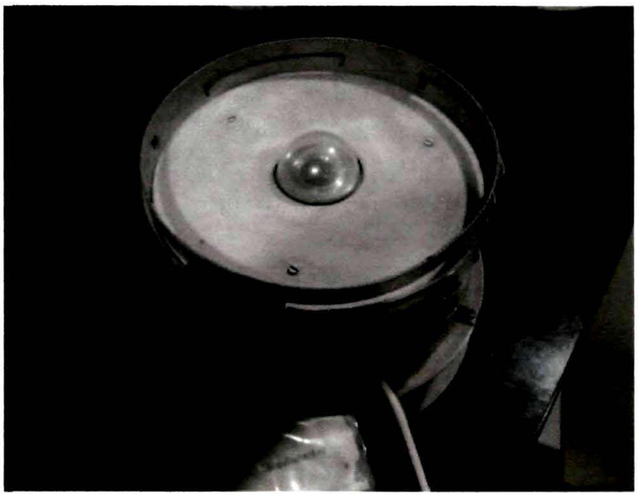


Fig:3.4. Photograph of pyranometer

(iii) **Solarimeter/Suryamapi:** A solarimeter can generally be interpreted to mean the same as a pyranometer [17]. The instrument is also known as Suryamapi. It is used for measurement of radiation falling on the surface of the cooker. The manufacturer of the instrument available in the laboratory is the Central Electronics Ltd. India.

Fig3.5. Photograph of solarimeter

(iv) **Research Radiometer:** The total solar radiation is also measured by using ILT 1700 Research Radiometer. Two sensors are provided to measure solar radiation in UV and solar range respectively. The sensor used for measurement of solar radiation in the visible range is SED033 (serial no: 8645). The sensor provided for measurement of radiation in the UV range is SED005 (serial no: 1076). The ILT1700 Research Radiometer and photometer is one of the most versatile current measurement instruments in the world. Designed specifically to measure photo detector current, the ILT1700 maintains linearity over a 10 billion to 1 dynamic range. The accuracy of this instrument is very high.

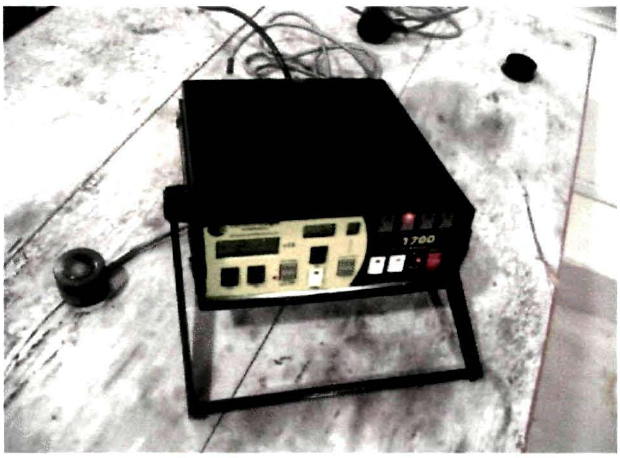
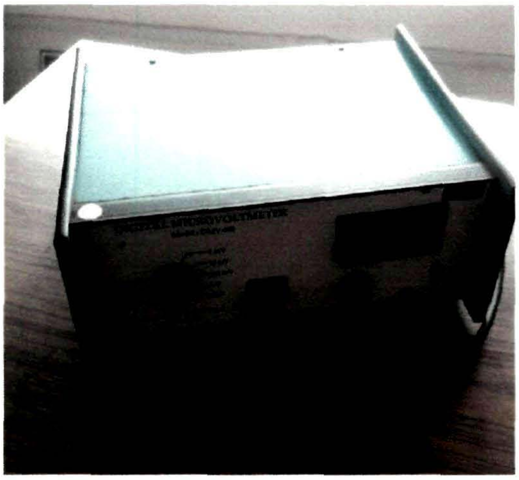


Fig.3.6. Photograpph of Research Radiometer

(i) **Micro volt meter:** Digital microvolt meter (model: DMV-001, serial no: 499) made by Scientific Equipment Company of Roorkee (India) was used to measure the voltage developed at the two ends of the thermocouple. With this instrument change in temperature of fluid used in sensible heating test could be measured accurately. It is a very versatile multipurpose instrument for the measurement of low D.C. voltage. It has 5 decade ranges from 1 mV to 10 V with 100% over ranging. The accuracy of this instrument is one micro volt. Direct measurement of thermocouple output to read temperatures with a resolution of 1/40th of a degree was possible.



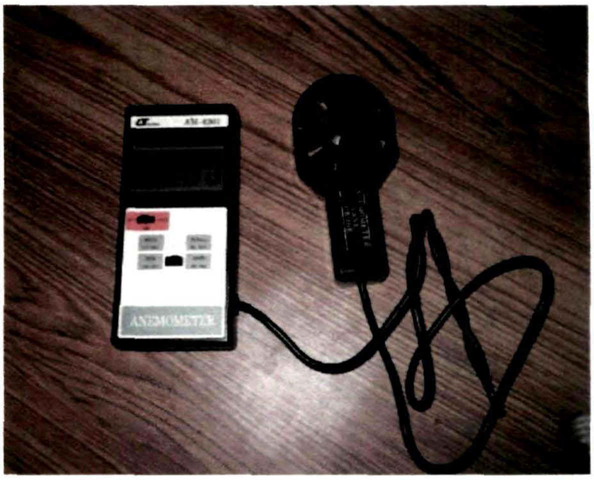


Fig. 3.7. Photograph of Micro volt meter Fig.3.8. Photograph of Anemometer

vi) **Anemometer:** Anemometer is used to measure velocity of wind during experimentation. The portable anemometer provides fast accurate readings with digital readability and convenience of a remote sensor separately. It could provide air flow measurements in units such as: m/s, km/h, ft/min, knots. Low friction ball bearing design allows free vane movement, resulting in accuracy at both high and low velocities. A sensitive balanced vane wheel rotates freely in response to air flow. The operating temperature should be 0-50 ^{o}C. The manufacturer of the Anemometer is Lutron of Taiwan.

vii) **Thermo couple:** A thermocouple is a device consisting of two different conductors that produce a voltage proportional to a temperature difference between either ends of the pair of conductors. Thermocouples are a widely used temperature sensor for measurement and control. They are inexpensive, interchangeable and can measure wide range of temperatures. Thermocouples are self powered and require no external form of excitation. The main limitation with thermocouples is accuracy and system errors of less than one degree Celsius can be difficult to achieve. During experimentation copper- constantan thermo couples were used.

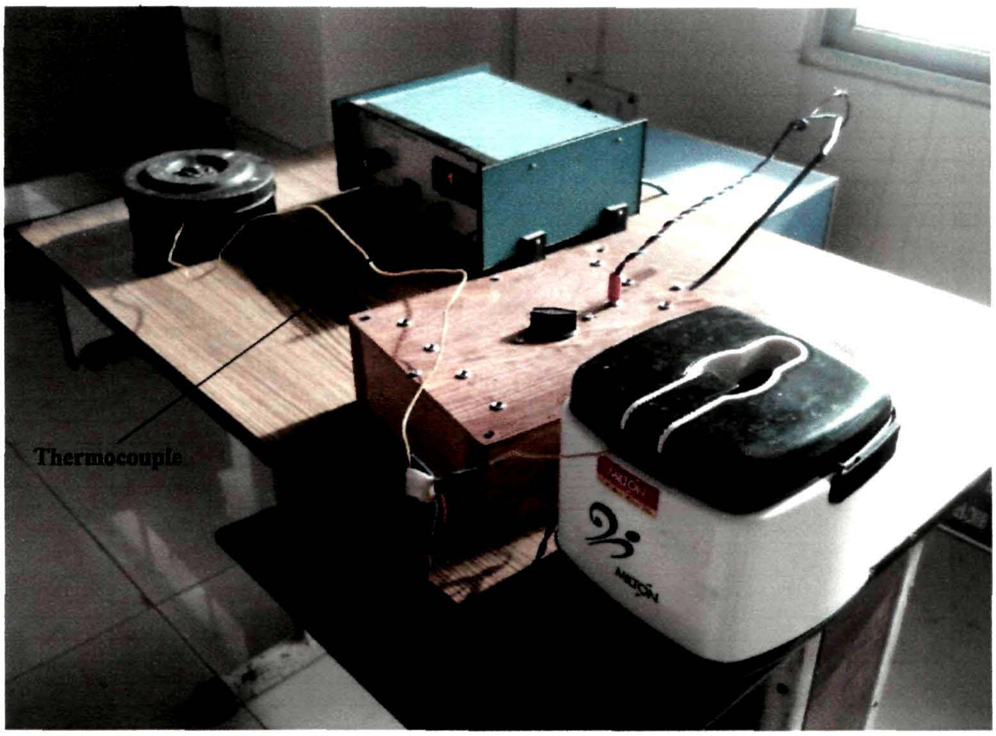


Fig. 3.9. Photograph showing thermocouple

b) Test Procedure:

The test set-up (Fig.3.10) consists of a pot (essentially a pressure cooker) filled with double distilled water of mass 4.751 kg (@ 3kg/m^2 of aperture area) kept at the focus of the PCC so that bright spot of the concentrated radiation falls at the bottom of the cooking pot.

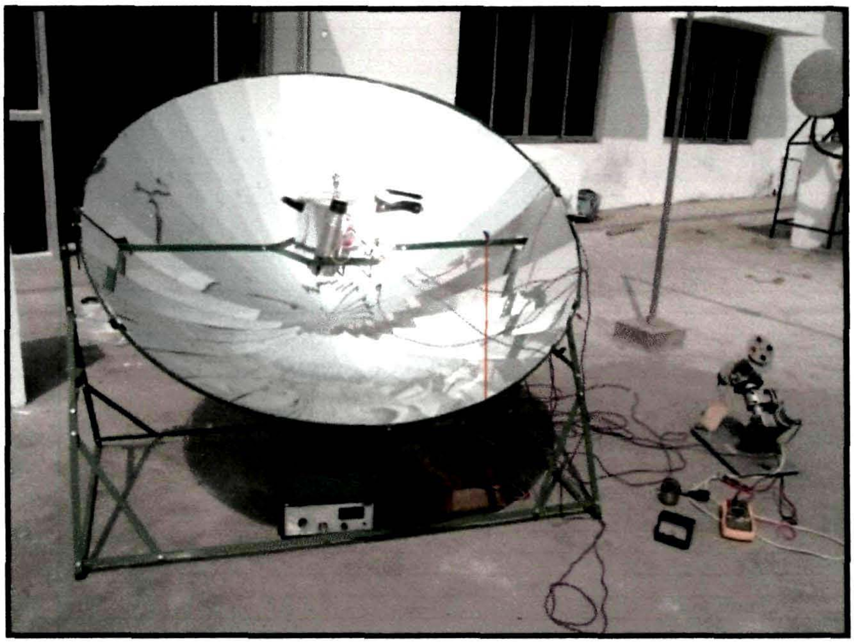


Fig3.10: Experimental set up of parabolic dish type solar cooker

During the test the water temperature was recorded at 5 minute interval till the temperature reaches close to the boiling point. The temperature was recorded using a calibrated copper-constantan thermocouple placed about 5cm above the bottom where boundary effect on temperature is absent through the hole available at the centre of the cooker lid. The hole was sealed so that vapor does not escape through it. Thermocouples were placed at the lid as well as at the cylindrical surface of the pot to monitor the rise in temperature of outer body of the cooker. The solar beam radiation G_b was also noted down at five minutes interval. Research Radiometer (ILT1700) was used to measure total radiation and Recording pyrheliometer (National Instruments, India) to measure beam radiation. The experiments were performed between ±1h 30 min of solar noon. Finally, the values of $(T_{wm} - \overline{T}_a)/\overline{G}_b$ and $\dot{Q}''$ are also found out from the readings for a suitable interval using the relation

$$\dot{Q}'' = \frac{(MC_w)_w'(T_{w2} - T_{w1})}{A_c \Delta t} \tag{3.12}$$

where $\dot{Q}''$ is the rate of useful heat gain by water per unit aperture area, M is the mass of water, C_w is the specific heat capacity of water, and $(MC_w)'_w$ is the sum of heat capacity of water and the pot. T_{w1} and T_{w2} is the initial and final temperature of water, A_c is the aperture area of cooker, and t is the time interval.

Now the data is plotted as discussed in Section 3.4.1 to determine the proposed TPPs $F'\eta_o$ and $F'U_L/C$. Using the ratio of these two values $U_L/\eta_o C$ is estimated for further calculations. The tests were conducted under the following conditions: $G_b \geq 600$ W/m^2; $20 \leq Ta \leq 40$ °C; wind speed < 1 m/s. It is desirable to carry out experiments under identical conditions.

The cooling experiment was also carried out by shadowing the cooker for verifying the values obtained from the analytical equation for τ_{hr}. The values of heating and cooling temperatures have been plotted with time and shown in Fig.3.11 for a typical day. It may be noted here that the proposed test procedure does not require carrying out of cooling test.

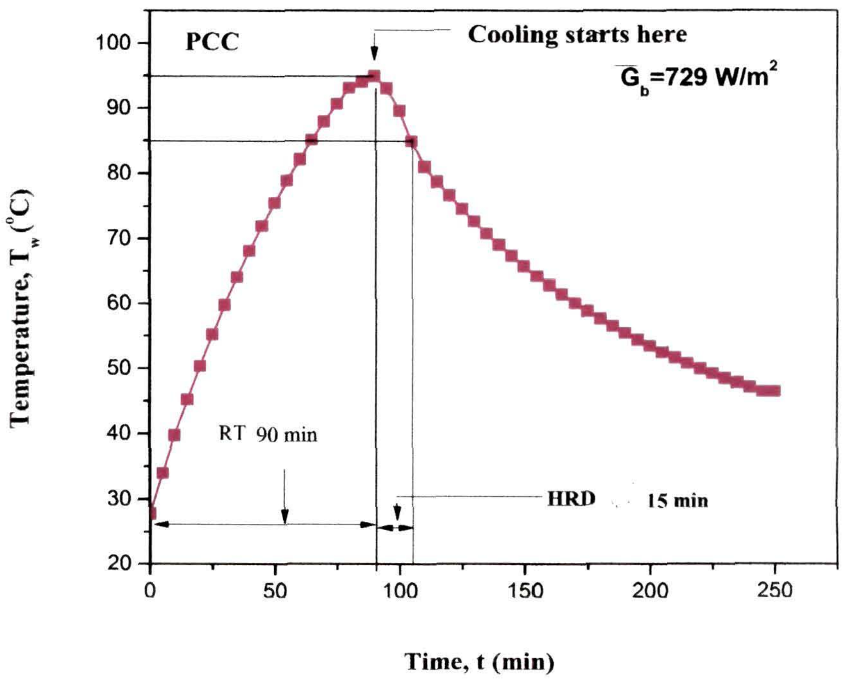


Fig.3.11: Heating and cooling curve of water

3.3. Correlating Proposed Thermal Performance parameters with objective parameters:

This section explores the possibility of determination of the three OPs from the TPPs for PCCs. In the case of PCC under steady state condition

$$\left[\eta_0 - \frac{U_L}{C}\frac{\left(T_{fx} - \overline{T}_a\right)}{\overline{G}_b}\right] = 0 \tag{3.13}$$

where T_{fx} is the maximum achievable fluid temperature(MAT) in °C

Hence the first OP, T_{fx}(MAT) can be derived from the following relation

$$T_{fx} = \frac{\eta_0 C \overline{G}_b}{U_L} + \overline{T}_a \tag{3.14}$$

where η_o is the optical efficiency, C is the concentration ratio, U_L is the heat loss factor, $\overline{G}_b$ is the beam radiation in W/m^2 and $\overline{T}_a$ is the ambient temperature in °C.

The second OP, τ_r (Reference time) may be expressed as:

$$\tau_r = \frac{(MC_w)'_w}{A_c F' U_L / C}\ln\left[\frac{\overline{G}_b - \frac{U_L}{\eta_0 C}\left(T_{w1} - \overline{T}_a\right)}{\overline{G}_b - \frac{U_L}{\eta_0 C}\left(T_{w2} - \overline{T}_a\right)}\right] \tag{3.15}$$

which for $T_{w1} = 303K$ and $T_{w2} = 368K$ will be

$$= \frac{(MC_w)'_w}{A_c F' U_L / C}\ln\left[\frac{\overline{G}_b - \frac{U_L}{\eta_0 C}\left(303 - \overline{T}_a\right)}{\overline{G}_b - \frac{U_L}{\eta_0 C}\left(368 - \overline{T}_a\right)}\right] \tag{3.16}$$

The ratio $U_L/\eta_o C$, and $F'U_L/C$ are taken from the values determined in earlier sections. Measured or standard values are used for other variable in eqn (3.14) and (3.15) from Table-1.

The third OP τ_{hr} (heat retention duration) is computed from the following equation:

$$\tau_{hr} = \frac{(MC_w)'_w C}{A_c F'U_L} \ln\left[(T_{w2} - \overline{T}_a)/(T_{w1} - \overline{T}_a)\right] \qquad (3.17)$$

Here $T_{w2} > T_{w1}$. For calculation of τ_{hr}, $F'U_L$ /C is taken from the values determined earlier. The values of the variables used for the purpose are given in Table -3.1.

Table-3.2: Values of the variables used in calculations

Variable	Value	Variable	Value
A_c	1.545m^2	$\overline{T}_a$	30° C
A_t*	0.174m^2	T_{w1}	30° C
M	4.751 Kg	T_{w2}	95°C
C_w	4186 J/kg-K		

3.4 .Results and Discussion:

The value of the two TPPs and the three OPs found from the method discussed earlier are presented in the Table-3.3, and 3.4.

The method uses the data of a single test to obtain the TPPs - $F'\eta_o$ and $F'U_L/C$. The $\dot{Q}''/\overline{G}_b$ versus $(T_{wm} - \overline{T}_a)/\overline{G}_b$ plots obtained as per the method outlined in section 3.4.1 are depicted in Figs 3.14, 3.16 and 3.18. The temporal variation of G_b and T_a for a typical day is shown in Fig.3.12. From the plot it was seen that there is little variation in beam radiation and ambient temperature as required for the experimentation. The corresponding plots are shown in Figs 3.13 and 3.14 for determination of the TPPs. The plots for two other days are also shown in Figs.3.15-3.18.

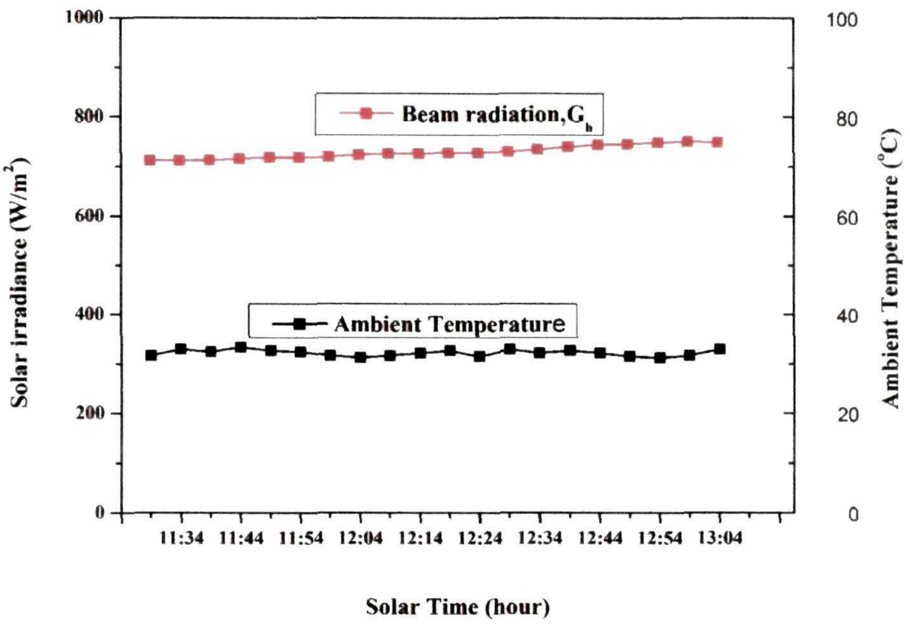


Fig.3.12. Measured solar beam radiation and ambient temperature on 26th April 2010 at Tezpur (Lat: 26° 41'46" Long= 92°50'05" MSL= 230 ft.)($\overline{G_b}$=729 W/m^2)

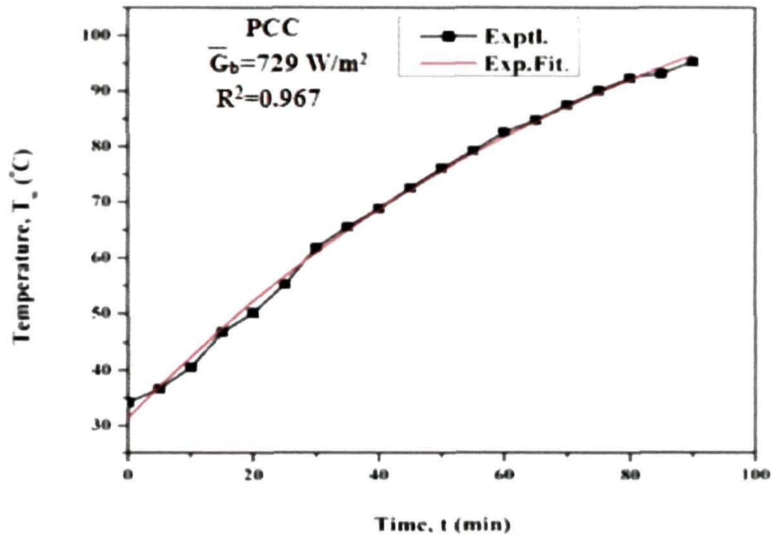


Fig.3.13. Rise in water temperature T_w with time t ($\overline{G_b}$ =729 W/m^2, $\overline{T_a}$= 30 °C)

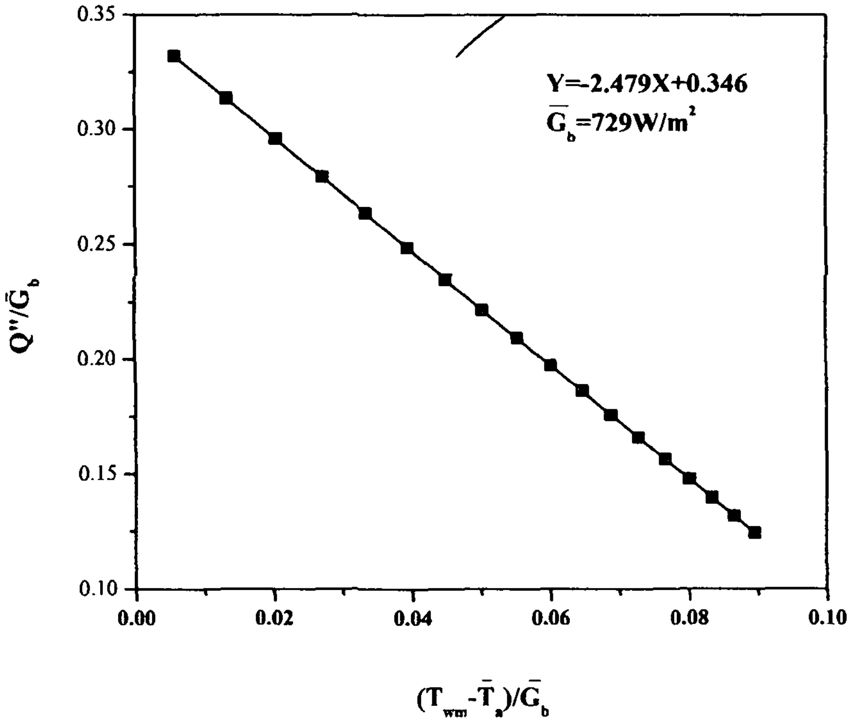


Fig.3.14. $\dot{Q}''/\overline{G_b}$ vs. $\left(T_{wm}-\overline{T_a}\right)/\overline{G_b}$ plot (From fig.3.13)

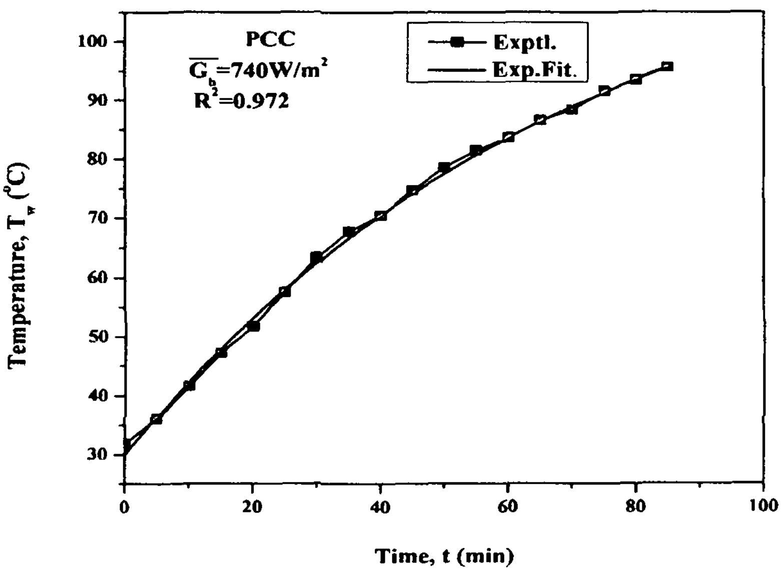


Fig.3.15. Rise in water temperature T_w with time t ($\overline{G_b}$ =740 W/m^2, $\overline{T_a}$= 30 °C)

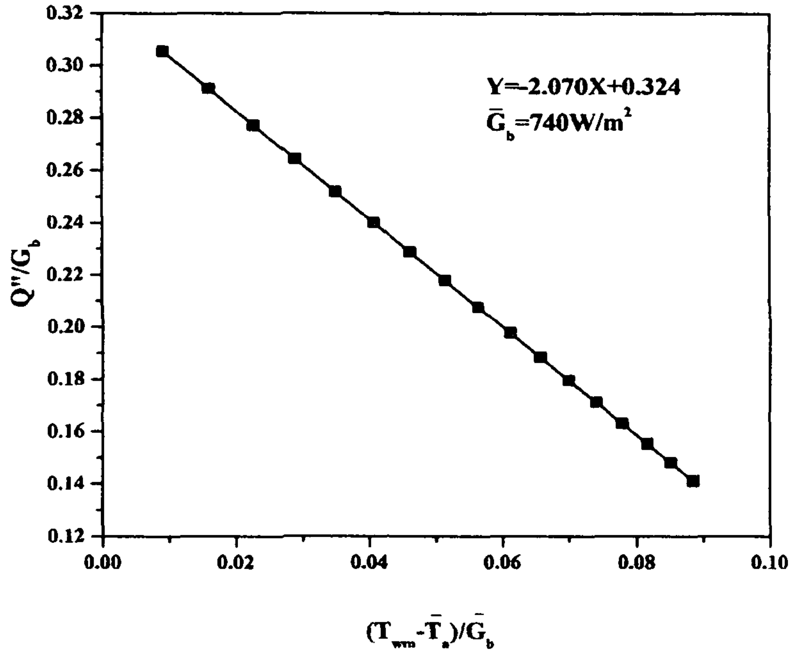


Fig.3.16. $\dot{Q}''/\overline{G}_b$ vs. $(T_{wm} - \overline{T}_a)/\overline{G}_b$ plot (From Fig.3.15)

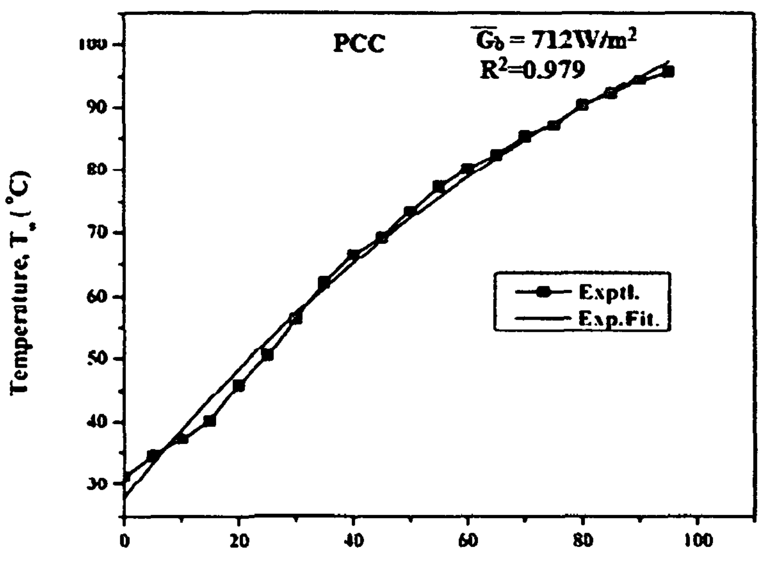


Fig.3.17. Rise in water temperature T_w with time t($\overline{G}_b$ =712 W/m^2, $\overline{T}_a$= 30 °C)

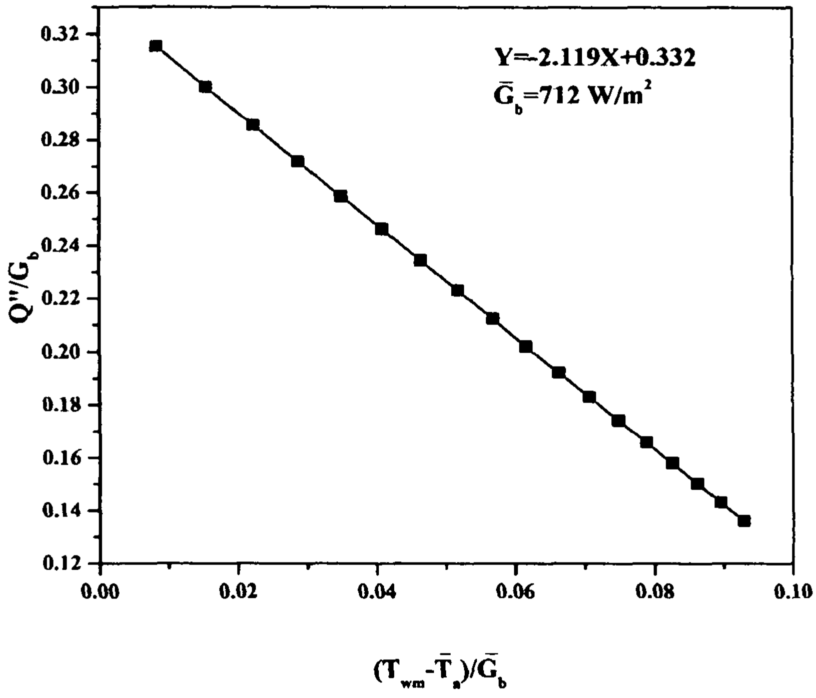


Fig.3.18. $\dot{Q}''/\overline{G}_b$ **vs.** $(T_{wm}-\overline{T}_a)/\overline{G}_b$ (plot From Fig. 3.17)

Table-3.3: Thermal Performance Parameters (TPPs)

Sl.No.	$F'U_L/C$	$F'\eta_o$	$F'\eta_o$	$G_b(W/m^2)$
1	2.070	0.324		740
2	2.479	0.346	0.334	729
3	2.119	0.332		712

Table-3.4: Objective parameters (OPs)

T_{fx}(°C)	τ_r (Exptl.) (min)	τ_r (predicted) (min)	Error %	τ_{hr} (Exptl.) (min)	τ_{hr} (predicted (min))	Error%	$\overline{G_b}$ W/m²
145.83	85	88.21	1.99	18	17.31	-3.78	740
131.75	90	88.14	2.07	15	14.46	3.62	729
141.55	95	88.48	6.87	17.5	16.91	3.37	712

It is important to note that $F'\eta_o$ is not expected to show much variation from one cooker to another while $F'U_L/C$ may vary considerably. As given in Table 3.2 the variation in $F'\eta_o$ is about ±3% based on values obtained from data of three days. The value of $F'U_L/C$ however varies by about ±10% which is high. However the values obtained here agree well with the values derived from the earlier work [5]. To get a consistent value of $F'U_L/C$ it is advised to carry out experiments when $G_b > 600$ W/m². It is to be seen if taking the total radiation G_T has any impact on these parameters or not.. It may be noted that at low irradiance the fraction of diffuse component would be high and would impact the results accordingly. A good concentrator with high acceptance angle ($2\theta_a$) will be able to utilize some fraction of diffuse radiation as well.

Using these values of TPPs, the objective parameters T_{fx} and τ_r are calculated from analytical equation (3.14) and (3.15) respectively. For computation of heat retention duration, τ_{hr}, (time elapsed during fall of temperature for 95°C to 85°C in absence of irradiation) the duration for which cooking process continues after reaching boiling temperature in the absence of radiation, the analytical equation (3.17) has been used. The values of all the OPs derived from the TPPs are shown in Table-3.3.

The predicted value of τ_r determined from the analytical equation (3.15) is compared with the respective experimental value in Fig.3.20 for a typical day identified with $\overline{G_b}$ =729 W/m².

The TPPs are able to predict it within ±7% of experimental value as shown in Fig.3.19 and the bar diagram in Fig.3.20.

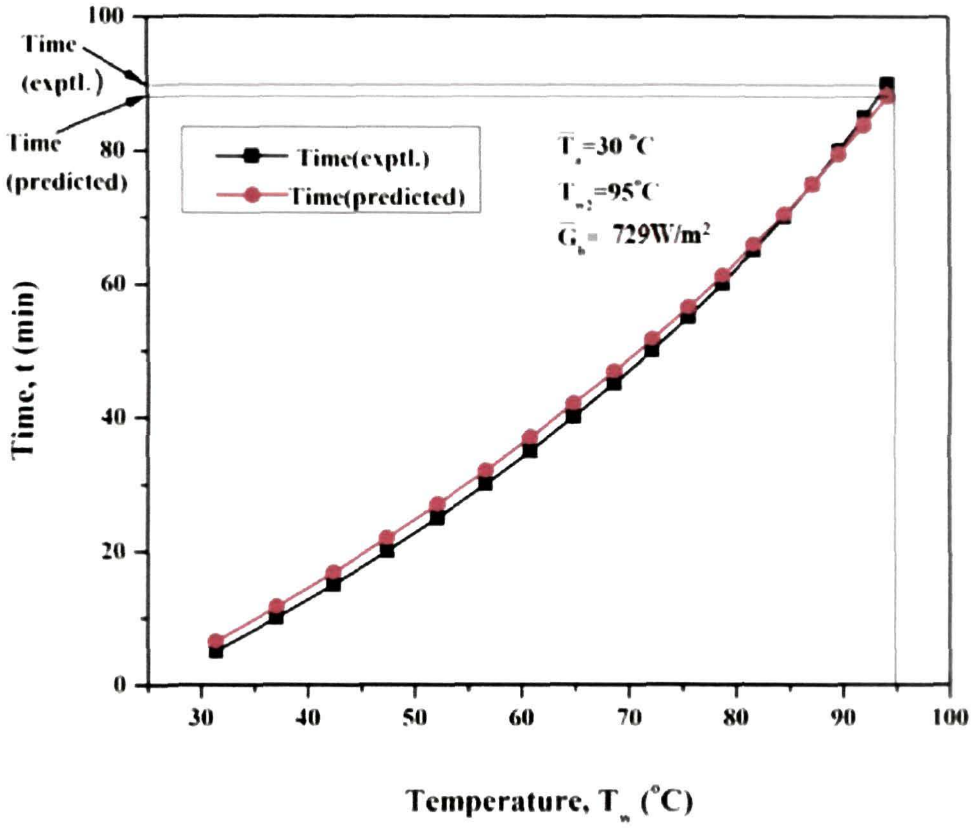
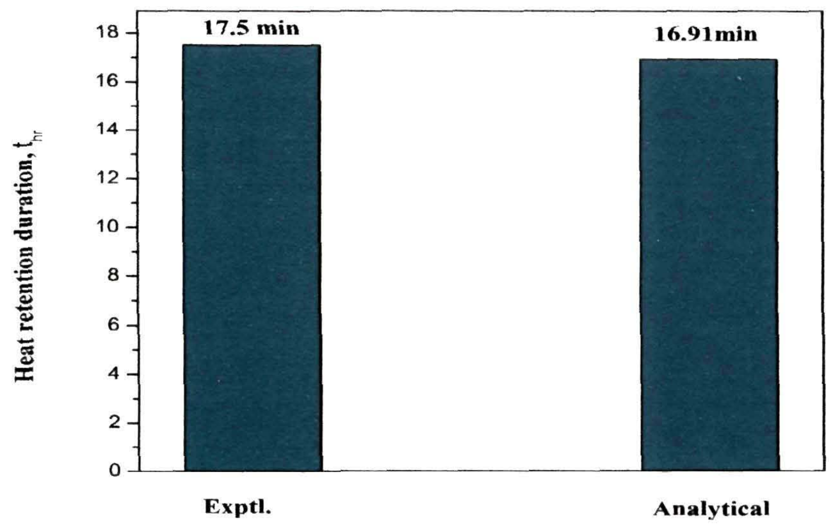


Fig.3.19: Time vs. Temperature, T_W curve showing experimental and predicted values of Reference Time, τ_r.



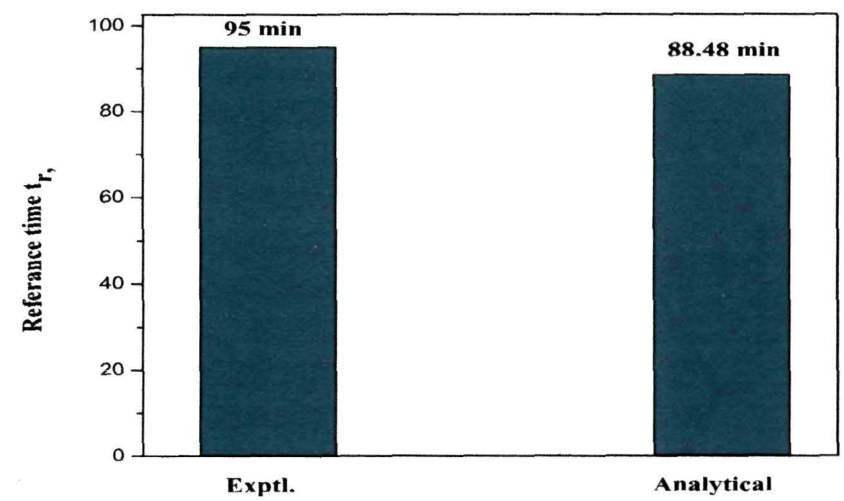


Fig.3.20: (a) τ_r, and (b) τ_{hr} determined using analytical expressions along with the respective experimentally measured values .

The same TPPs are used to predict τ_{hr} as well. On experimental verification by the cooling test [fig.3.11] it was found to be within ±7% of the experimental value. It could have been possible because τ_{hr} is defined for high temperature range (85-95 °C). So it further supports the proposed single test method. The value of T_{fx} obtained from the analytical equation (3.14) could not be verified because of the need to have a fluid having all its properties identical to water except the boiling temperature which should be high In many occasions, due to pressure restrictions on absorbers pressurized water loops cannot be used above even 110°C Heat transfer fluids which are suitable besides water are listed in Table 3 5 [19]

Table 3.5.Typical properties of some heat transfer liquids

SN	Details	Working Range °C	Lower limit for adequate measure-ment °C	Composition	Pour point °C	Flash point °C	Fire point °C	Cp @150 °C kJkg^{-1}K^{-1}
1	Essotherm BP Transcal N Shell Thermia 27 Mobiltherm 605	-10 to 316	70	Mineral oil	-12	210	243	2 4
2	Uniroyal PAO LJ 10 20 E	-	-	Polyalpha-olefin	-62 -40 -37	202 204 276	218 260 307	-
3	Dow corning Silicone Q2-1132	-45 to 204	100	Silicone	-85	232	260	1 7
4	Dow chemicals Dow Therm J	-71 to 181	-20	Alkylated Aromatic	-75	63	68	2 3
5	Rhone poulene Gilotherm ADX10	-50 to 260	20	Synthetic Alkylbenzene	-80	136	140	2 3
6	Monsanto Therminol 66	-9 to 343	70	Modified terphenyl	-28	178	194	2 0
7	Ethelene glycol	-13 to 197 6	-	Dihydric alcohol with aliphatic carbon chain	-	110	410	-
8	Water (Pressurized)	0 to 360	-	H_2 and O_2	-	-	-	4 32

N B For serial number (1)-(6) Ref [19]

3.5. Conclusion:

This chapter presents a generic single step test procedure for determination of the identified TPPs. The results and their analysis suggest the following:

i) The two TPPs viz. $F'\eta_o$ and $F'U_L/C$ derived experimentally and may be used for characterizing a cooker, because
   a) The suggested single step method is simple.
   b) It is possible to determine the three OPs some of which are verifiable experimentally with reasonable accuracy (within ±7%)
   c) A cooker with high value of $F'\eta_o$ and low value of $F'U_L/C$ may be graded higher than the one having lower value of the former and higher value of the later.

ii) The experimentation should be done when the beam component of solar radiation is high. For this $\overline{G_b}$ >600 W/m^2.

iii) This work does not provide a limit for the TPPs which characterize a PCC which successfully accomplishes the cooking. For this it is needed to compare the performance of a number of PCCs with different design parameters.

iv) It is possible to develop a generalized TPP and test procedure following the same approach as in this work. It has the potential to enable comparison of different types of cooker and grading different designs of a cooker type.

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Chapter -4

Enabling inter-cooker comparison through common TPPs for Box type and Paraboloid concentrator type cookers

Chapter -4

Enabling inter-cooker comparison through common TPPs for Box type and Paraboloid concentrator type cookers

This chapter analyzes the possibility of the applicability of the two TPPs developed for CC to be extended to BC as well. It is well known that box type cooker has completely different architectural design from PCC. While BC has conduction as the dominant mechanisms of heat transfer from collector to the pot as they are in contact with the absorber plate, in addition to convection the PCC has radiation as the dominant mechanism. The aperture is well defined in PCC whereas the BC has a variable aperture depending on season as per the definition of the aperture. This calls for thinking about the TPPs and test procedure afresh.

It is always better to have a single parameter to denote the thermal performance of a cooker in place of two ($F'\eta_o$ and $F'U_L/C$) proposed in chapter-3, or more. The single parameter may be able to characterize all types of cookers. This chapter introduces Cooker Opto-thermal Ratio (COR) as a single parameter derivable form $F'\eta_o$ and $F'U_L/C$ and also analyzes its applicability in enabling inter-cooker comparison i.e. BC and CC.

An attempt has been made to develop correlation for OPs, identified in chapter- 2 with TPPs for BC. It is also endeavored to see if the proposed test procedure and TPPs enable determination of all the OPs.

4.1. Introduction:

Box type cooker (BC) is one of the most popular solar cookers because of various reasons outlined in Chapter-1. CC has now started gaining popularity due to some superior features discussed in Chapter-1 and 3. Some special features of BC and CC are given in Table 4.1. In Chapter-3, a set of TPPs for CC with associated test procedures are proposed. The motivation of the proposal was to provide more holistic TPPs and a simple test procedure. As explained earlier, it has been done with reasonable degree of success.

Table: 4.1: Special features of Box type cooker and Paraboloid concentrator cooker:

Sl.No.	BC	CC
1	Integrated collector and absorber	Separate collector and absorber
2	Needs intermittent tracking	Continuous tracking
3	Variable aperture	Constant aperture
4	Conductive and radiative heat transfer to pot	Radiative heat transfer to pot
5	Only boiling type cooking	All type of cooking
6	Absorber plate defined	Absorber plate not defined
7	Pots are not exposed to ambient	Pot is exposed to ambient
9	$F'<1$	$F' \sim 1$

In Chapter-3 sets of other existing TPPs and the respective test procedures are also given which are hitherto used to facilitate evaluation and grading of CCs. The details of the three of them are given in the Appendices of Chapter-3 As these TPPs and test procedures are different from those for BC hence, as stated earlier, they enable grading of only concentrator type cookers (i.e. intra-cooker grading). It means that it is not possible to carry out inter-cooker performance comparison. There is a need for a common TPP and a corresponding test procedure which is independent of a cooker type. Consequently it should permit intra-cooker gradation and inter-cooker comparison on the basis of their thermal performance [1]. This forms the additional motivation of the work presented in this chapter. It may be noted that the corresponding test procedure is also needed to be developed. Thus the chapter also dwells upon the results of the quest for a simple, less time consuming and a common test procedure for both CC and BC.

Unlike CC many TPPs exist for evaluation of BC. Some of the available TPPs for BC which can be used to compare the intra-cooker performance parameters are Figure of merit (F_1, F_2) [2, 3], efficiency η [1, 4-6], cooking power [7], standard cooking power (P_s) [3, 8]. Details of some of these have been discussed in Chapter-2. In Chapter -3 a set of two TPPs were identified and proposed for CC. This chapter attempts to carry out theoretical analysis and experimentation to see the applicability of the same to BC

4.2. Proposed thermal performance parameter and test procedure for their determination:

4.2.1. Basic Theory of BC:

The box type solar cooker is the simplest device to convert solar energy to heat energy which is finally used for cooking purposes [9].

The heat collected by the BC depends upon the amount of incident radiation absorbed by the absorber plate after getting reflected and transmitted through the glass cover. Under a given operational condition heat collection is dependent upon the properties of the material used. The net heat gain depends upon the loss of the heat collected by the cooker. The heat loss, in turn, is dependent upon design and operational parameters in addition to material parameters. Hence, the estimation of heat losses is of utmost importance for performance evaluation of BC. The total heat loss from the BC is the sum of heat losses from top, bottom, sidewalls, edges, corners, and sealing of the corner.

The heat balance equations from plate to ambient through top, as shown in Fig.4.1and 4.2 can be written as

$$\dot{Q}''_{p1} = (h_{rp1} + h_{cp1})(T_{pm} - T_{c1}) \quad (4.1)$$

$$\dot{Q}''_{12} = (h_{r12} + h_{c12})(T_{c1} - T_{c2}) \quad (4.2)$$

$$\dot{Q}''_{2a} = (h_{r2a} + h_{w})(T_{c2} - T_{a}) \quad (4.3)$$

where, $\dot{Q}''_{p1}, \dot{Q}''_{12}, \dot{Q}''_{2a}$ are the heat loss factor per unit time per unit area (W/m^2) from absorber plate to glass cover 1, glass cover1 to glass cover 2, and glass cover 2 to ambient respectively. h_{rp1},h_{r12}, h_{r2a} are the radiative heat transfer coefficient (W/m^2 K) from absorber plate to glass cover 1, glass cover1 to glass cover 2, and glass cover 2 to ambient respectively. h_{cp1},h_{c12}, h_w are the convective heat transfer coefficient (W/m^2 K) from absorber plate to glass cover 1, glass cover1 to glass cover 2, and wind heat transfer coefficient respectively. T_{pm} is the mean absorber plate temperature, T_{c1}, T_{c2}, T_a are the temperature of the glass cover 1, 2 and ambient respectively (Fig.4.2).

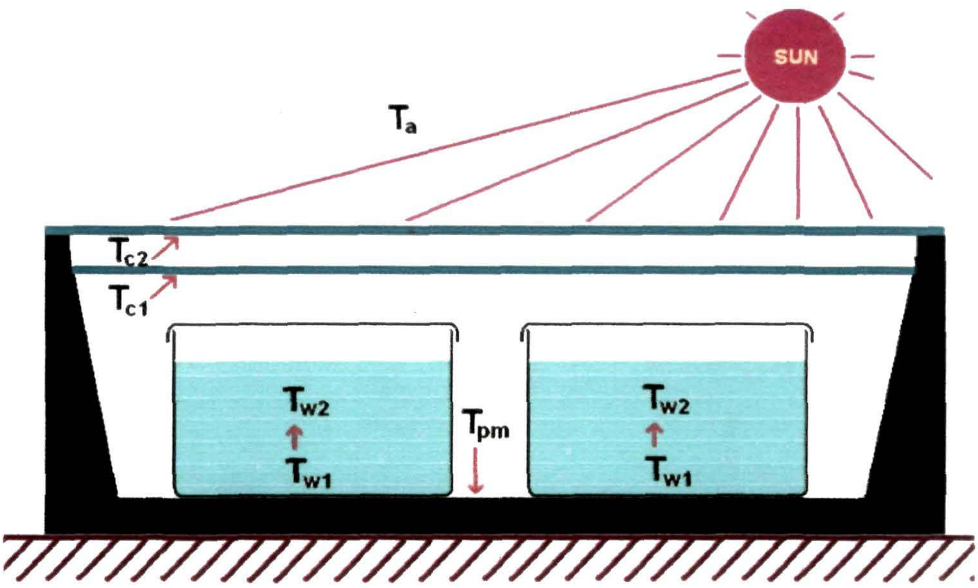

Fig.4.1: Heat transfer to the pot.

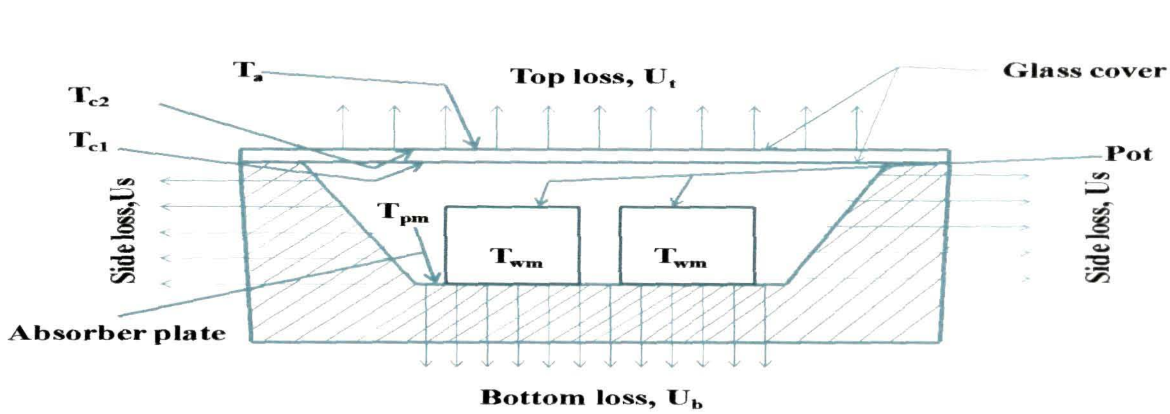

Fig.4.2: Schematic diagram of heat loss through BC

Under steady state the three heat loss equations (4.1), (4.2), (4.3) are equal. By solving the three simultaneous equations we can estimate the top heat loss factor from

$$U_t = \frac{\dot{Q}_t''}{(T_{pm} - T_a)} \tag{4.4}$$

As the solution of the simultaneous equations is quite involved and needs computational support attempts have been made to develop analytical equations.

An analytical equation for the top heat loss factor U_t of BC with double glass cover can be written in terms of individual heat transfer coefficient [10] as:

$$U_t^{-1} = (h_{cp1} + h_{rp1})^{-1} + (h_{c12} + h_{r12})^{-1} + (h_w + h_{r2a})^{-1} + \frac{2t_g}{k_g} \tag{4.5}$$

where, k_g is the thermal conductivity of glass (W/mK) and t_g is the thickness of glass cover (m). Other variables are same as stated above. The simplified equation for the top heat loss factor in analytical form which can predict U_t within ±4% has been developed and is given by the following expression [10]:

$$U_t^{-1} = \left(\frac{5.78\left[\left(T_{pm} - T_{c1}\right)\cos\beta\right]^{0.27}}{T_{m12}^{\ 0.31} L_{12}^{\ 0.21}} + \frac{\sigma\left(T_{pm}^{\ 2} + T_{c1}^{\ 2}\right)\left(T_{pm} + T_{c1}\right)}{1/\varepsilon_p + 1/\varepsilon_g - 1} \right)^{-1} +$$
$$\left(\frac{5.78\left[\left(T_{c1} - T_{c2}\right)\cos\beta\right]^{0.27}}{T_{m23}^{\ 0.31} L_{23}^{\ 0.21}} + \frac{\sigma\left(T_{c1}^{\ 2} + T_{c2}^{\ 2}\right)\left(T_{c1} + T_{c2}\right)}{1/\varepsilon_g + 1/\varepsilon_g - 1} \right)^{-1} +$$
$$\left(h_w + \sigma\varepsilon_g\left(T_{c2}^{\ 2} + T_a^{\ 2}\right)\left(T_{c2} + T_a\right)\right)^{-1} + 2t_g/k_g \tag{4.6}$$

where

$$T_{c2} = T_a + h_w^{\ -0.4}(0.0021T_{pm} + 0.57\varepsilon_p - 0.146)(T_{pm} - T_a)$$
$$T_{c1} = T_{pm} - (0.7 - 0.34\varepsilon_p)(T_{pm} - T_{c2}) \tag{4.7}$$

where ε_p and ε_g are the emittance of the absorber and glass plate respectively. β is the collector tilt from horizontal (degree). T_{m12}, T_{m23} are the arithmetic mean temperature of absorber plate and glass cover1and glass cover1 and glass cover 2. L_{12} and L_{23} are the air gap spacing between absorber plate and glass cover1 and glass cover1 and glass cover2 in m respectively. σ is the Stefan-Boltzmann constant (W/m^2K^4). Other variables are the same as stated earlier.

The relations for bottom loss and side loss are given as:

$$U_b = \frac{k_i}{t_b} \tag{4.8}$$

$$U_s = ((L_l + L_w)L_t k_i)/L_l L_w t_s \tag{4.9}$$

where U_b and U_s are the bottom and side loss respectively. k_i is the thermal conductivity of insulation (W/mK). t_b, and t_s are the bottom and side insulation thickness respectively; and L_l, L_w L_t are the length, width, and thickness of the collector respectively.

Now the overall heat loss factor would be

$$U_L = U_t + U_b + U_s \tag{4.10}$$

Under steady state condition the external energy, $\dot{Q}_{in}$ supplied to the cooker equals the total heat loss $\dot{Q}_L$ from the cooker. Thus

$$\begin{aligned} \dot{Q}_{in} &= \dot{Q}_L = U_L A_p \left(T_{pm} - T_a\right) \\ U_L &= \frac{\dot{Q}_{in}}{A_p (T_{pm} - T_a)} \end{aligned} \tag{4.11}$$

For horizontal absorber plate, the flux S absorbed in the absorber plate of area A_p is

$$\dot{Q}_{in} = A_c S = A_c (\tau\alpha) \overline{G}_T \tag{4.12}$$

where τ is the transmissivity of the glass cover system, α is the absorptivity of the absorber plate and (τα) is the product of transmissivity and absorptivity.

The transmissivity-absorptivity product is defined as the ratio of the flux absorbed in the absorber plate to the flux incident on the cover system and is denoted by the symbol (τα). This incorporates (τα) for both beam and diffuse component of solar radiation

Hence the net heat gain rate is given by

$$\begin{aligned} \dot{Q}_u &= A_c S - \dot{Q}_L \\ &= A_c (\tau\alpha) \overline{G}_T - U_L A_p \left(T_{pm} - T_a\right) \\ &= A_c \eta_0 \overline{G}_T - U_L A_p \left(T_{pm} - T_a\right) \end{aligned} \tag{4.13}$$

$$\dot{Q}_u'' = \eta_0 \overline{G}_T - \frac{U_L(T_{pm} - T_a)}{C} \tag{4.14}$$

where $\eta_o=(\tau\alpha)$ and is termed as optical efficiency, C is the concentration ratio($=A_c/A_p$) which is a variable in a given BC.

In the equation (4.14) it is difficult to determine T_{pm}, hence Hottel Whillier and Bliss (HWB) [11] defined a ratio in terms of heat exchange efficiency factor F′ as the ratio of actual heat gain to the heat gain by the fluid locally. Different terminologies have been used by different workers to indicate F′. The terminology used here for F′is heat exchange efficiency factor as this terminology is first used by Mullick *et al* [2]. Hence as discussed in Chapter-3 the HWB equation is given by

$$\dot{Q}_u'' = F'\left[\eta_0 \overline{G}_T - \left(\frac{U_L}{C}\right)(T_{wm} - \overline{T}_a)\right] \tag{4.15}$$

where, F′ is the heat exchange efficiency factor and is defined and discussed in detail in Chapter-3. The formulation of F′ for BC is given in next paragraph. $\dot{Q}_u''$ is the rate of useful heat gain per unit area by water, η_o is the optical efficiency, $\overline{G}_T$ is the average irradiance, U_L is the heat loss factor, C is the concentration ratio and other notations are the same as mentioned earlier.

<u>The expression for F′ for BC:</u>

It is derived following the procedure discussed in Chapter-3 [11].

$$F' = \cfrac{1}{\cfrac{WU_L}{\pi Dh} + \cfrac{1}{\cfrac{D}{W} + \cfrac{1}{\cfrac{WU_L}{C_{contact}} + \cfrac{W}{(W-D)F}}}} \tag{4.16}$$

where W is the average distance between two pots, D is the diameter of the pot, U_L is the total heat loss factor of the cooker, C is the coefficient of contact between pot and absorber plate, F is the fin efficiency factor, h is the heat transfer coefficient

4.2.2 Identification of TPPs for BC:

From equation (4 15) we observe that parameters that play crucial role in determining the thermal performance of solar cookers BC and PCC, are optical efficiency factor ($F'\eta_o$) and heat loss factor ($F'U_L$) and the concentration ratio(C) The optical efficiency factor ($F'\eta_o$) identifies the upper limit of performance and is basically dependent on reflectance of surface, absorptance of the cooking pot, accuracy of tracking etc [12, 13] The heat loss factor ($F'U_L$) depends on design parameters and operational conditions such that it increases with rise in pot water temperature and wind velocity [14] It is also affected by loss of vapour and hence it is required to have a vapour tight pot for better cooker performance The tilt of the reflector and change in aperture also has an effect on the value of $F'U_L$, $F'\eta_o$ and C [15]

It is assumed that the value of C is 1 but practically it is a variable and its value is in the range of $0<C<2$ in the common design of BC In fact many designs of BCs have been proposed with two or more reflectors making the value of C even greater [16] than 2 Thus the TPP $F'U_L/C$ with C in the denominator may be needed to reflect the BC's performance Unlike Mullick *et al.* [2, 17], inclusion of C in the expression facilitates representation of TPP of BC as well in more ways than one

i. It takes into account both box and reflector system hence it is more holistic.

ii. It takes care of other existing design where in more than one reflectors and their different configurations have been utilized. In fact inclusion of C not only reflects the material properties but also the design configurations. It also promises to take care of the future designs.

iii. The reflector(s) affect the radiative as well as convective loss from the cooker in addition to the augmentation of radiation flux in the cooker. It makes it essential to keep it in the TPPs for BCs.

iv. Inclusion of C makes it identical to the TP used in the case of CC.

v. It may lead us to generalization of TPPs as endeavored in this work.

4.2.3. Proposed Test Procedure:

One of the important design parameters of a cooker is the aperture area. It needs to be considered properly so as to make its determination less confusing, uniform and hence applicable for both CC and BC.

a) Determination of aperture area (A_c) of cookers:

As per the definition A_c for BC, it is the unobstructed cover area or the total cover area less the area of cover support [11]. In solar systems the aperture area should always be related to the plane normal to the incident radiation. In that case the aperture of the concentrator is the opening through which the solar radiation enters the concentrators. Normally the maximum solar flux falling on this area is measured. It is straight forward in the case of CC as it is the physical aperture area of cooker because it is always inclined towards the beam radiation. The present work intends to propose a test procedure which is common for BC as well as CC. Also the test procedure should provide TPPs which are holistic i.e. which represents the complete system (Box plus mirror). In this case in BC the aperture area is not exactly the physical aperture area as defined in the beginning. Also if we want to relate the aperture area with plane of measurement entrance of radiation the best plane would be the plane (shown as CN in fig.4.3) receiving the beam radiation normally. This is in line with our intention to propose a common test procedure both for CC and BC.

But this proposal has another problem. As shown in fig. 4.4, 4,5and 4.6 the position of the mirror with respect to the opening of the box is variable. As a result the aperture area is variable in BC. During summer the physical aperture area will be slightly more to make the reflected radiation fall inside the box (fig.4.4) and during winter it will be less as shown in fig.4.5. In this case the aperture area can be the area of the rectangle made by joining the corresponding unhinged corners of the box and mirror (fig.4.7)

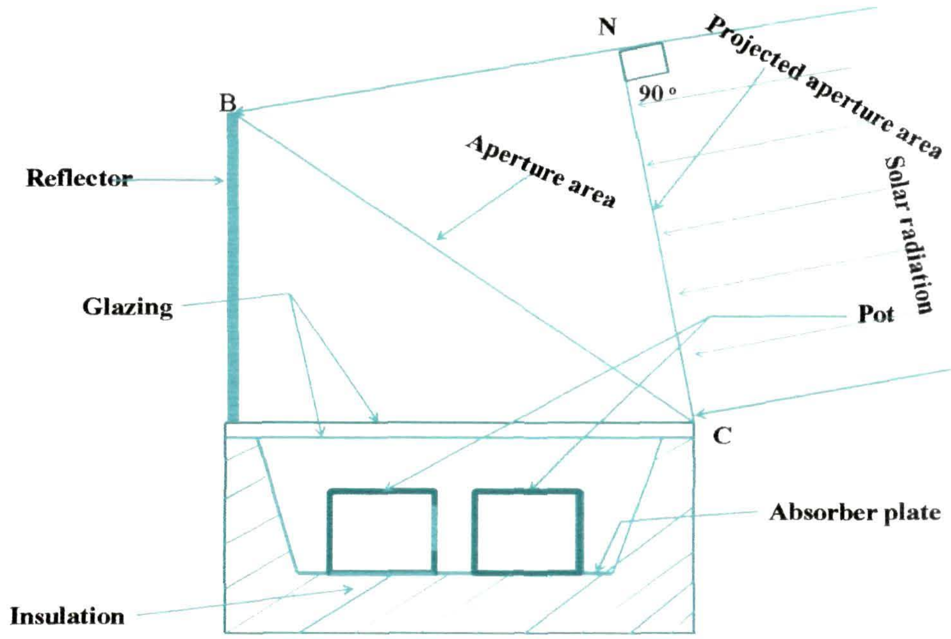

Fig.4.3: Schematic diagram for aperture area (BC)

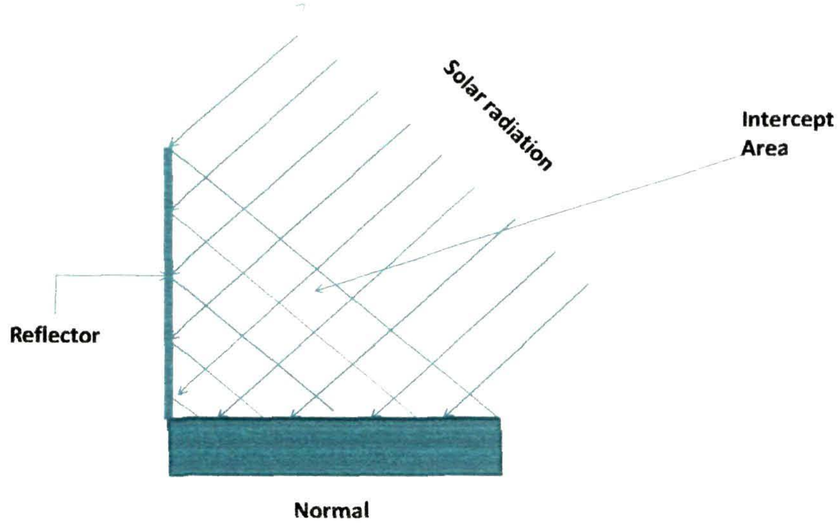

Fig.4.4: Aperture area of box type cooker (Normal).

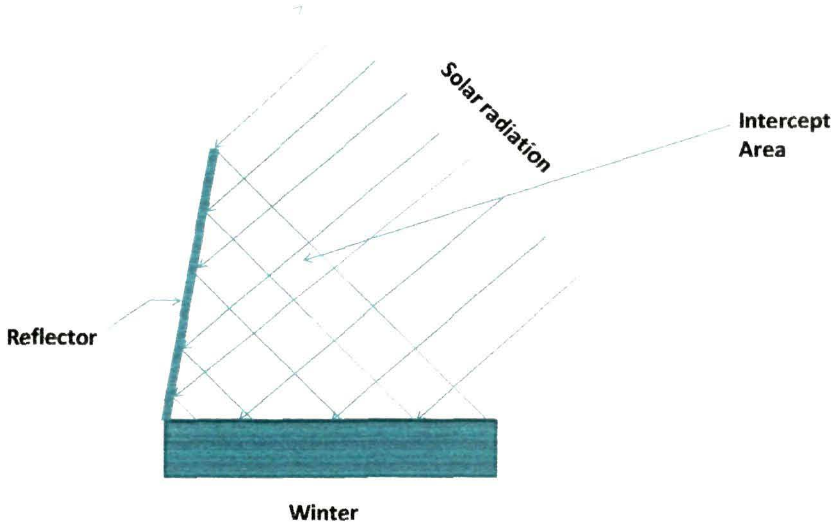

Fig.4.5. Aperture area of box type cooker (winter)

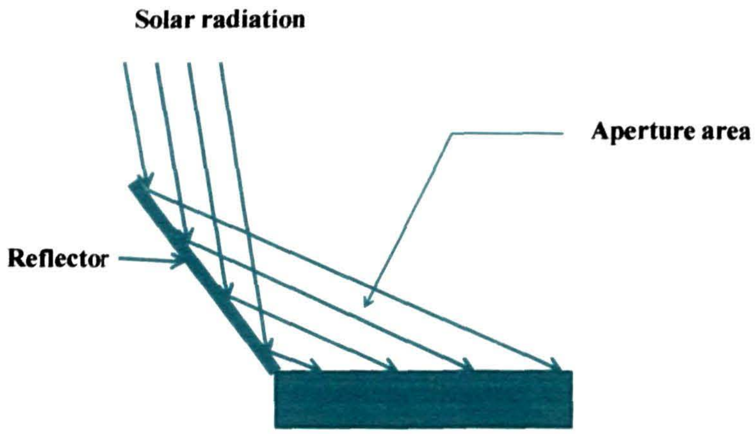

Fig.4.6: Aperture area of box type cooker (summer)

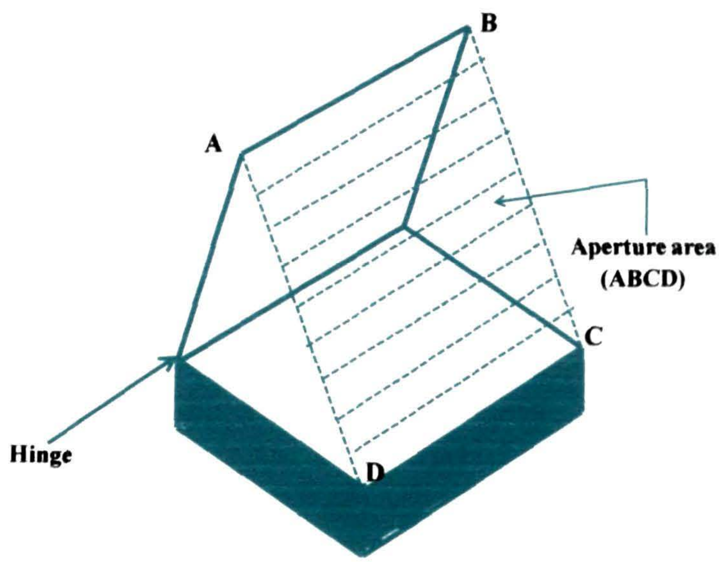

Fig.4.7. Schematic diagram for aperture area (BC)

Hence it is reasonable to take this physical aperture area for calculation purposes. This makes the determination of aperture area more generalized for both type of cookers. It may be noted that radiation flux should be measured in the plane normal to beam radiation which would always be the maximum value in that direction.

b) Total radiation G_T versus beam radiation G_b:

For determination of various parameters of BC, G_T is considered to be pertinent while for CC G_b is appropriate. Apparently these are the respective influencing parameters. However for identical G_T values the one with lower fraction of G_b on a given day will get inferior performance CC while BC will maintain the same performance. But a CC with high acceptance angle will perform better than the one with low acceptance angle. Thus keeping G_T as a common parameter is justified. This is discussed on the basis of experimental results using G_b as well as G_T in calculation.

c) Experimental determination of proposed TPPs.

For determining the proposed thermal performance parameters, experimental recording of certain variables at regular intervals is needed. For this, water is heated in the cooking pot by keeping it at the focus of the parabola in the case of the PCC and inside the box in box type cooker. T_w, T_a and G_T are recorded at regular interval. The rate of useful heat gain per unit area by water can be expressed in the form of HWB equation (4.15). Dividing by $\overline{G}_T$ it yields the expression

$$\frac{\dot{Q}''}{\overline{G}_T} = \left[F'\eta_0 - \left(\frac{F'U_L}{C} \right) \frac{\left(T_{wm} - \overline{T}_a \right)}{\overline{G}_T} \right] \tag{4.17}$$

where T_{wm} is the mean water temperature and other variables are same as mentioned in equation [4.15] and [4.16].

In the present work $F'\eta_0$ and $F'U_L/C$ are being proposed as two thermal performance parameters which are identical to those proposed in chapter -3. Here the denominator of the later one consists of C which enables characterization of the reflecting surface simultaneously which might play an active role in enhancing the radiative component of the heat transfer process. Determination of these parameters using the experimentally recorded data is possible by the method which is discussed next.

In this method an exponential curve is fitted through the points of the temperature T_w versus time, t graph with R^2>85% which may be an equation of the form given in equation 3.11 of Chapter- 3.

The equation of the curve is used to determine statistically corrected value of the rate of temperature rise at different time intervals. This data is used to plot $\dot{Q}''_u/\overline{G}_T$ versus $(T_{wm} - \overline{T}_a)/\overline{G}_T$. The experimental test procedure followed to determine the two thermal performance parameters is outlined in the following section.

Fig. 4. 8: Experimental set up for PCC and BC.

The test on both for BC and CC were conducted simultaneously under identical conditions using identical set up (Fig.4.8). In CC the pot filled with double distilled water was kept at the focus of the CC so that bright spot of the concentrated radiation falls at the bottom of the cooking pot. Double distilled water was loaded at 3kg/m^2 of aperture area. In BC the load was distributed uniformly in four pots [18]. The aperture area in the case of BC may be safely taken as the area of opening (the rectangular area obtained by connecting the unhinged corners of the box and the mirror), which receives the solar flux (Fig: 4.5, 4.6, and 4.7). During the test the water temperature was recorded at 5 minute interval till the temperature reached close to the boiling point (~95 ^{o}C). The temperature was recorded using a calibrated copper-constantan thermocouple placed at a point above the bottom of the pot where the boundary effect on temperature is absent through the hole available at the centre of the cooker/cooking pot lid. The hole was sealed so that vapor does not escape through it. The total solar radiation G_T was also noted down at every five minutes interval. It was measured by recording the value of radiation falling on the projected aperture plane normal to beam radiation. This corresponds to the maximum value of solar flux in that direction. To measure total solar radiation Research Radiometer (ILT1700) was used. Beam radiation was recorded using Pyrheliometer (National Instrument Ltd., India). The experiments were performed between ±1h 30 min of solar noon. The experimental data was used to get regression equation as discussed in earlier section. The statistically corrected experimental values of water temperature (using eqn. (3.11)) is used to find $\dot{Q}_u''$

$$\dot{Q}_u'' = \frac{(MC_w)_w'(T_{w2} - T_{w1})}{A_c \Delta t} \quad (4.18)$$

where $\dot{Q}_u''$ is the rate of useful heat gain by water per unit area, M is the mass of water C_w is the specific heat capacity of water, and $(MC_w)'_w$ is the sum of heat capacity of water and the pot. T_{w1} and T_{w2} are the initial and final temperature of water, for calculation of $(T_{wm} - \overline{T}_a)/\overline{G}_T$, T_{wm} is taken as the mean of T_{w1} and T_{w2}, A_c is the aperture area of cooker, and Δt is the time interval.

Now the data is plotted as discussed in to determine $F'\eta_o$ and $F'U_L/C$. The test was conducted under the following conditions: $G_T \geq 700 W/m^2$; $20 \leq T_a \leq 40$ °C; and wind speed < 0.5 m/s. It is desirable to carry out experiments under similar conditions. The tests for both the cookers were carried out simultaneously under the identical environment. Thus the same values of T_a and G_T were used for both the cookers.

4.3. Proposal for inter- cooker thermal performance comparison using cooker Opto –thermal ratio (COR):

COR is the ratio of the product of optical efficiency and C and the heat loss factor. A high optical efficiency and a low heat loss factor are required to get the better performance of the cooker [2]. Thus a high COR value suggests a better cooker from opto-thermal performance point of view. Two points which must be noted here are – Firstly, unlike the existing TPPs it is a function of Concentration ratiol as well. Hence COR can be considered as a single TPP representing the thermal performances of cooker irrespective of their type and design. Secondly, it is pertinent to have a TPP which indicates the performance of the cooker including the devices used to augment the radiation (e.g. one or more mirror(s) in the case of box type cookers). COR, as defined, takes care of this aspect. Also it will be discussed later that the proposed test procedure is in conformity with objectives of this work.

The existing test procedures to determine the cookers' thermal performance parameter need measurement of stagnation temperature (T_{px}) of cooker's absorber plate [2], and time (t) of sensible heating of a known amount of standard load in cooking pot [2] etc. in addition to climatic variables like radiation flux falling on the projected aperture plane normal to the beam radiation G_T, ambient temp T_a and wind velocity V_w. It is important to note here that in certain variants of box type cookers it is not possible to ascertain and measure the plate temperature [19, 20]. In the present work the performance parameter $F'U_L/C$ and $F'\eta_o$ are determined through curve fitting method for both the cookers i.e. BC and CC. Then ratio of $F'\eta_o$ to $F'U_L/C$ gives the values of COR as:

$$COR = \frac{\eta_0 C}{U_L} \tag{4.19}$$

Here experimental method may be same for all types of cooker. However in this chapter the analysis is limited to only two types of cooker i.e. BC and CC. In case of BC booster mirror is used during the experimentation and average total radiation on projected aperture plane normal to beam radiation is taken for calculation of COR for both box type cooker and CC to maintain the uniformity.

4.4. Results and Discussion:

For results and discussion experimental data for three days is taken.

Fig. 4.9 shows the variation of ambient temperature and total solar irradiance with time during the experimentation.

Fig. 4.10, 4.12, 4.14 and Fig. 4.16, 4.18, 4.20 depicts the rise in water temperature in BC and CC respectively for the experiments conducted on three different days. CC takes less time to reach the temperature of 95°C from ambient as expected. The $\dot{Q}''/\overline{G}_T$ versus $(T_{wm} - \overline{T}_a)/\overline{G}_T$ plots obtained as per the method outlined in section 4.2.3(c) are depicted in Fig 4.10,4.12, 4.14 and Fig.4.16, 4.18, 4.20 for BC and CC respectively.

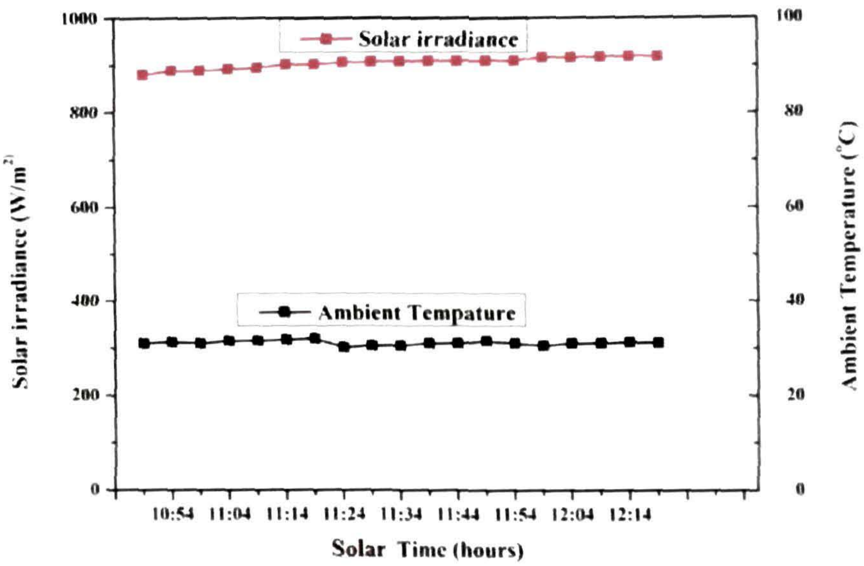

Fig. 4.9.Measured solar irradiance and ambient temperature on 5th May 2010 at Tezpur (Latitude: 26° 41'46" Longitude= 92°50'05 MSL= 230 ft.)(G_T= 906W/m^2)

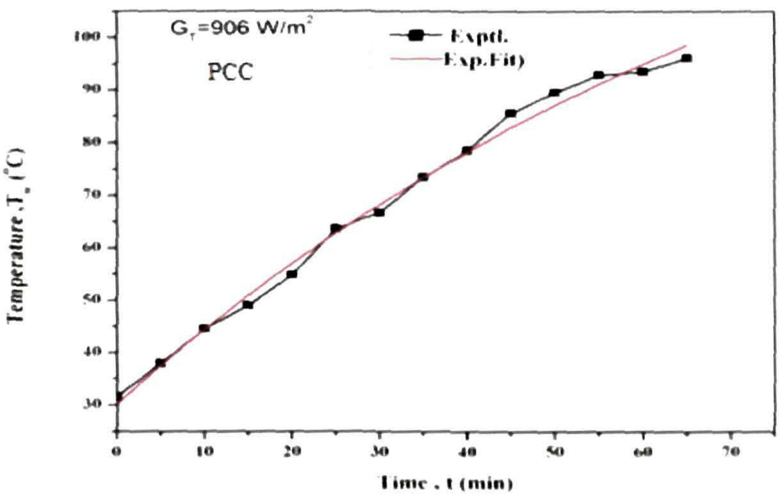

Fig.4.10. Rise of water temperature with time t in PCC

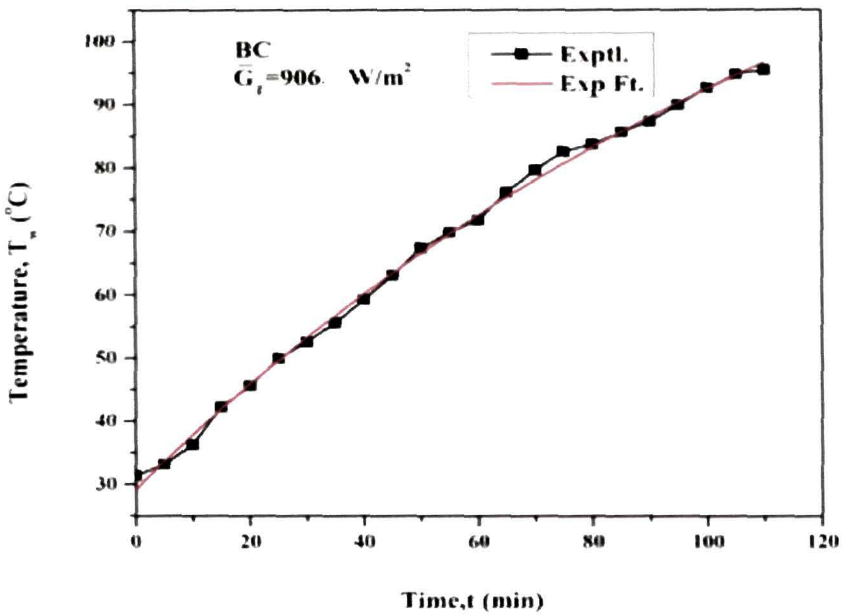

Fig.4.11. Rise in water temperature T_w with time t in BC

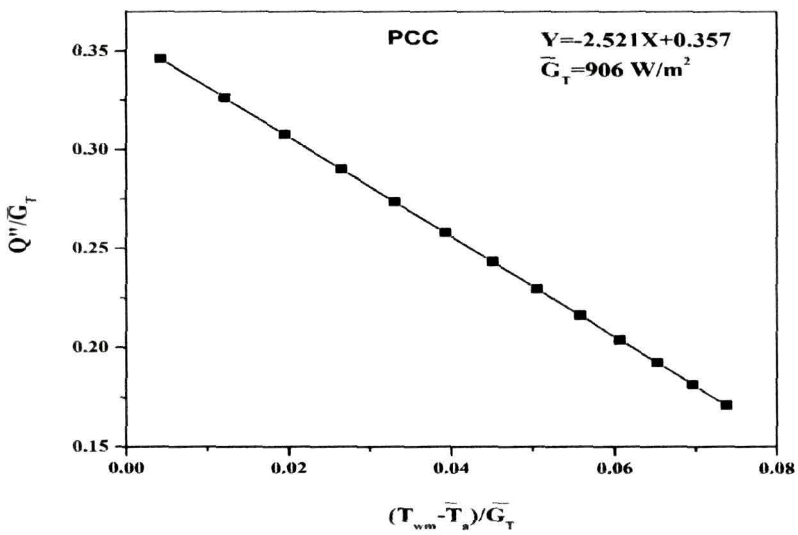

Fig. 4.12. $\left(T_{wm} - \overline{T}_a\right)/\overline{G}_T$ plot for PCC for Fig. (4.10).

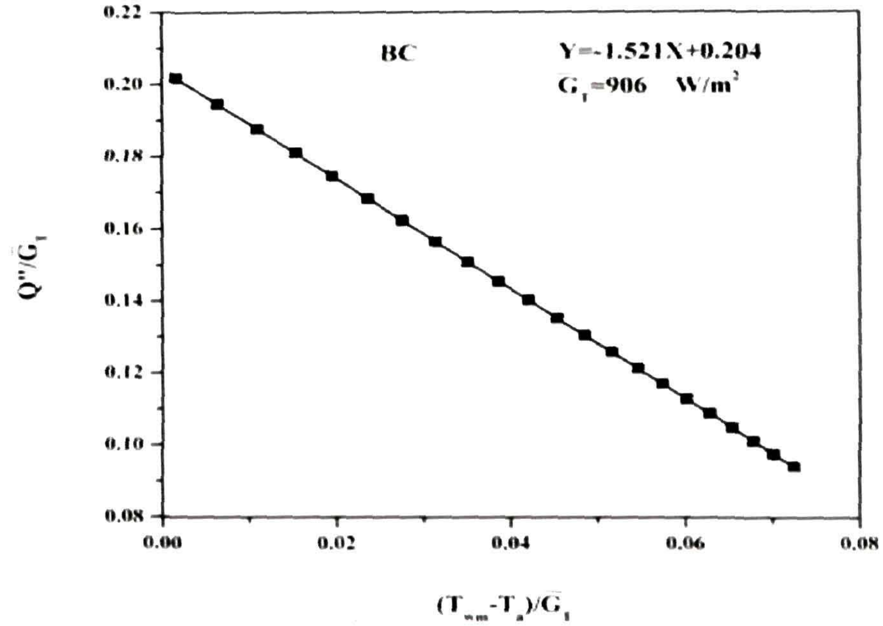

Fig.4.13: $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm}-\overline{T}_a\right)/\overline{G}_T$ plot for BC for Fig. (4.11).

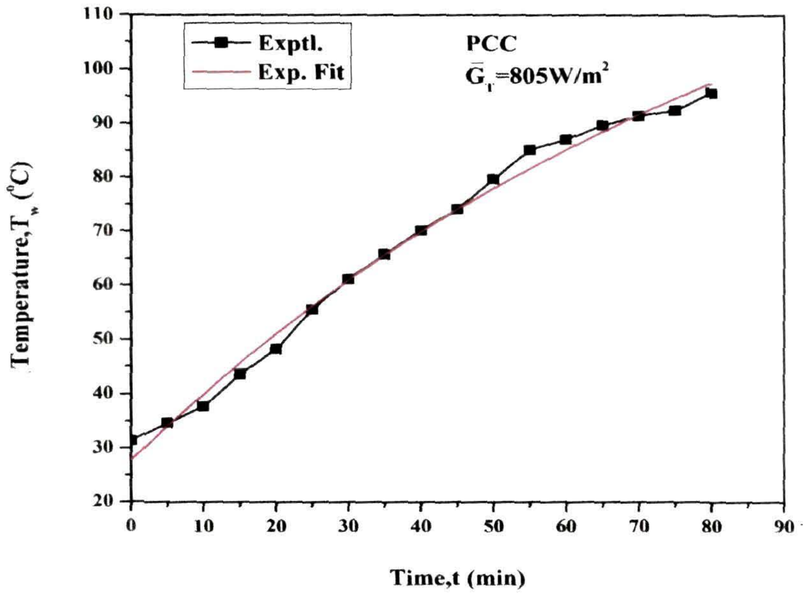

Fig.4.14. Rise in water temperature T_w with time t in PCC

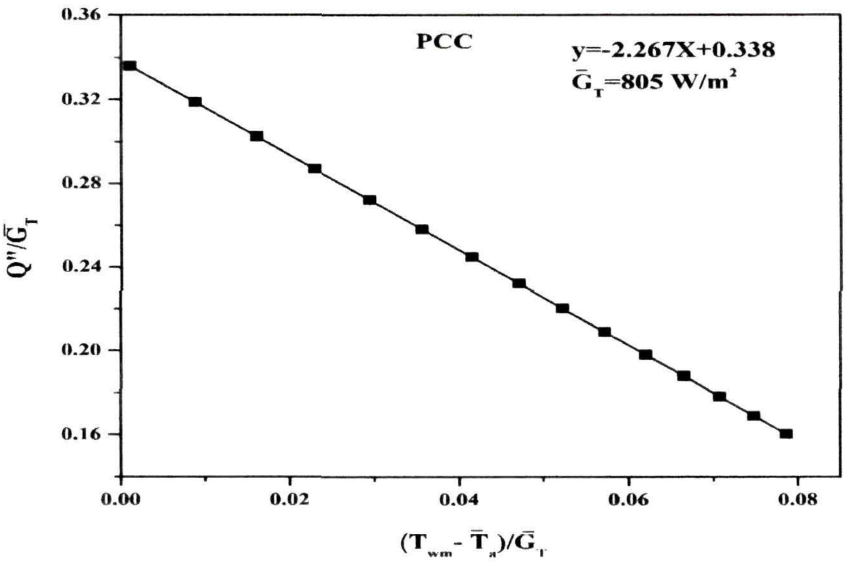

Fig.4.15. $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm} - \overline{T}_a\right)/\overline{G}_T$ plot for PCC for Fig. (4.14).

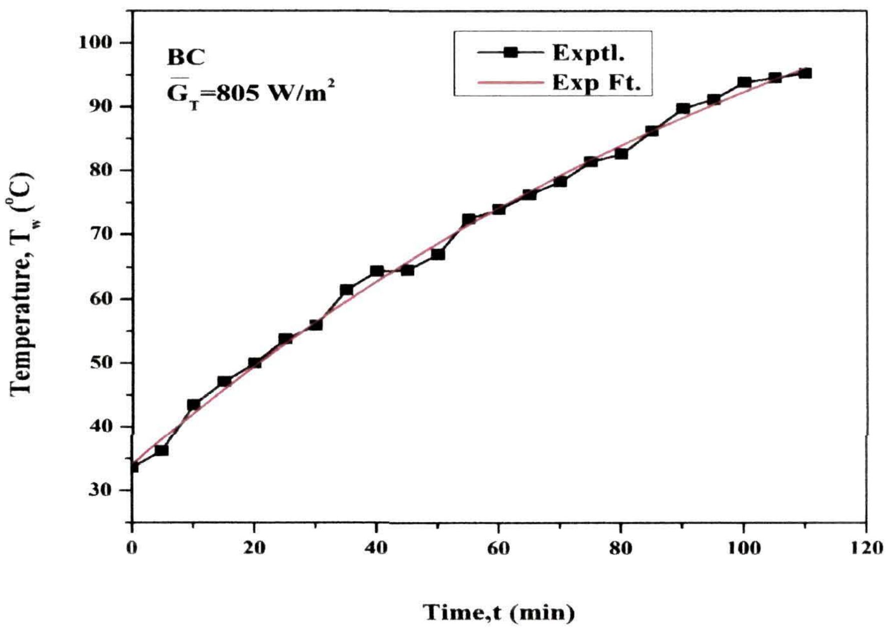

Fig.4.16. Rise in water temperature T_w with time t in BC

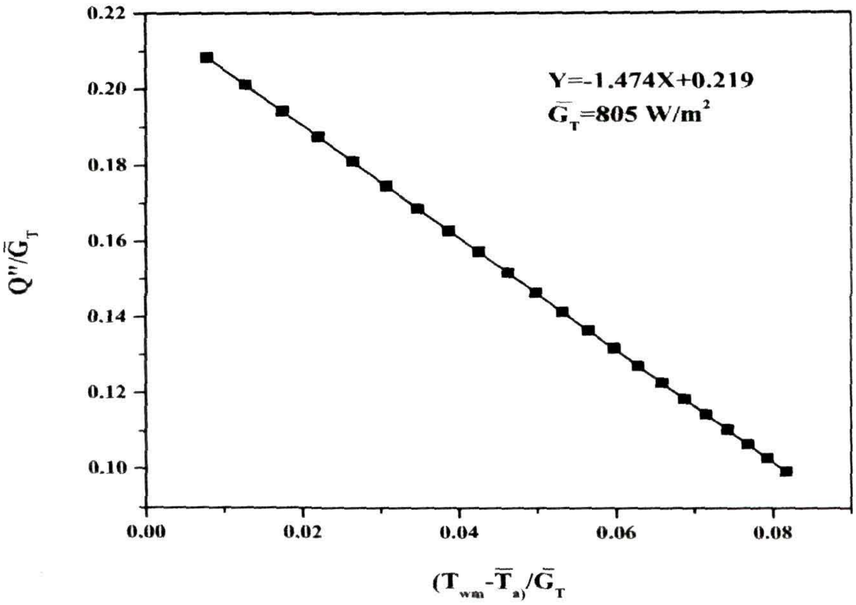

Fig.4.17: $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm} - \overline{T}_a\right)/\overline{G}_T$ plot for BC for Fig. (4.16).

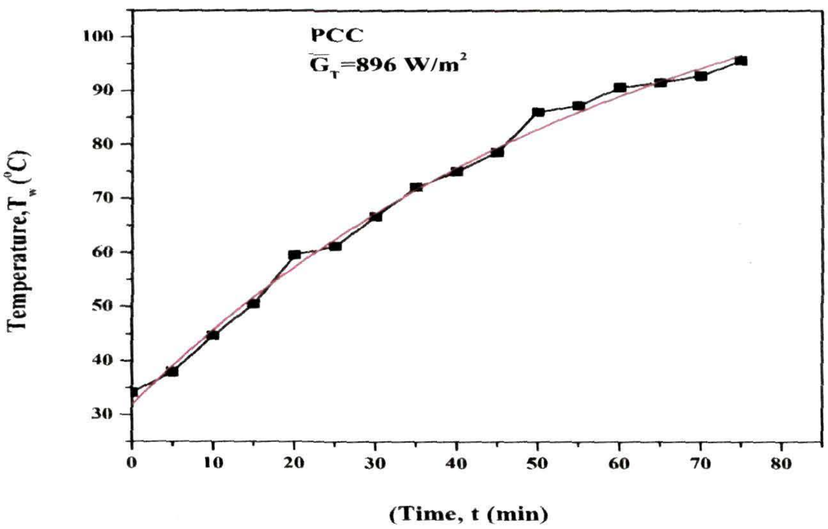

Fig.4.18. Rise in water temperature T_w with time t in PCC

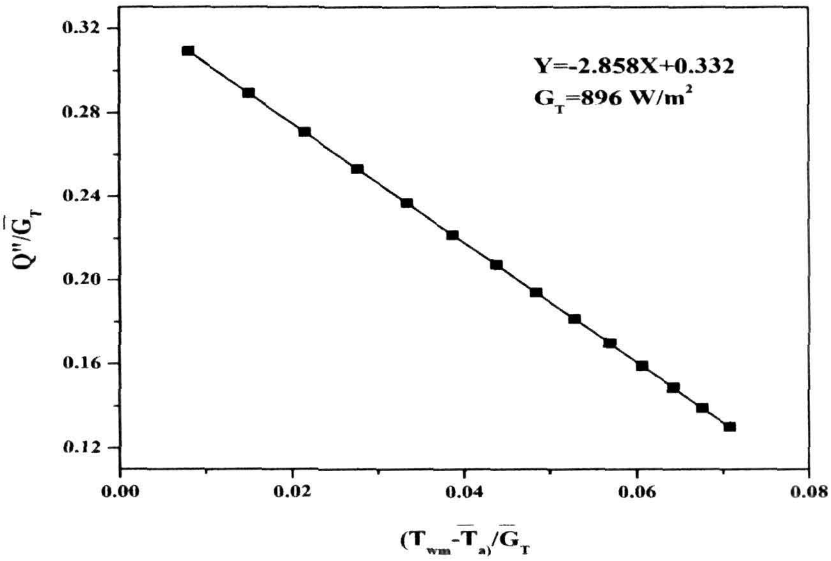

Fig.4.19: $\dot{Q}''/\overline{G_T}$ vs. $\left(T_{wm} - \overline{T_a}\right)/\overline{G_T}$ plot for BC for Fig. (4.18).

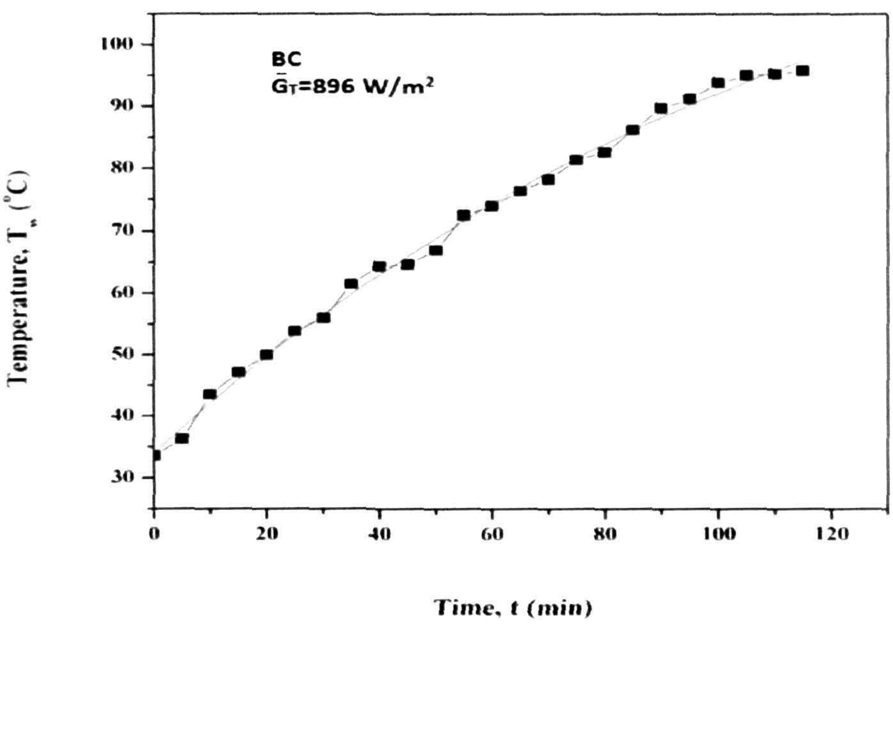

Fig.4.20. Rise in water temperature T_w with time t in BC

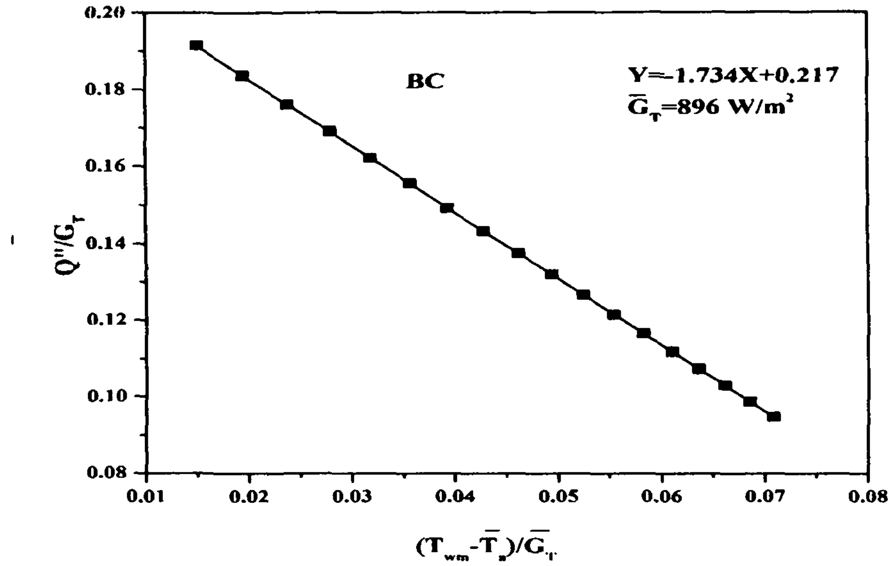

Fig.4.21: $\dot{Q}''/\overline{G}_T$ vs. $(T_{wm}-\overline{T}_a)/\overline{G}_T$ plot for BC for Fig. (4.20).

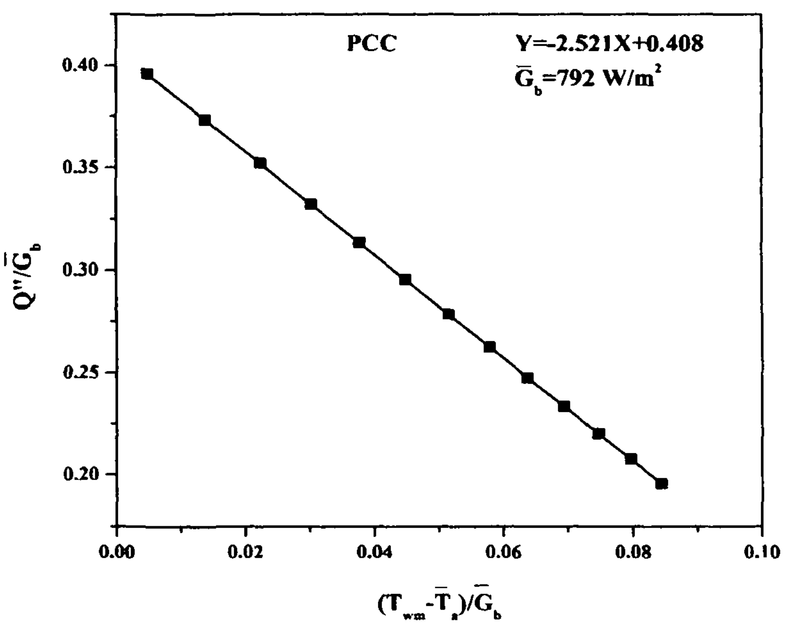

Fig.4.22: $\dot{Q}''/\overline{G}_T$ vs. $(T_{wm}-\overline{T}_a)/\overline{G}_T$ plot for PCC for Fig. (4.10).

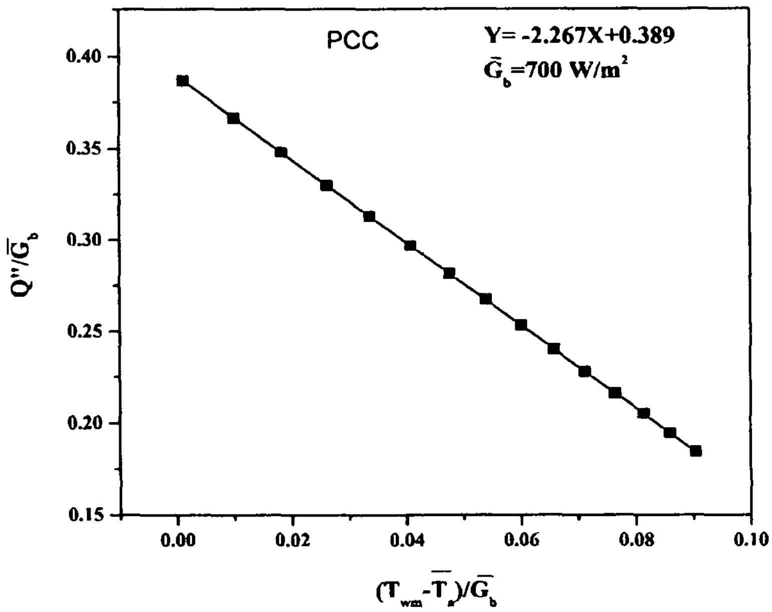

Fig.4.23: $\dot{Q}''/\overline{G}_T$ vs. $(T_{wm}-\overline{T}_a)/\overline{G}_T$ plot for PCC for Fig. (4.14).

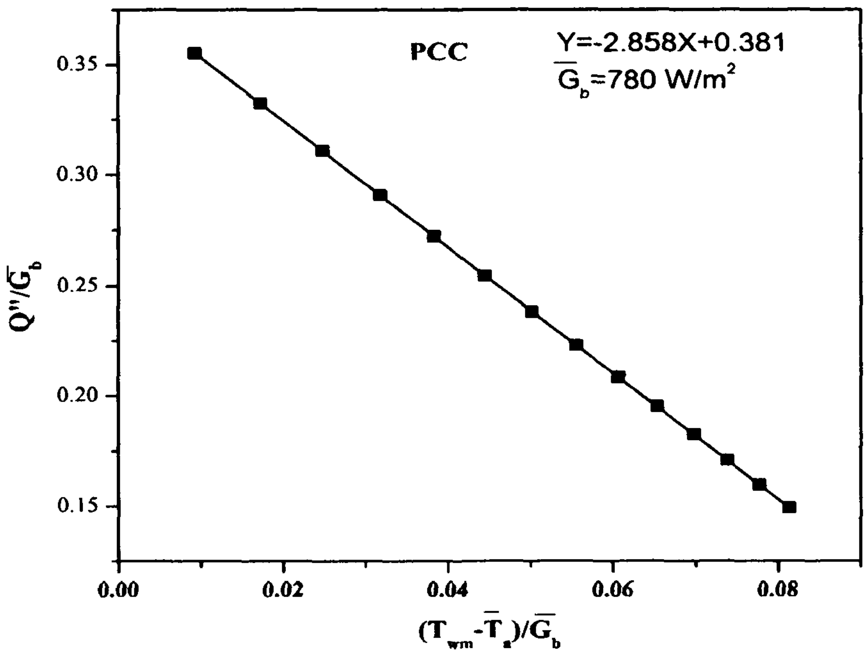

Fig.4.24: $\dot{Q}''/\overline{G}_T$ vs. $(T_{wm}-\overline{T}_a)/\overline{G}_T$ plot for PCC for Fig. (4.18).

In Fig 4 22-4 24 for PCC, the beam component $\overline{G}_b$ has been considered in place of $\overline{G}_T$ It may be noted that all the existing test procedures for PCC suggest measurement of beam component only This necessitates a separate measurement device for measuring beam radiation for PCC The TPPs - $F'\eta_o$ and $F'U_L/C$, have been obtained from these plots for BC and PCC are presented in Table 2 3 (for PCC both beam and total radiation is considered) From three days' data it is observed that $F'\eta o$ has shown slight variation in the values for each day for both cookers BC and PCC In case of PCC if total and beam radiation is considered then value of $F'\eta_o$ is more in case of beam component and increasing/decreasing trend of $F'\eta_o$ is same for both the component

Table-4.2. Values of the variables used in calculations

Variable	Value	Variable	Value
A_c(BC)	0 492 m^2	C(PCC)	8 88
A_c(PCC)	1 545m^2	M_1	1 477kg
A_t	0 174m^2	M_2	4 751 Kg
A_g	0 270 m^2	$\overline{T}_a$	30^0C
C_w	4186 J/kg-K	T_{w2}	95 °C
C(BC)	1 82		

Table-4.3: Values of Thermal Performance Parameters (TPPs)

	BC			PCC			PCC (with beam component)		
$F'U_L/C$	1.474	1.734	1.521	2.267	2.858	2.252	2.267	2.858	2.252
$F'\eta_o$	0.219	0.217	0.204	0.338	0.332	0.357	0.389	0.381	0.408
$G_T(W/m^2)$	805	896	906	805	896	906	700	780	792
Time(min)	105	115	110	80	75	65	80	75	65

Table-4.4: Values of Objective Parameters (OPs)

OPs	**BC**			**PCC**			**PCC(beam component only)**		
$T_{fx}(^{o}C)$	149.60	142.13	151.51	150.02	134.08	173.62	150.11	133.98	173.48
τ_r(predicted)(min)	111.44	107.03	107.13	73.5	73.08	65.16	73.72	73.65	57.47
τ_r (exptl.) (min)	105	115	110	80	75	65	80	75	65
Error %	-6.13	6.93	2.61	8.13	2.54	-1.75	7.85	1.71	11.58
τ_{hr}(predicted)(min)	23.72	20.17	22.99	15.8	12.54	14.21	15.8	12.54	14.21
τ_{hr} (exptl.)(min)	23	21	22	15	13	15	15	13	15
Error %	-3.14	3.97	-4.5	-5.39	3.53	5.22	-5.39	3.53	5.22
G_T (W/m^2)	805	896	906	805	896	906	700	780	792

The predicted value of τ_r for PCC is less than the predicted value of BC. This indicates that the reflectivity of the reflector used in PCC has higher value. However transmissivity of glass cover used in BC is less. This may be reason due to which PCC is taking less time. Data used to obtain the TPPs for both the cookers are from the single step test procedure. $F'\eta_o$ for PCC has higher value than for BC. It may be because of the double glazing used in BC and reflection losses from the pot used in PCC. Also the $F'U_L/C$ value for PCC is higher than that for BC. It may be noted here that the value of C is approximately 1.82 for BC and 8.88 for PCC. The C for BC has been taken as the ratio of aperture area and the glazed heat loss area. For PCC it is the ratio of the aperture area of concentrator and surface area of the pot. For PCC the value of $F'U_L$ in that case will be around 20-26 W/m^2-K, which is almost identical to the value obtained by Mullick et al [17]. For BC it is around 3 W/m^2K. An experimental value may be determined using cooling test as well. T_{fx} is also high for PCC.

From the proposed TPP and test procedure it has been possible to predict the performance of cookers with reasonable degree of accuracy. The determination of OPs will further enable us to decide on their applicability to both the cookers. The test proposal for this is also in conformity with an endeavour to develop a common TPP and Test procedure for both the cookers. Percentage of error is also below ±10% for both the cookers

It is to be noted that

i. The aperture area has been taken to make it identical for both the cookers to makes it common.
ii. The radiation flux determination has been redesigned.
iii. It has been shown that measurement of total radiation on aperture area is sufficient.
iv. The amount of load has been taken uniformly to be 3 kg/m^2.
v. It is the water temperature rise profile which provides desired information. Plate temperature is not required.

Determination of objective parameters (OPs)

The three OPs maximum achievable fluid temperature (T_{fx}), Reference time (τ_r) and Heat retention duration (τ_{hr}) which were discussed and formulated in Chapter -2 is determined and given in Table-4.3. Error is in the range of ±8% in case of Reference time and in the range of ±6% in case of heat retention duration. In present case for reference time, both positive and negative error is seen similarly in case of heat retention duration it is positive and negative.

Determination of COR

These values of TPPs are used to calculate COR using analytical equation (4.20). Further this value of COR is used to derive MAT for both the cookers. High value of COR gives the high value of MAT. From the results it is seen that the value of COR and hence the MAT is more for PCC than for BC as shown in Table 4.4.. Thus COR is able to predict the MAT reasonably well for both the cookers. If all the conditions (input values) are same COR helps the user to select the cooker as per their requirement.

The value of COR may vary within ±10% which may be considered within the limit. However, in that case difference in the COR values of the two cookers i.e. BC and PCC will be narrowed down. It is expected because the pot surface is exposed to the environment in PCC. Some sort of insulation is desirable to keep COR of PCC high.

It is seen that during evaluation process, the total radiation ($\overline{G}_T$) is taken for both PCC and BC though diffused radiation has no or limited role in the case of PCC. Taking into account only beam radiation (Fig.4.22-4.24) it is seen that the COR value for PCC is higher than that for total radiation ($\overline{G}_T$). It is shown in Table-4.5

Table-4.5: Values of COR

Parameters	BC			PCC			PCC (beam component only)		
COR	0 15	0 13	0 13	0 15	0 12	0 16	0 17	0 13	0 18
$G_T(W/m^2)$	805	896	906	805	896	906	700	780	792

4.7. Conclusions:

This chapter presents a single step test procedure to estimate TPPs, $F'U_L/C$ and $F'\eta_o$ for both the cookers BC and PCC To determine the TPPs, experiments were performed under identical condition Same load per m^2 aperture area was taken for this purpose Though beam component of solar radiation is used for estimation of $F'U_L/C$ and $F'\eta_o$ for PCC, here total radiation G_T is used for the same So use of G_T is not changing the value of $F'U_L/C$ But $F'\eta_o$ is changing It has no effect on intra-cooker grading But inter-cooker thermal performance may be slightly affected due to difference in values of $F'\eta_o$ of PCC in comparison to the value of $F'\eta_o$ of BC which is measured from G_T absorbed by the cooking pot in PCC A performance parameter COR has been proposed for both the cookers From the results and their analysis it may be concluded that COR and the single-step test procedure for BC and PCC may be used for characterizing a cooker because

i The suggested single step method to determine COR is simple

ii It is possible to determine the MAT value from this

iii It enables inter-cooker thermal performance comparison and intra-cooker grading

iv COR is a parameter which is design dependent, so it should not change with variation in intensity of radiation, wind speed, ambient temperature etc COR is generally seen to be independent of external variables However further investigation is needed to know in detail about their role

v. A cooker with high value of COR may be graded higher than the one having lower value of COR.

This procedure suffers from some defects and disadvantages. Prediction of OPs is not always very accurate because it is measured at 95°C only up to which the variation in TPPs is considered to show linear behavior. At higher temperature higher order terms will appear which will affect the values of TPPs.

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Chapter –5

Generalization of TPPs and test procedure for evaluation of different types of Solar Cookers

Chapter 5

Generalization of TPPs and test procedure for evaluation of different types of Solar Cookers

This chapter explores the possibility of generalization of the TPPs and test procedures for solar cookers of all the three types. Here basis for selection of TPPs for both BC and CC are discussed. Consequently the possibility of using the TPPs proposed earlier for BC and CC as generalized TPP (GTPP) is investigated and discussed. The advanced type cooker has separate collector (tracking/non-tracking and concentrating/non-concentrating type) and cooking chamber or plate which is fixed conveniently. Normally a heat transfer fluid is used to transfer the heat from the collector to the cooking chamber. Some times energy is transferred radiatively as in the Scheffler type (Fig.1.4). The design, fabrication and detailed analysis of such a cooker is beyond the scope of the thesis. However by considering the basic design of such a cooker through a qualitative analysis of the same the possibility of use of proposed TPPs has been explored for advanced type cookers including other cookers. A similar approach has been taken for generalizing the test procedure as well. For generalization the parameters needed for determining TPPs and conditions set for carrying out the generalized test procedure (GTP) must be same for all types of cookers.

5.1 Introduction

As reported in the earlier chapters, across the globe, especially in the solar rich regions, the researchers have been trying to develop new cooking systems and upgrade the existing ones through innovation in design, incorporation of new features, employing engineered materials, etc. This was necessitated because the cooker of each type, hitherto discussed, has one or the other drawbacks. The major drawbacks of conventional box type cookers (BC) are

i) It does not provide high temperature.
ii) Cooking has to be done/attended in the sun.
iii) It is inconvenient to load/unload the cooking pot/material in open.
iv) The food material may get spoiled in the event of sudden rains or other external disturbances if not attended for a long duration. Please note that low temperature cooking facilitates unattended cooking and is considered to be one of the advantages of the box type cookers.

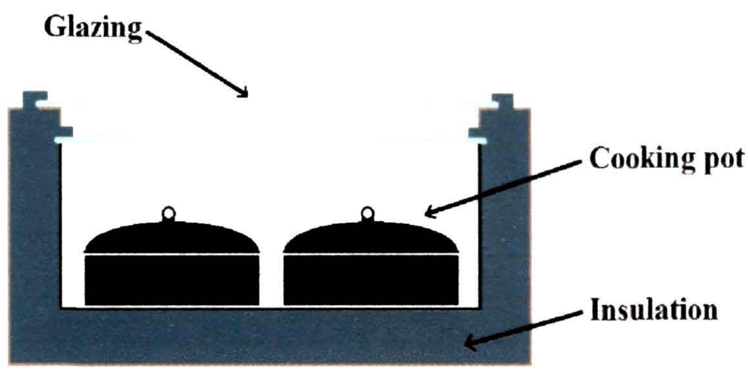

Fig.5.1. Schematic diagram of box type cooker (BC) [1]

Similarly the concentrating cookers (CCs), in spite of achieving higher temperature, have some drawbacks like

i) Cooking has to be done in sun.
ii) In addition to the drawback of loading/unloading inconvenience there is a danger of getting injured through exposure to high concentration radiation.
iii) Cooking pot is fully exposed and hence food may get spoiled in case of sudden change in weather conditions (Fig.5.2).
iv) It is not possible to have storage facility in these.

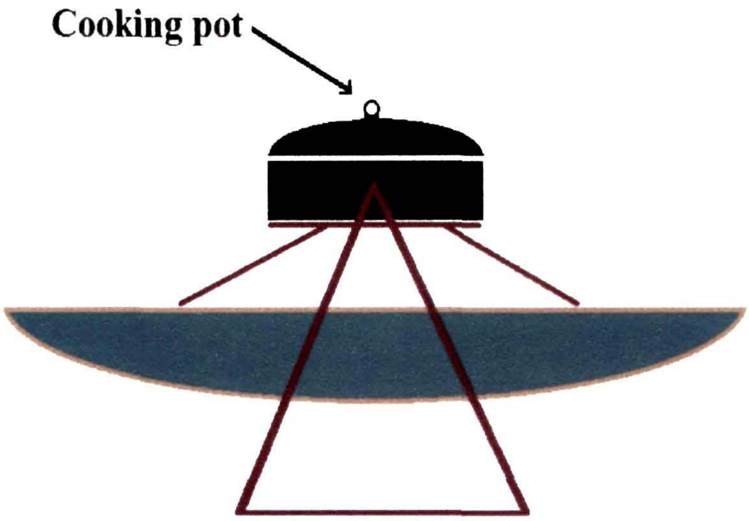

Fig.5.2. Schematic diagram of concentrating type cooker (CC) [1]

All these problems were partially solved with the development of the third category of cookers i.e. advanced type (AC). In advanced type cookers the collector and the cooking chamber are isolated. This has the potential of solving most of the teething problems in dissemination of solar cookers. In ACs the heat/radiant energy collected by the collector is transferred to the cooking chamber either i) convectively through heat transfer fluid or ii) radiatively through reflectors (Fig. 5.3, 5.4, 5.5).

The former of the ACs i.e. convective AC consists of evacuated tubular collector (ETC) or flat plate collector (FPC). The hot fluid in the tubes carries the heat to the cooking chamber where the heat is transferred to the cooking pot (Fig. 5.4). The later one has a concentrating collector with a tracking mechanism which directs the concentrated beam towards the cooking chamber (Fig.5.3, 5.4). Hence the cooking pot receives the energy through a radiative mechanism.

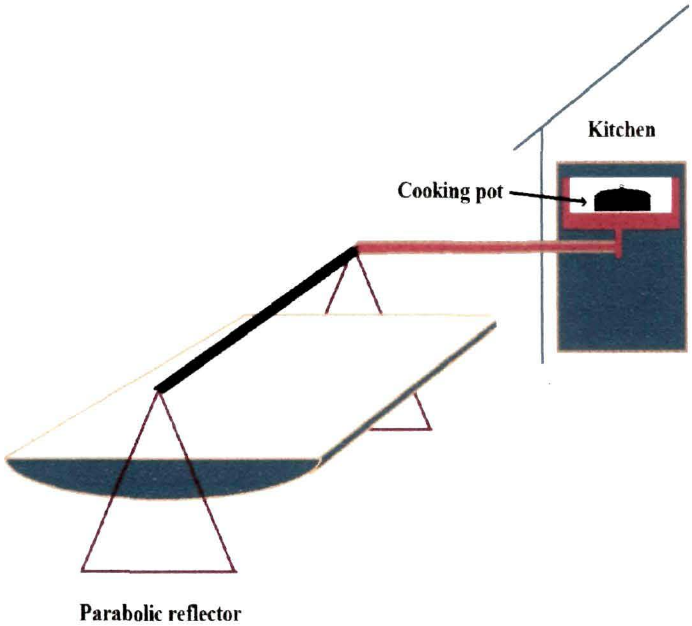

Fig. 5.3. Schematic diagram of advanced type cooker (AC) [1]

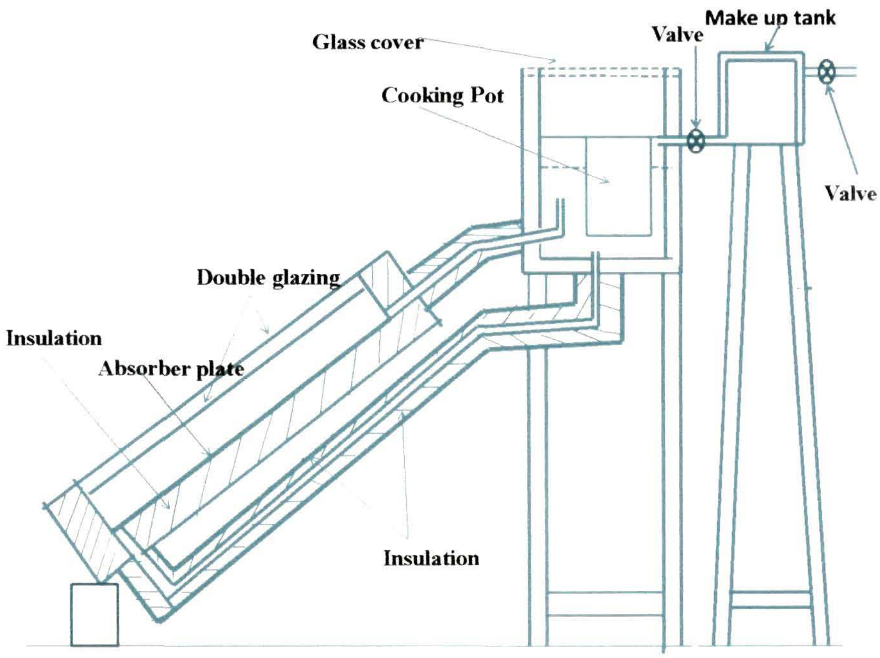

Fig: 5.4. Schematic diagram of advanced type cooker (AC)

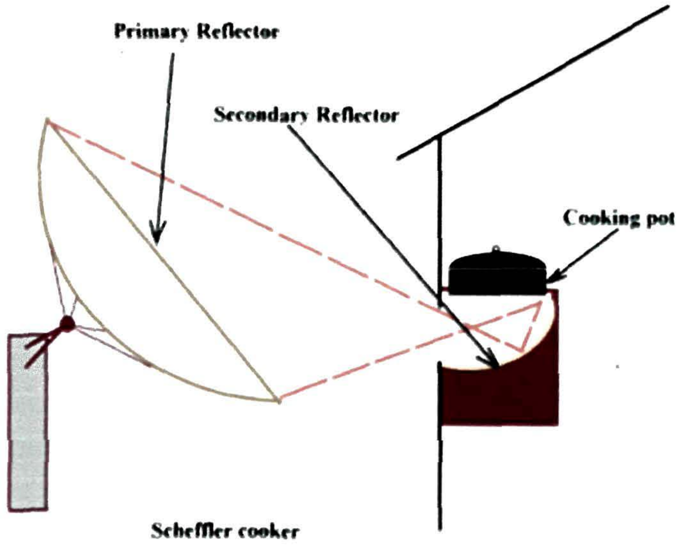

Fig. 5.5. Schematic diagram of Schefflar cooker [1]

As mentioned in chapter I and IV some of the ACs and BCs respectively have an in-built storage. Although the CC and BC cookers used for experimentation and reported in Chapter III and IV respectively did not have such storage but any GTPP and GTP should have a mechanism to determine the absolute thermal performance of such cookers as well.

These new design features appear to pose a new set of challenges in testing and representing their thermal performance. However analysis of the objective of this thesis which aims to develop a cooker-type independent, feature/design responsive, holistic/inclusive, absolute TPP, values of which may be determined repeat ably with a corresponding simple test procedure, directs us to look into the dependent and independent - design, operational, weather input parameters which need to be taken into account. If the input parameters used in the case of BC or CC is sufficient then we may think of using the same TPPs as discussed in chapter-III and Chapter-IV as GTPP.

5.2. Generalization of variables:

The variables need to be considered for generalizations are discussed.

5.2.1. Solar Irradiance:

It may be identical to the one used in the case of BC and CC. It is basically the irradiance in the direction of the beam radiation. The maximum value of the total irradiance is measured using an appropriate pyranometer or radiometer. The values should be greater than 700 W/m^2 during the experimentation and variation may be within ±50 W/m^2 [3]. The reason is that we intend to achieve a maximum temperature of about 95°C as OPs have been defined accordingly. It will take around one hour for a load of $3kg/m^2$ to reach this temperature at T_a ~25 °C. Other equally important reasons are – around this temperature the heat loss may be assumed to vary approximately linearly with temperature, and cooking is done close to this temperature and hence the prediction will be more realistic. The conclusion of chapter-4 that total irradiance may be used in place of beam irradiance in CC helps to generalize the solar irradiance measurement issue. In fact it helps us in taking acceptance angle of CC as an influencing design parameter.

5.2.2. Aperture area:

As in the case of BC and CC this will correspond to actual open area of the aperture receiving the radiation. The BCs have variable aperture. The proposed method for BC in chapter-4 has an in-built mechanism to take into account these diurnal and seasonal variations through alteration in the aperture area in the calculations, the loading and the plane of measurement of radiation flux. By this approach the use of additional radiation augmentation devices [2] are also automatically taken care of. In non-tracking systems however there may be small diurnal variations during experimentation which may be ignored.

5.2.3. Ambient temperature:

Cooking is temperature dependent. At very low temperature cooking may not be accomplished at all. Even at low ambient temperature a concentrating cooker may achieve a temperature of 95°C needed for the proposed procedure. But it may not be possible for a box type cooker. Hence the test procedure may not have any limitation on ambient but it is advisable to have a value close to average ambient temperature of about 25°C with a permissible fluctuation of ±5°C[3,4]. Thus GTPPs based on measurements at ambient temperature below 30 °C is expected to give reproducible results.

5.2.4 Load (water) temperature:

The load (water) temperature has been taken to be between 30°-95°C. This is because the lower limit is always above the average ambient temperature and also the upper limit is below the boiling temperature wherein linearity in the heat loss is maintained. It may be noted that at certain locations where T_a is high (~50 °C) a range of 60- 95 °C is suggested. This range may be considered for determining GTPP values for all types of cookers.

5.2.5. Wind speed:

It may be maintained at less than 1.0 m/s. Wind has high impact on any parameter and may be a source of scatter in the data [4]. The limit takes into account the fact that natural convection losses are close to this value under experimental conditions. It is possible to maintain this value to enable determination of GTPPs.

5.2.6. Test Timing:

The test shall be conducted within ±1:30 hrs of solar noon of the place. This is to maintain constancy in radiation value for outdoor testing.

5.2.7. Loading:

As the generalized test procedure includes CC with large area having a single small pot the load has been carefully taken to be 3.0 kg/m^2. The same value may be maintained for BC and AC cookers as well without much problem.

5.2.8. Tracking:

Tracking should be done such that the reflected and/or concentrated radiation always falls on the absorber surface.

5.2.9. Specific heat:

As the procedure requires achieving a temperature of 95°C only water may be used conveniently in all the three types of cookers. The specific heat of water C_p is known within 0.08 percent in this range [5].

5.3. Generalized Test procedure:

The test procedure requires recording of some measurable variables such as – load temperature, ambient temperature, total(maximum) radiation flux on aperture, wind speed, beam radiation flux, aperture area. This is valid for generalized test procedure as well. It will also entail the conditions to be set under which the test would be conducted. Finally, the details of the manner/method, in which the test is to be carried out need to be mentioned correctly.

5.4. Measurement and accuracy of variables:

5.4.1. Load temperature:

It may be measured by using a copper-constantan thermocouple with its junction dipped in the load(distilled water) about 1 cm above the base of the cooking pot preferably close to the center where convective currents are fully grown and thermal stratification has minimum impact. However an arrangement for mixing of fluid would be preferred. This is valid for all the three cookers AC, BC and CC in spite of the fact that the cooking temperature may be different in them. The interval should be kept at 5 minutes. The accuracy of measurement may be within ±0.5°C.

5.4.2. Ambient temperature:

It should be measured using a thermocouple at an open but shadowed place close to the experimental set-up. The interval should be same as the load temperature i.e. 5 minutes. The accuracy of measurement may be within ±0.25°C.

5.4.3. Total (maximum) solar radiation flux:

It is measured on the plane close to the plane of opening with the instruments which may have an accuracy of about ±1.5% for normal incidence which is valid for the GTP [3-5]. Even beam radiation may be measured in an identical manner. But for GTO the value of beam radiation is needed for comparison purpose only.

5.4.4. Wind speed:

This is measured within an accuracy of ±0.5 m/s.

5.4.5. Aperture area:

It should be determined from the measurement of appropriate length dimensions of rectangular, circular or oval openings. Each length dimension may have an accuracy of measurement within ±0.5 mm [5-7].

5.4.6. Angle of tilt of collector opening and beam radiation:

It should be measured within ±1° [5-7].

Conditions for conducting the test:

a) The test should be carried out during ±1:30 hrs of solar noon for all the cookers. There should not be any source of significant reflected radiation. This will ensure the variation in the solar radiation within the limit mentioned earlier.

b) Variation in the wind speed should be kept to a minimum as mentioned earlier.

Test details:

a) The cooker should reach thermal steady state before being loaded with food for both the AC and BC. For CC the load should be in equilibrium with the ambient air before starting an experiment.

b) The load temperature should be measured as frequently as possible in addition to other variables.

c) Although it may not be necessary but tracking should be done frequently during the experiments. In the case of CC the concentrated beam radiation should be allowed to fall on one side of pot bottom initially as suggested by Mullick *et al* [8] to minimize the tracking requirement.

d) To carry out cooling test the collector should be shadowed and the data should be recorded as discussed in (b) above. It may be noted that in proposed GTP it is needed only for verification purpose.

5.5 Generalized thermal performance parameters and their evaluation:

The two TPPs identified earlier may be used in all the three cookers. The method would be the same as followed in chapter III and IV, i.e.

i) Temperature vs. time curve is plotted after sensible heating of water up to 95 °C.

ii) Through the experimental points, a regression fitted curve with $R^2>0.85$ is generated to make temperature time curve smoother. An exponential fit is suitable.

iii) Then the statistically corrected value of T_w and the corresponding t is determined from the plot.

iv) $\dot{Q}''/G_T$, and ΔT/G is calculated from the statistically corrected data available from the Temperature vs. time curve after exponential fit.

v) From this, $\dot{Q}''/G_T$ vs. $\Delta T/G_T$ points are to be plotted.

vi) A straight line is fitted though the points. It may be noted that a higher order non-linear plot will provide better value for $F'U_L/C$.

vii) Extend the line to get an intercept at ordinate. This gives the value of $F'\eta_o$ and the slope give the averaged value of $F'U_L/C$.

5.6. Derivation of objective parameters:

The objective parameters may be determined using the equations used earlier with the first, second, and third OPs derivable respectively from the following correlations with the generalized TPP

(i) $$T_{fx} = \frac{\eta_0 C \overline{G}_T}{U_L} + \overline{T}_a$$

(ii) $$\tau_r = \frac{(MC_w)'_w}{A_c F' U_L / C} \ln\left[\frac{\overline{G}_T - \frac{U_L}{\eta_0 C}\left(303 - \overline{T}_a\right)}{\overline{G}_T - \frac{U_L}{\eta_0 C}\left(368 - \overline{T}_a\right)}\right]$$

(iii) $$\tau_{hr} = \frac{(MC_w)'_w C}{A_c F' U_L} \ln\left[\left(368 - \overline{T}_a\right)/\left(358 - \overline{T}_a\right)\right]$$

5.7. Test Report:

The test report should essentially have the values of two TPPs. The manufacturers may provide expected values of OPs for a given location as well and average value of input parameters.

5.8. Conclusions:

i) The need for the development of advanced type cookers and its features has been discussed in detail in the light of the limitations of other types of cookers.

ii) The difficulties in employing one of the existing TPPs in assessing the performance of AC have also been explained.

iii) Based on the analysis of the TPPs proposed in the earlier chapters it has been concluded that the same may be applied to ACs also. This is needed to establish the TPPs for general assessment of all types of cookers.

iv) Finally a number of variables have been carefully identified which may be measured and needed with specific details about each one of them.

v) The GTP has been discussed keeping in view different existing and future designs of the cookers with conditions for conducting the test and specific steps of the test.

vi) These values of GTPPs derived from regression fit of the experimental date are independent of location and date provided the conditions given in GTP have been maintained during their determination. The GTPP of cookers of different variants of same or different category/class/type can be estimated by following the GTP proposed here.

vii) The GTP is simple and applicable to all type of cookers even for cookers having storage facilities (through HRD, τ_{hr}) or for cookers having booster mirror facilities to enhance performance (through RT, τ_{r}.).

viii) It has been shown that the OPs can be determined from the values of GTPP which is a useful in correlating the data of other TPPs and also for the users. It is recommended that the values of two GTPPs may be provided by the manufacturers and the values of OPs may be provided for a given location

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Chapter-6

Proposal of a new cooker design feature and its evaluation using GTPPs and the corresponding generalized test procedure.

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Proposal of a new cooker design feature and its evaluation using GTPPs and the corresponding generalized test procedure.

The conventional box type solar cooker with single reflector has several desirable features like a simple design, portable, cooking each batch of meal with minimal tracking, flat absorber plate, minimum chances of spillage of food during loading and unloading, a shallow cooking box with small heat loss area, and loading and unloading of food from top making all the cooking space easily accessible [1].

In spite of all the above mentioned features, the cooking time in this type of cookers is more [2, 3]. The performance of box type cooker can be improved by new component design, fabrication of new variant of cooker, by boosting the solar energy flux falling on the cooker, by incorporating energy storage device to the cooker etc. Out of many options available, one of the options is superior design of cooking pot [2] with appropriate knowledge of heat flow/energy transfer to the material to be cooked [4]. In order to make box type solar cooker more effective in terms of cooking time a new design of the cooking pot is proposed where opaque conducting material of the pot lid is replaced by transparent insulating material. This chapter discusses the basics of such a design and response of the GTTP to this new design feature. Comparative analysis of the test data has also been done to verify the response.

6.1. Introduction:

In the present work the top of the conventional pot lid is replaced by glass while the container is kept metallic (Aluminium). The glass is fitted with the help adhesive on the aluminum ring to make the lid air tight with the pot.

The objective of the new design is to increase the gain in energy and reduce the loss from the top. That can be made possible by using thin glass top on the lid. Secondly by this new design, the loss can be minimized by keeping the gain constant as glass has certain properties like the glass top will transmit the shorter wavelength solar radiation but block the longer wavelength re-radiation from the cooking pot. The radiation falling on the top of the lid will be trapped and directly absorbed by the food item kept inside the box. The conduction and radiative heat loss will be reduced due to glass lid. It also reduces the heat loss by convection from the top of the cooking item in the cooking pot. Another advantage of having glass lid is that it will facilitate the person to observe the condition of the food being cooked. The glass can break easily, however this disadvantage can be minimized by using tempered glass [5].

Glass is transparent for the solar range and opaque for infra red radiation [6]. Thermal properties of glass cover such as transmittance, reflectance and absorptance are function of wave length, angle of incidence of the incoming radiation etc. Glass can be considered as a cover for pot also as it absorbs almost all the infrared radiation re-emitted by the inner part of the cooking pot, it is expected to result in an enhancement of the thermal efficiency of the cooking pot [7]. It may be noted that the heat capacity of glass (0.84J/gm/K) and Al (0.9 J/gm/K) is almost same so it will not affect the calculations.

The proposed design with the metallic container maintains the advantage of conventional solar cooker pot also.

In conventional type cooking pot the food item kept on the cooking pot is heated from the side and top of the container by the hot air trapped inside the BC. The bottom of the cooking pot receives heat from the absorber plate by conduction process. Food material is converted to semi solid state after initial phase of heat distribution. A temperature gradient is set up in the food. The temperature will have maximum value at the wall of the cooking vessel/pot. It decreases as the distance from the wall increases and even may reach a level which is insufficient to carry forward cooking process [8]. This deficiency may be partially overcome by introduction of transparent cover on the cooking pot as shown in Fig. 6.1. The transparent cover will help to absorb heat energy directly from the source and entire food material will get equal amount of heat. Condensation of vapour on glass top of lid may limit the transmissivity of glass during final stages of cooking [9].Fig.6.2 and 6.3 show the two views of the cooker tested with the glass lid pot.

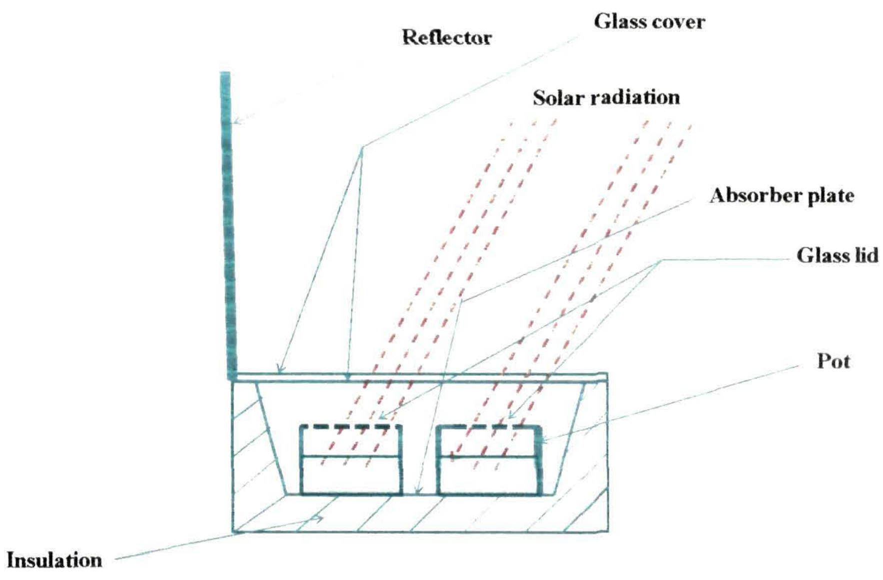

Fig: **6.1. Schematic diagram of Box type of cooker with pot design**

Fig.6.2. Box type cooker with glass lid pot

Fig.6.3. Box type cooker with glass lid pot

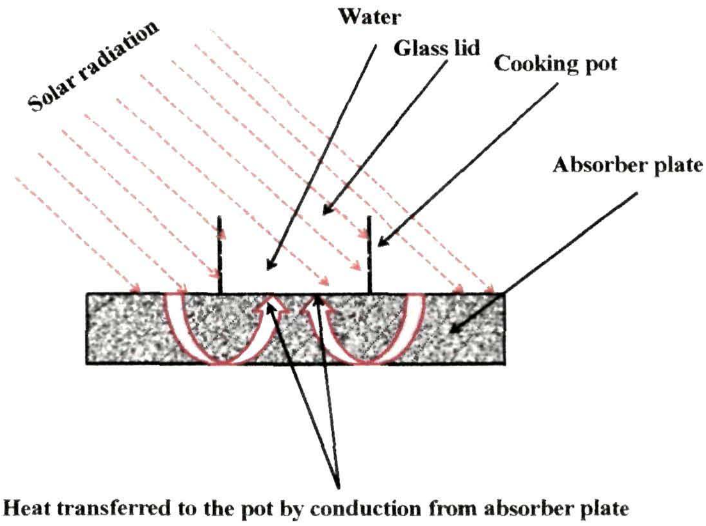

Fig.6.4. Ray diagram of heat transfer to cooking pot from sun and absorber plate

With the proposed new design this chapter tries to investigate the performance of the cooker in terms of the Generalized TPPs proposed in Chapter-5 using the corresponding generalized test procedure. This also aims to see whether it is reflected in the GTPPs sufficiently with high sensitivity and precision. The same has been supported on the basis of comparative data analysis. The proposed pot design will directly receive the radiative heat from top, convective heat from side and conductive heat from bottom as shown in Fig. 6.4.

6.2. Proposed thermal performance parameters and Test procedure for their determination:

6.2.1 Theory:

The aim of the present work is to check whether the new design feature is reflected in the GTPPs ($F'\eta_o$ and $F'U_L/C$) i.e. whether the new design has any impact on cooker's performance. The internal heat transfer mode that is heat exchange from the water surface to the glass cover inside the pot is governed by radiation, convection, and evaporation and hence these heat transfer modes and energy balances from the pot are discussed separately. All other energy balance equations will remain identical to the one for BC as discussed in Chapter-4.

The thermal circuit diagram of various heat transfers through the different component of cooking pot like bottom of the pot, water in the pot and glass lid of the pot to the cooker interior (spaced enclosed inside the box of the cooker) is shown in the fig. 6.5. In the circuit diagram C_g represents the heat capacity of glass, C_w , heat capacity of water. T_{gp}, T_g and T_a represent the temperature of the glass of the pot lid and temperature of the glass of the cooker cover, and ambient air temperature air respectively. T_w and T_{wf} is the temperature of water and water vapour.

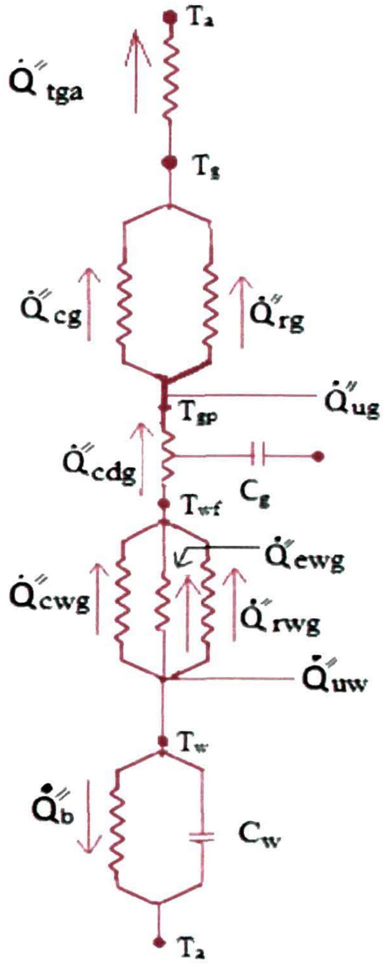

Fig.6.5. Thermal circuit diagram of various heat transfers with specific parameters.

Energy balance in the cooking pot with glass lid: (Fig. 6.5)

a) **Radiative loss coefficient (h_{rwg}) from water surface to the glass lid:**

In this case water surface and glass lid are considered as infinite parallel plane and here heat transfer process is considered as one-dimensional. The rate of radiative heat transfer [10] from the water surface to the glass lid is given by

$$\dot{Q}''_{rwg} = \varepsilon_{eff}\, \sigma \left[(T_w + 273)^4 - (T_{gp} + 273)^4 \right] \quad (6.1)$$

$$\dot{Q}''_{rwg} = h_{rwg} \left(T_w - T_{gp} \right) \quad (6.2)$$

where h_{rwg} is the radiative heat transfer coefficient from the water surface to the glass lid and ε_{eff} is the effective emissivity, σ is the Steffan-Boltzman constant, T_w is the water temperature, and T_{gp} is the temperature of the glass lid of the pot. The expression for h_{rwg} is :

$$h_{rwg} = \varepsilon_{eff}\sigma\left[(T_w + 273)^2 + (T_{gp} + 273)^2\right]\left[T_w + T_{gp} + 546\right] \quad (6.3)$$

It is to be noted that water and glass are parallel surfaces in this case; hence the radiation shape factor is 1.

b) **Convective loss coefficient (h_{cwg}) from water surface to the glass lid of the cooking pot:**

The rate of heat transfer from the water surface to the glass cover (Q_{cwg}) by convection in the upward direction through the humid fluid can be estimated by

$$\dot{Q}_{cwg} = h_{cwg}\left(T_w - T_{gp}\right) \quad (6.4)$$

where h_{cwg} is the convective heat transfer coefficient from water to glass and other notations are same as stated above.

The coefficient h_{cwg} can be determined by the relation

$$Nu = \frac{h_{cwg} d_f}{K_f} = C(Gr\,\Pr)^n \qquad (6.5)$$

$$Gr = \frac{d_f^3 \rho_f^2 g \beta'}{\mu_f^2} \Delta T' \qquad (6.6)$$

$$\Pr = \mu_f C_f / K_f \qquad (6.7)$$

$$\Delta T' = \left[\Delta T + \frac{(P_{wo} - P_{go})(T_{wo} + 273)}{268.9 \times 10^3 - P_{wo}} \right] \qquad (6.8)$$

where, Nu is the Nusselt number, K_f is the thermal conductivity of fluid

For a normal cooking temperature range say 95° C and $\Delta T = 2^{\circ}C$, the expression for Grashof number given above is reduced to

$$Gr = Const \;\; d_f^3 \qquad (6.9)$$

c) Evaporative loss coefficient (h_{ew}):

$$\frac{h_e}{h_{cwg}} = \frac{L}{C_{pa}} \frac{M_w}{M_a} \frac{1}{P_T} \qquad (6.10)$$

where P_T is total gas pressure M_w is the mass of water vapor M_a mass of air, and C_{pa} the specific heat per unit volume at constant pressure of the mixture. h_e is the mass transfer coefficient

The energy balance equation for different component of the cooking pot, glass lid and from pot to the outside i.e.to cooker interior is discussed below.

d) Energy balance between the glass cover and ambient:

$$\dot{Q}''_{rg} + \dot{Q}''_{cg} = \dot{Q}''_{tga} \qquad (6.11a)$$

where $\dot{Q}''_{rg} + \dot{Q}''_{cg}$ is the rate of heat loss to cooker interior from glass lid by radiation and convection $\dot{Q}''_{tga}$ is the rate of heat loss through glass cover to the ambient by combined heat transfer by conduction followed by convection and radiation.

e) Energy balance between glass lid to cooker interior:

$$\dot{Q}''_{ug} + \dot{Q}''_{cdg} = \dot{Q}''_{rg} + \dot{Q}''_{cg} \tag{6.11b}$$

where, $\dot{Q}''_{ug}$: rate of energy absorbed by glass; $\dot{Q}''_{cdg}$ is the rate of energy received by the outer surface of the glass lid by conduction ;

$$\left[\dot{Q}''_{rwg} + \dot{Q}''_{cwg} + \dot{Q}''_{ewg}\right] = \dot{Q}''_{cdg} \tag{6.11c}$$

where, $\left[\dot{Q}''_{rwg} + \dot{Q}''_{cwg} + \dot{Q}''_{ewg}\right]$: rate of energy received from water surface by radiation convection and evaporation by glass lid interior;

f) Energy balance between water mass to glass lid:

$$\dot{Q}''_{uw} + \dot{Q}''_{cw} = (MC)_w \frac{dT_w}{dt} + \dot{Q}''_{rwg} + \dot{Q}''_{cwg} + \dot{Q}''_{ewg} \tag{6.12}$$

where, $\dot{Q}''_{uw}$: rate of energy absorbed; $\dot{Q}''_{cw}$: rate of energy convected from pot bottom; $(MC)_w \frac{dT_w}{dt}$: rate of energy stored; $\dot{Q}''_{rwg} + \dot{Q}''_{cwg} + \dot{Q}''_{ewg}$: rate of energy transferred to glass cover by radiation, convection and evaporation

g) Energy balance between bottom and sides of the pot to water:

$$\dot{Q}''_{ub} = \dot{Q}''_{w} + \left[\dot{Q}''_{b} + \dot{Q}''_{b}(A_{ss}/A)\right] \tag{6.13}$$

where, $\dot{Q}''_{ub}$ is the rate of energy absorbed; $\dot{Q}''_{w}$: rate of energy transferred to water; $\left[\dot{Q}''_{b} + \dot{Q}''_{b}(A_{ss}/A)\right]$: rate of energy lost by conduction through bottom/ sides of cooking pot.

From the thermal circuit we may infer that the values of the rate of energy lost to the cooker interior from the top of the glass surface of the pot will be governed the two terms $\dot{Q}''_{rg}$ and $\dot{Q}''_{cg}$ corresponding to radiation and convection. However the heat energy received at the bottom of the glass lid of the pot will face the conductive as well as radiative resistance from the glass owing to its low thermal conductivity and low transmssivity to IR radiation and thus the values of $\dot{Q}''_{rg}$ and $\dot{Q}''_{cg}$ will be quite low. This will affect the steady state thermal behaviour of the cooker. It is to be indirectly seen in terms of improvement in the GTPP values determined through the GTP outlined in the following section.

6.2.2. Generalized Test procedure:

Here experimental method is same as discussed in chapter-4. However in this chapter the analysis is limited to only newly designed BC. Hence the conclusions will be drawn on the basis of comparison. The number of pots taken is two and quantity of load taken is $3kg/m^2$ of aperture area. It is distributed between two pots in such a way that the height of the water levels remains equal [10]. As booster mirror is used during the experimentation, so average total radiation on projected aperture plane normal to beam radiation is taken for calculation of two GTPPs

A box type cooker which was used earlier and tested was taken for this purpose. The newly designed pots were taken for experimentation. The two pots filled with water taken at $3kg /m^2$ of aperture area and heated up to 95°C. The parameters required for measuring TPPs were recorded. After that tests were performed in the same cooker by placing two conventional type cooking pot after removing the earlier one, with same amount of load and equally distributed between the pots as it is done in case of the proposed pots. The conventional type pots taken were identical in all respects except the lid of the pot which was metallic and opaque. In both cases, certain parameters were measured and recorded with regular interval of time. To study the effect of glass lid on the performance of box type solar cooker, the two GTPPs defined earlier in Chapter -5 are determined from the test.

For determining the proposed GTPPs, experimental recording of certain variables at regular interval is needed. For this, water is heated in the cooking pot kept inside the box of the solar cooker. The experiments are performed in two batches. First it is performed by keeping newly designed pot and then by keeping conventional pot. In both cases T_w, T_a and G_T are recorded at regular intervals. The rate of useful heat gain per unit area by water can be estimated from the equation (4.15) and (4.16).

In this method an exponential curve is fitted through the points of the temperature T_w versus time t graph as discussed in chapter- 3. This data derived from this graph is used to plot $\dot{Q}''/\overline{G}_T$ versus $(T_{wm} - \overline{T}_a)/\overline{G}_T$. The values of the important parameters used for the purpose are given in Table 6.1.

Fig: 6.6(i). Photo graph of cooking pot with glass lid.

Fig: 6.6(ii). Photo graph of cooking pot with glass lid.

Table-6.1. Values of the variables used in calculations

Variable	Value	Variable	Value
A_c(BC)	0.492 m^2	M_l	1.477kg
A_t	0.174m^2	$\bar{T}_a$	30^{0}C
A_g	0.270 m^2	T_{w2}	95 °C
C(BC)	1.82	C_w	4186 J/kg-K
G_T *	709-815 W/m^2	V_w	<1 m/sec

• Dependent on the day of experimentation.

6.3. Results and Discussion:

Two sets of experimental data for the two types of pots are shown in the graphs 6.9 – 6.16. Fig. 6.7 and 6.8 show the radiation, ambient temperature vs. time graph corresponding to the duration of the experiments, respectively.

The TPPs determined from experiments of two different days are given in Table 6.2 both for pot with metal lid and pot with glass lid. From both the data sets, it is seen that $F'U_L/C$ is more for pot with metal lid as compared to pot with glass lid. This may be due to property of glass which blocks the longer wavelength re-radiation from the cooking pot. Moreover glass lid reduces convective and conduction loss from the pot. Interestingly, contrary to expectation an opposite picture is seen in case of $F'\eta_o$. It is less in case of the pot with glass lid. The reason for this may be attributed to the glass top which transmits only the shorter wavelength solar radiation to pot. The pot with metal lid absorbs complete range of spectrum but has high conductivity thus having more $F'U_L/C$. But low value of $F'U_L/C$ in pot with glass lid more than compensates the loss in optical efficiency $F'\eta_o$.

To calculate OPs, the value of TPPs is taken from Table 6.2. The improvement in the performance of the cooker with proposed design modification in the pot can be seen from the three OPs given in Table 6.3. The τ_r is less in the case of the cooker using pot with glass lid. The impact of lower value of $F'U_L/C$ is clearly visible. But it

$F'\eta_o$ has minimum effect on the performance of the cooker in comparison to $F'U_L/C$. It has a positive impact on heat retention duration τ_{hr} also. T_{fx} is also higher in the cooker having glass lid.

The impact of this improvement on the value of COR has been seen. As shown in Table 6.2 the COR value for the glass lid is higher compared to the one with the metal lid. Hence COR seems to be sufficient to reflect this aspect of cooker as well. However after comparing the COR value for metal lid with the corresponding results of Chapter-4 it is seen that the COR value are higher there. It may be attributed to the number of pots with metal lid which was four. This shows that the COR value increases with the number of pots used.

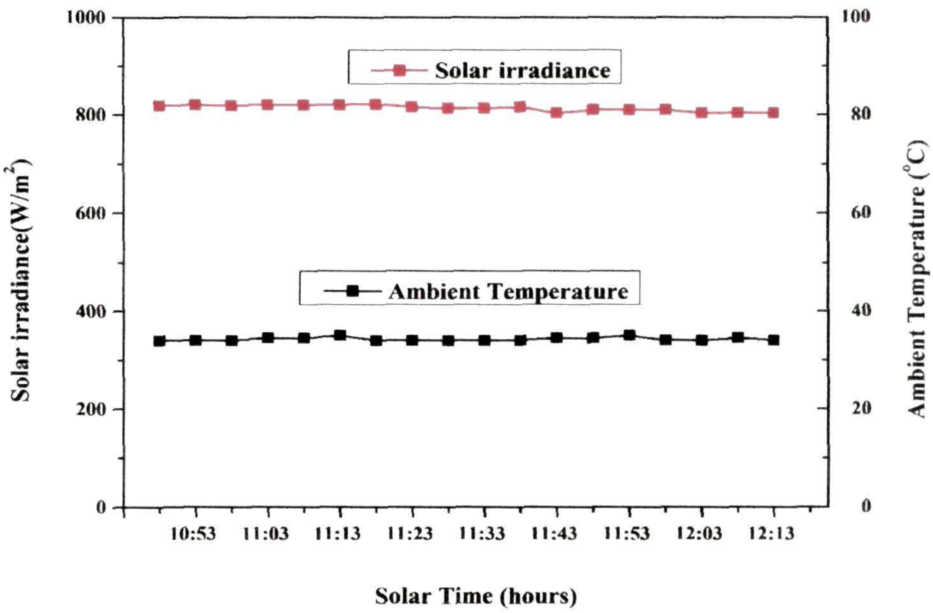

Fig. 6.7.Measured solar irradiance and ambient temperature on 26th May 2010 at Tezpur (Latitude: 26° 41'46" Longitude= 92°50'05'' MSL= 230 ft.) (GT=815 W/m^2)

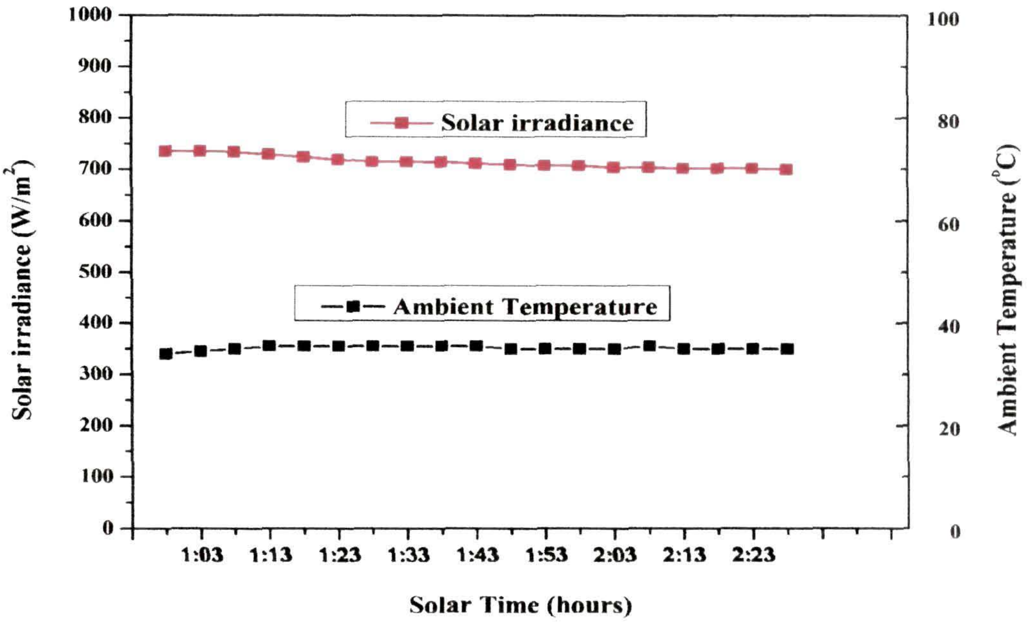

Fig. 6.8.Measured solar irradiance and ambient temperature on 26th May 2010 at Tezpur (Latitude: 26° 41'46" Longitude= 92°50'05 MSL= 230 ft.) (G_T= 716 W/m^2)

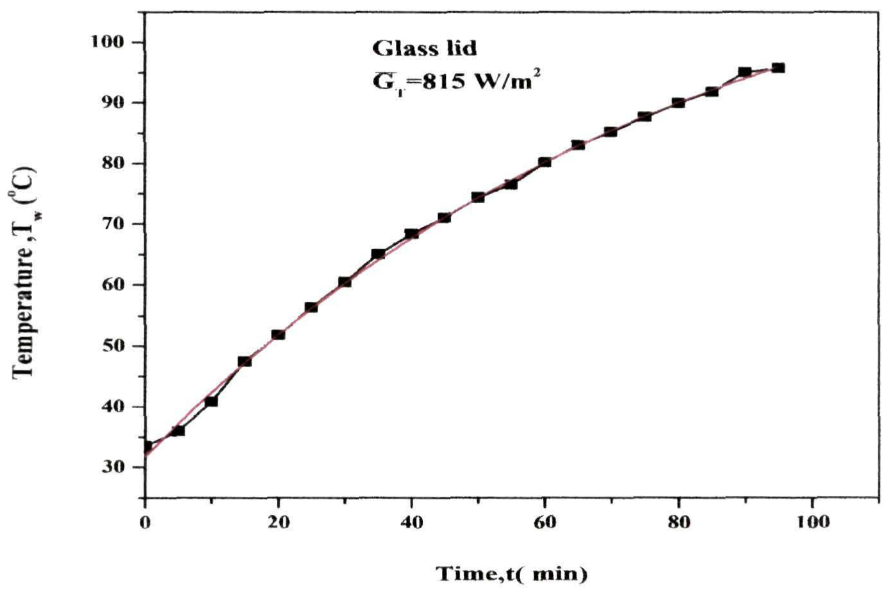

Fig.6.9.Rise in water temperature T_W with time t (Glass lid)

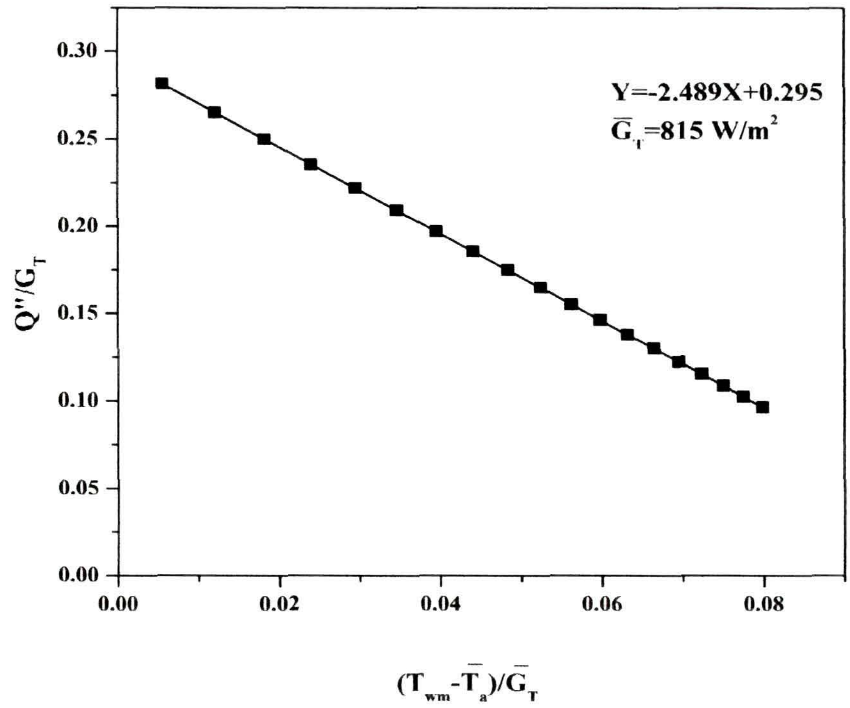

Fig.6.10. $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm} - \overline{T}_a\right)/\overline{G}_T$ plot (Glass lid).

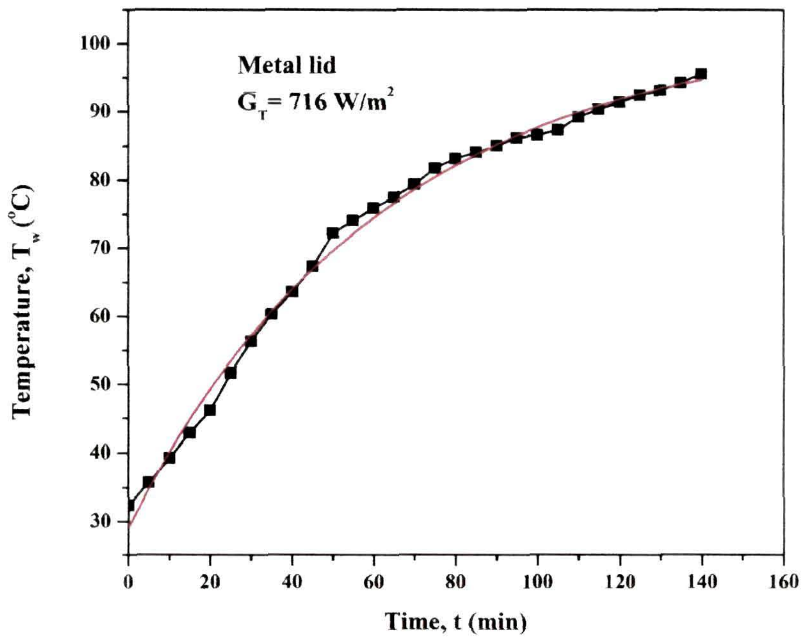

Fig.6.11.Rise in water temperature T_w with time t (Metal lid)

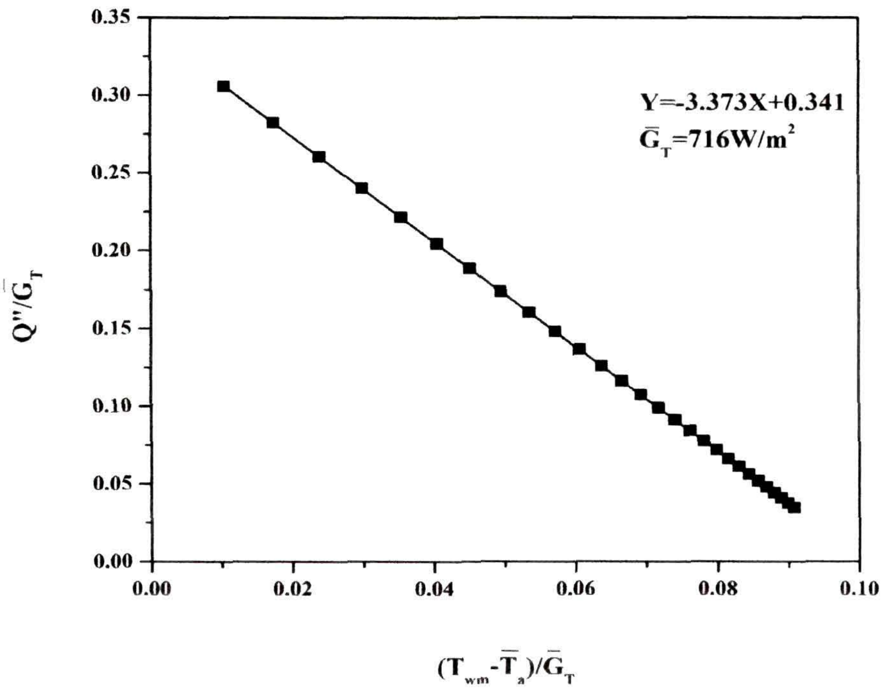

Fig.6.12. $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm} - \overline{T}_a\right)/\overline{G}_T$ plot (Metal lid).

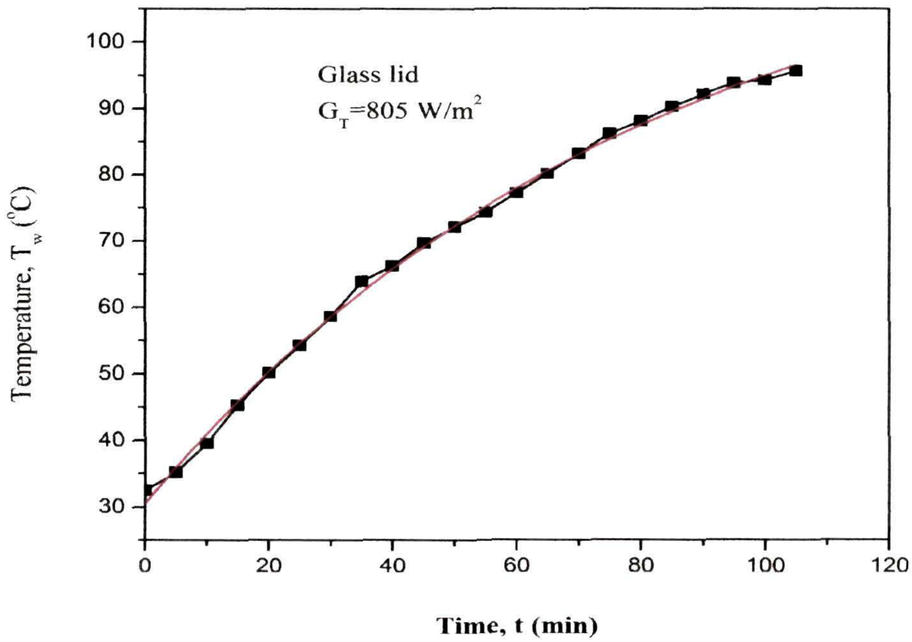

Fig.6.13.Rise in water temperature T_w with time t (Glass lid)

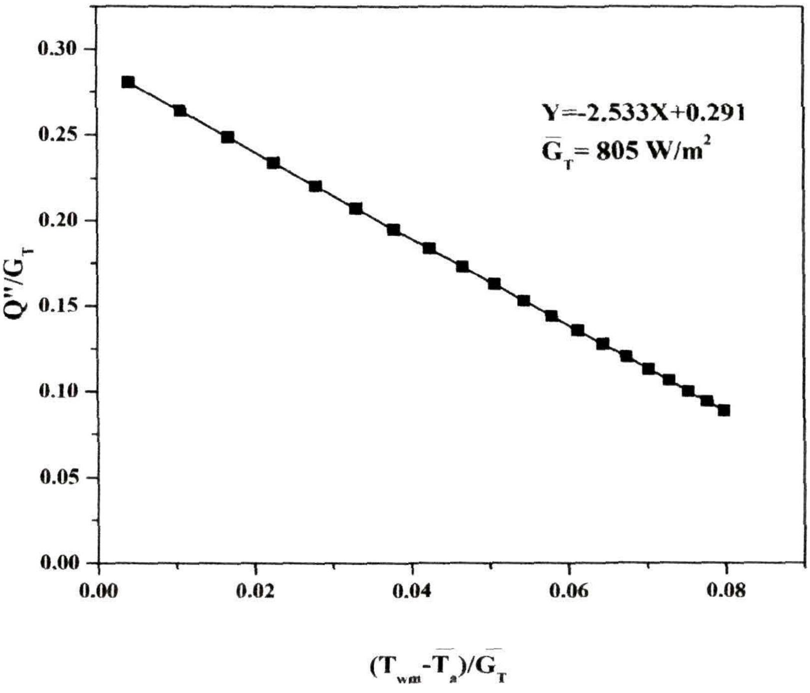

Fig.6.14. $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm}-\overline{T}_a\right)/\overline{G}_T$ plot (Glass lid).

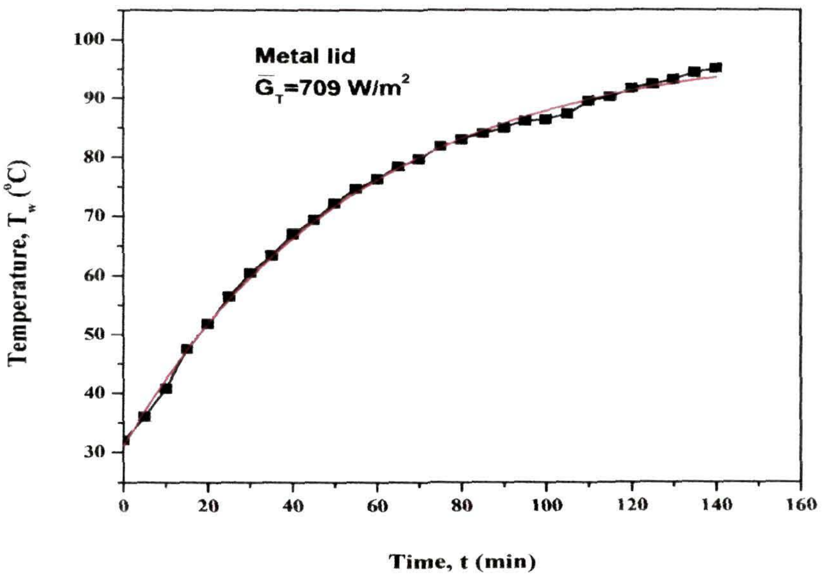

Fig.6.15.Rise in water temperature T_w with time t (metal lid)

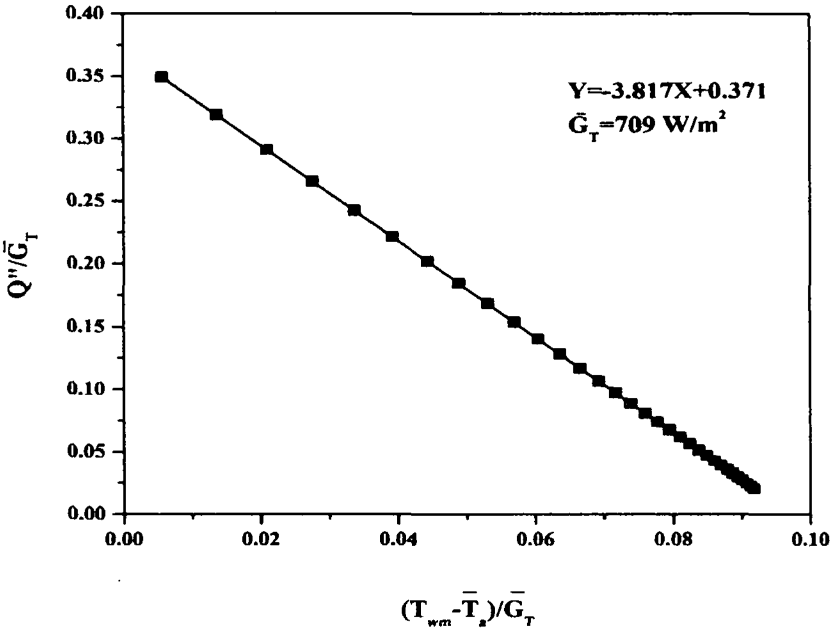

Fig.6.16. $\dot{Q}''/\overline{G}_T$ vs. $\left(T_{wm}-\overline{T}_a\right)/\overline{G}_T$ plot (Metal lid).

Table: 6.2. Thermal Performance Parameter (TPPs)

TPPs	Pot with glass lid		Pot with metal lid	
$F'U_L/C$ (W/m^2K)	2.489	2.533	3.373	3.817
$F'\eta_o$	0.295	0.291	0.341	0.371
COR	0.118	0.114	0.101	0.097
G_T (W/m^2)	815	805	716	709

Table-6.3: Objective parameters:

OPs	Pot with glass lid		Pot with metal lid	
τ_r predicted (min)	100.99	96.41	148.95	135.93
τ_r experimental (min)	95.00	105.00	140.00	140.00
Error (%)	-6.31	8.18	-6.40	2.91
τ_{hr} predicted (min)	13.81	14.05	9.16	10.37
τ_{hr} experimental (min)	15.00	15.00	10.00	11.00
Error (%)	7.96	6.34	8.39	5.73
T_{fx} (°C) (predicted)	123.63	125.41	101.60	101.68
COR	0.12	0.11	0.10	0.10
$\dot{G}_T$ (W/m^2)	815	805	716	709

6.4. Conclusions:

The new pot design shows marked improvement in the performance of the cooker. The efficient thermal barrier between glass lid of pot and surface above the water in the pot obstructs the heat rejection through the glass lid from the pot interior. This is useful for pot having glass lid as the heat loss is reduced. Even with very high water temperatures the major factor is the low water-glass temperature difference. Although a high water temperature leads to higher evaporation, the low temperature difference results in a significantly reduced total energy transfer. Total energy transfer from the pot may be further reduced by decreasing the value of thermal conductance of air in between glass, but combined effects of radiative and convective heat transfer across the air gap makes it almost same. This may be the reason which improves the performance of the cooker having glass lid.

Two important conclusions may be drawn. One with regard to cooker performance improvement due to pot lid design and another capability of the GTPP and GTP to respond to design change.

a) Improvement in the performance of the cooker due to transparent lid is demonstrated.
b) GTPP has been successfully used to unambiguously and explicitly quantify the improvement in cooker performance due to improvement in design of one of the components of the cooker.

Some other important information it provides are

c) Glass lid may improve the performance of other such cookers as well.
d) GTPP and GTP may be used for the purpose of carrying out and studying design modification in cookers.

COR value can respond to the improvement in performance due to

i) Improvement in pot design as the glass lid shows higher value of COR.
ii) Number of pots used as the COR value increases with number of pots with identical lid.

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Chapter -7

Conclusion and scope for future work

Chapter-7

Conclusions and scope for future work:

7.1. Conclusions:

In the present work generalized thermal performance parameters (GTPPs) with corresponding generalized test procedure (GTP) has been proposed for testing cookers of different types, designs and their improvised variants. For this the existing TPPs were analyzed through correlations in terms of three objective parameters developed for the purpose. Subsequently this thesis proposes the guidelines and attempts to develop GTPPs in terms of two identified parameters followed by experimental testing of two different types of cookers using the GTP. A new parameter cooker opto-thermal ratio (COR) was also proposed.

A new design improvement was also incorporated in the box type cooker. The cooker was tested using the GTP and resultant response of the GTPPs was analyzed to draw conclusions.

Following specific conclusions may be drawn from the results of the present work.

i) One of the basic requirements of the present work was to be able to represent the existing TPPs in terms of comparable parameters. The OPs developed in the present work are envisaged to be important tool to compare and correlate different thermal performance parameters.

Some of the OPs may be derived from the existing TPPs and may be used to compare the performance of the cooker represented in the form of different TPPs. Further they may be also be utilized as a tool to judge the cooker's utilizability for a given location/climate. OPs are design as well as climate dependent.

ii) Subsequently two GTTPs have been identified in the present work. These were identified on the basis of analytical study of the basic theory of cooker keeping in mind that they should be unique, absolute, and holistic as per the requirements of generalization. Also it should be possible to determine them using the GTP developed for the purpose. The GTPPs are essentially design dependent and climate independent.

iii) The GTP developed and used in the present work is able to provide the values of the two GTPPs. As these values are absolute, unique and holistic, the comparative method of testing prevalent in the literature may not be required at all. In addition to this the GTP is simple, practicable and less time consuming than many of the existing GTPs.

iv) The proposed GTPPs and GTPs enable intra- and inter-cooker performance grading.

v) A new design incorporated in the lid of cooking pot of box type cooker resulted in positive enhancement in the absolute value of GTPPs which led to the improvement in the cooker performance. The results were verified and confirmed through comparative method.

vi) A new performance parameter COR also responded well to the designs providing valuable information about different types of cookers. It responded well to the design variations as well.

vii) It is possible to predict the performance of additions/modification in cooker's optical system, storage component etc.

Thus GTPPs and GTPs may be used as important tool for cooker grading, designing and promotion. The OPs on the other hand may be used to compare and correlate the results of the existing TPPs and help the users.

7.2. Future scope:

The work presented in the thesis has opened a large number of challenges which fall under the purview of the future scope to upgrade, refine and widen the applicability of work. Some of these are

i) The guidelines for determining GTPPs and GTP, as claimed, still need to be tested for advanced type of cookers to satisfy the users and justify the work completely.

ii) A number of large cookers with multiple numbers of Scheffler type arrangements exist. It needs to be seen if the GTPP and GTP can help grade these cookers.

iii) If a hybrid cooker e.g. one with electrical back up or with a futuristic hydrogen/methane based system is to be tested and graded, the GTPPs and GTP may again be challenged.

iv) In the tests water has been used as the load which has been tested only up to 95 °C. It will be better if any other fluid with stable properties up to a temperature of 150-200°C is used for the test. This will help in verifying the objective parameters (OP) T_{fx} value which was predicted using the GTPPs.

v) Reflection of the rate of tracking on GTPPs still needs to be investigated.

vi) Robustness of GTPPs may be under scanner if both irradiance and ambient temperature are low.

vii) A large number of experimental data base is required to establish the accuracy needed in measurements.

All the issues discussed above are real and they surely enhance the scope of this work to be extended in future.

Appendix -I.

Photo catalyst and Cooking Preservation

Appendix-I.

Photo catalyst and Cooking Preservation

A.1.1.Introduction:

Solar photo catalytic detoxification refers to the destruction of hazardous chemical and biological pollutants from the environment by solar photo catalytic oxidation or reduction reactions. Solar detoxification has shown great promise for the treatment of ground water, industrial wastewater and contaminated air and soil. In recent years the process has also shown great potential for disinfection air and water, making possible a number of applications. Research studies on the photo catalytic oxidation process have been conducted over at least last three decades. TiO_2 has been the most commonly used photo catalyst. The use of TiO_2 in water detoxification was first demonstrated by Carey *et al.*[1976]. They showed that polychlorinated biphenyls PCBs were dechlorinated in aqueous suspension of TiO_2. TiO_2 is insoluble under most conditions, photo stable, and nontoxic.

The energy needed to activate TiO_2 is 3.2 eV or more which corresponds to near UV radiation of a wavelength of 388 nm or less. As 4-6% of sunlight reaching the earth's surface is characterized by this wavelength, the sun can be used as the illumination source. However , since UV does form 4-6 % of the usable solar spectrum , recent research have been aimed at improving the catalyst's performance by improving the reaction kinetics, increasing the useful wavelength range to utilize larger portions of the solar spectrum, developing appropriate reactors, and finding new engineering applications of the process for practical problems [1].

One of the pressing environmental problems that the textile industries are facing is the removal of colour from dye bath effluents prior to discharge to local sewage. The release of the colour wastewater in the ecosystem is a source of aqueous pollution and perturbations in the aquatic life. Physical methods (adsorption stripping) [2], biological methods (microbiological degradation) [2, 3] and chemical methods (chlorination, ozonation etc) are the more frequently used methods for the treatment of these textile dyes.

It has been observed that the photo catalytic activity of TiO_2 is influenced by various parameters such as crystal structure, surface area, porosity[1,5], pH initial dye concentration, catalyst loading, time of exposure, temperature etc. This demands a quantitative understanding of various parameters that affect the output of dye degradation, which in turn reflects the need of optimization of various experimental parameters involved. Taguchi robust designing approach [6, 7] is a multiple parameter optimization procedure found to be useful in identifying and optimizing the dominant parameters which control output of a process, with a minimum number of experiments. Further it also aids in identifying interaction between various experimental parameters in supporting the degradation of dye [8]. It has been successfully employed in optimizing of CVD process, waste water treatment, synthesis of TiO_2 nano particles etc. [9-12].

A.1.2.Taguchi method:

Taguchi method is based on "Orthogonal Array" experiments which give much reduced "variance" in the results. Orthogonal Arrays (OA) provide a set of well balanced (minimum) experiments and has a set of combination of parameters' levels [13]. For each combination, the Signal- to –noise ratio (S/N), which is the logarithmic functions of desired output, serves as objective function for optimization. Finally, it is used in data analysis and prediction of optimum results [8-12]. Here it is used larger the better type of objective function for the degradation process since such type of S/N ratio appears to be appropriate to study the mechanism of degradation process. S/N ratio corresponding to larger-the –better objective function can be computed using relation (1)

$$S/N(dB) = -10\log_{10}\frac{1}{n}\sum_{i}^{n} 1/y_i^2 \qquad \text{(A.1.1)}$$

where y_i is the signal (reaction rate) and n is the number of repetitions in each experiment. Taguchi method can be used to obtain effect of parameter level (deviation it causes from overall mean of the signal). To determine the effect of each parameter level (mi), average value of S/N ratios are calculated using analysis of mean (ANOM). For this calculation, the S/N ratios of experiments with corresponding parameter levels are employed [6]

$$m_i = \frac{1}{N_i}\sum S/N \qquad \text{(A.1.2)}$$

where N_i is the number of experiments conducted with same parameter levels. The parameters effects (or factor effect), i.e. the contribution of each experimental parameter to the reaction rate are calculated by the analysis of variance (ANOVA). This is done by summing the squares (SoS) of variances for all levels for a given parameter are obtained using equation (3). This term is divided by degree of freedom (DoF) of the corresponding parameter to obtain factor effects of various Experimental parameters (Eqn. (4)).

Sum of the squares (SOS),

$$(SoS) = \sum_{i=1}^{i=j}\left(N_i\left(m_i - \langle m_i \rangle\right)^2\right) \qquad \text{A.1.3)}$$

Where $\langle m_i \rangle$is the average of m_i's for a given parameter and the coefficient N_i represents the number of times the experiment is conducted with the same factor level.

$$Factor - effect = \frac{SoS}{DoF \times \sum \frac{SoS}{DoF}} \qquad \text{(A.1.4)}$$

Materials:

Degussa P25, Qualigens and Hombikat UV100 (HUV 100) TiO2 were used as Photo catalyst without any further treatment.

The fresh dilution of dye solution are prepared as per requirement using double distilled water and stored in dark at room temperature. The kinetics of adsorption is studied for the Congo red dye under dark in stirred condition at room temperature. It was observed that for all initial concentration of dye, the steady state of adsorption was reached within 1 h. Therefore this time is used for acquiring adsorption equilibrium before exposure to UV radiation. After reaching the adsorption equilibrium one sample is collected at 0 time interval (without exposure) and the irradiation of sample is started. Thereafter samples are collected at their required time interval respectively for all types of photo catalysts and are kept in dark to avoid exposure external radiation.

A.1.3. Parameters selection for optimization:

For optimization, five experimental parameters are selected: Temperature, catalyst type, concentration of dye, catalyst loading, and time of exposure. Various levels of each of these parameters used in the experiments. All parameters have three levels except the temperature which has two levels.

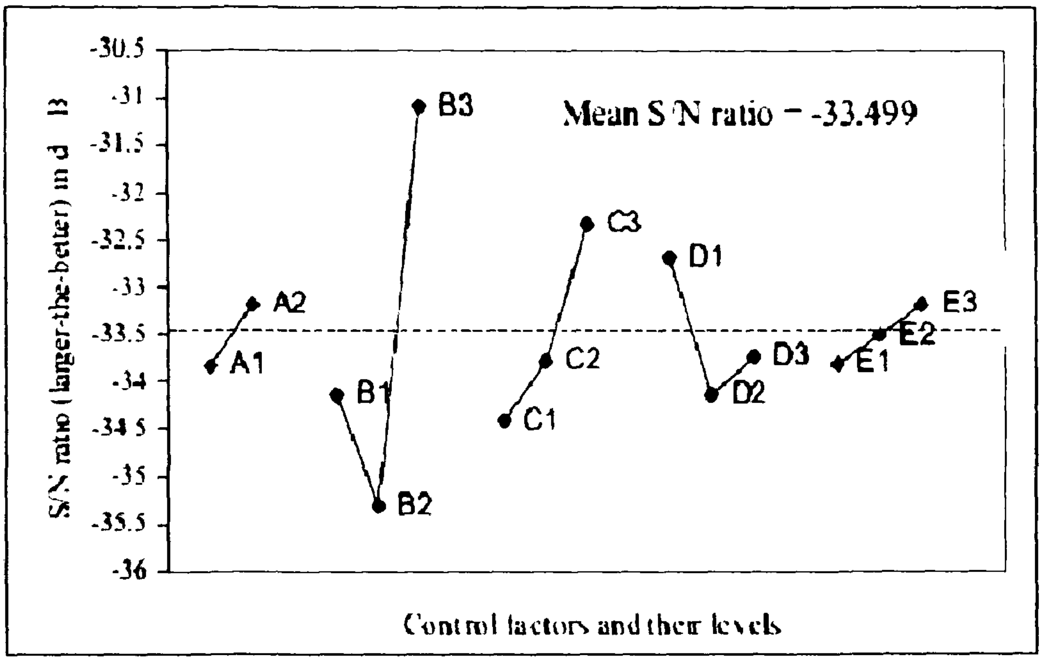

Fig A 1 1 Response diagram for the degradation of Congo- red

A.1.4.Photo catalytic degradation of Congo- red:

After verifying the degradation occurred in presence of photo catalyst and UV-radiation, the photo catalytic degradation of Congo- red was carried out for each experiment in the L-18 orthogonal array S/N ratios which determines the success of an experiment, is obtained from the reaction rate for each experiment and calculated using equation (A 1 1) S/N ratios for all parameters levels are graphically represented in response diagram (fig A 1 1) As seen in the response diagram, dye degradation is primarily dependent on catalyst type, concentration of dye and catalyst loading

A.1.5. Application of Photo catalysis on cooker/cooking preservation:

In Box type solar cooker (BC) which does not receive direct radiation can use catalytic coating in the shadowed portion to prevent growth of microorganism which may destroy the cooked food within a very short period of time. Photo catalysis prevents growth of microorganism. So food after cooking can be kept for long period of time without damage.

Carbon based photo catalysis may be used to improve the cooking process as well. Radiative photo catalytic preservation of food is possible in the case of the proposed new design of pot with transparent cover although it needs to be tested.

The applicability of Taguchi method to prevent growth of microorganism on cooked food items needs to be thoroughly investigated.

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Appendix-II.

Plastic cover for box type solar cooker.

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Plastic cover for box type solar cooker.

The use of plastic materials has been proposed by several workers as a way to reduce the weight, fragility, rigidity and enhance the portability [1]. They show better solar transmittance also. Transparent plastic covers have been used successfully in solar air collector. The life time of the plastic cover has increased with the development of UV-stabilized transparent polymeric materials.

Any glazing material should have high transmittance across the solar spectrum and must resist long term (10-20 years) exposure to operating conditions including elevated operating temperatures(55-95^{o}C)and solar ultraviolet (UV) light. They must retain mechanical integrity (for example, impact resistance and flexural rigidity) under these harsh environmental stresses. Another very important property is the transmittance across the infrared spectrum. This optical behavior is going to influence the top loss coefficient of the solar cooker and thus useful gain of the solar thermal system.

The purpose of using glazing or transparent cover in solar cooker /collector is to block the longer wavelength (IR radiation) radiation re-emitted by the absorber plate and thereby to reduce the heat loss from the absorber plate. Glass is the most common glazing material as it has the property to block the IR radiation re-emitted by the absorber plate [2]. Transparent plastics such as polycarbonate and acrylics are also used as glazing for flat plate collectors. The main disadvantage of plastics is that it cannot block the radiation re-emitted by the absorber plate. Other disadvantages include deterioration over a period of time due to ultraviolet solar radiation. Their main advantage is resistance to breakage. Although glass can break easily, this disadvantage can be minimized by using tempered glass. In order to minimize the upward heat loss from the cooker, more than one transparent glazing may be used. However, with the increase in number of cover plates may reduce the transmittance [3].

The maximum losses from the box type solar cooker are due to convection losses from the glass to the air. These losses can be reduced by using double glazing which however would increase complexity and further contribute to losses associated with the transmissivity of the glazing. Other losses from the side and top insulation can be reduced by increasing insulation thickness or using more efficient insulator. It is observed however that magnitude of these losses especially for boiling water case is comparatively low [3].

The use of plastic film as glazing for box type solar cooker has been suggested by several investigators. The reduced cost and weight can be cited as advantages of such designs. Study reveals that films of different thickness ranging from 10 μm to 100μm have been considered in design studies. The film radiative properties such as the long wave transmittance and the emissivity are functions of film thickness. Therefore top loss coefficient of the solar cooker cover also depends on the thickness of film chosen for the design. Wijeyasundera *et al.* [4] in their design used Teflon films of different thickness as the inner glazing of collectors with an outer glass cover. The top loss coefficient of the collector is computed over a range of design and operating conditions. For low values of εp the dependence of U_t on film thickness is small both for two and three cover collector. The effect of film thickness is most significant for collectors with larger ε_p. For very thin film of about 0.10μm the value of U_t for plastic cover collector is almost equal to that for all glass collectors. So it is economically more attractive to use a thin plastic inner cover in solar cooker with selectively coated absorber plate. For a three cover collector the value of U_t is about 10% larger for the plastic covered collector as compared with the all glass collector even at the low ε_p of 0.10. The difference is about 50% at the larger value of ε_p of 0.95 when the film thickness is small. At an emissivity of 0.1, U_t is almost independent of the film thickness. The value of U_t increases with h_w for all film thickness. The effect of h_w is more pronounced at higher values of ε_p [4]

Plastic cover is needed in cooker because the open able glass cover may break which need to be opened daily for cooking. More over from study it is found that losses through plastic cover and glass covers are almost the same [1]. So the useful energy delivered by plastic cover collector is cheaper than the glass cover collector. When cost of the system is an important criterion then plastic cover collector can be used in advanced type solar cooker also.

A.2.1.Heat Balance equation for loss in BC with two glass covers: [5]

In a steady state the heat transferred by convection and radiation between (i) the absorber plate and the first cover, (ii) the first cover and the second cover and (iii) the second cover and surroundings must be equal. Hence,

$$\dot{Q}'' = h_{p-c1}\left(T_{pm} - T_{c1}\right) + \frac{\sigma\left(T^4{}_{pm} - T^4{}_{c1}\right)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)} \qquad \text{(A.2.a)}$$

$$= h_{c1-c2}\left(T_{c1} - T_{c2}\right) + \frac{\sigma\left(T^4{}_{c1} - T^4{}_{c2}\right)}{\left(\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1\right)} \qquad \text{(A.2.b)}$$

$$= h_w\left(T_{c2} - T_a\right) + \sigma\varepsilon_c\left(T^4{}_{c2} - T^4{}_{sky}\right) \qquad \text{(A.2.c)}$$

Where, $\dot{Q}''_u$ is the heat transferred from absorber plate to glass cover 1, glass cover 1 to glass cover 2 and from glass cover 2 to ambient,per unit time per unit area, h_c, h_r and h_w are the convective, radiative and wind heat transfer coefficient and T is the temperature, A is the area, ε is the emmissivity. Suffix p, pm, c1, c2, a, sky indicates absorber plate, plate mean, glass cover1, glass cover 2 , ambient and sky.

The natural convection heat transfer coefficient for the enclosed space between the absorber plate and the first cover or between the two covers is calculated by using one of the following correlations suggested by Buchberg et al [7]

$$Nu_L = 1; Ra_L \cos\beta < 1708$$

$$Nu_L = 0.229(Ra_L \cos\beta)^{0.252}; 5900 < Ra_L \cos\beta < 9.23\times10^4$$

$$Nu_L = 0.157(Ra_L \cos\beta)^{0.285}; 9.23\times10^4 < Ra_L \cos\beta < 10^6$$

(A.2.d)

where, Nu_L, Ra_L are the Nusselt and Rayleigh numbers respectively. L is the spacing between the surfaces.

The expression for Nusselt number is

$$Nu = \frac{h_c L}{k} \quad \text{(A.2.e)}$$

Convective heat transfer coefficient h_c can be expressed from Nusselt number as

$$h_c = \frac{Nuk}{L} \quad \text{(A.2.f)}$$

Where, k is the conductivity of air and L is spacing between plate and cover and the two covers.

The convective heat transfer coefficient h_w can be expressed by the following expression [7]:

$$h_w = 5.7 + 3.8V_\infty \quad \text{(A.2.g)}$$

From Swinbank relation [7] the effective sky temperature is given as

$$T_{sky} = 0.0552T_a^{1.5} \quad \text{(A.2.h)}$$

where T_a is the ambient temperature and is in Kelvin.

For cooker having two glass cover system, the top loss coefficient from the absorber plate to ambient is expressed as follows.

$$U_t = \left(\frac{1}{h_{p-c1} + h_{r,p-c1}} + \frac{1}{h_{c1-c2} + h_{rc1-c2}} + \frac{1}{h_w + h_{r,c2-s}} \right)^{-1} \quad \text{(A.2.j)}$$

In the equation A.2.j the value of T_{c1} and T_{c2} are taken from empirical relation

$$T_{c2} = T_a + \left(0.0021 T_p + 0.57\varepsilon_p - 0.146\right) h_w^{-0.4} \quad \text{(A.2.k)}$$

$$T_{C1} = T_1 - \left(0.7 - 0.34\varepsilon_p\right) \quad \text{(A.2.l)}$$

A.2.2.Heat balance equation in BC with Two transparent covers - inner glass and outer plastic:

If plastic material is used to replace outer glass cover then the equation for U_t must be modified to account for some infra- red radiation passing directly through the cover. The thermal circuit for this is shown in Fig. A.2.1.

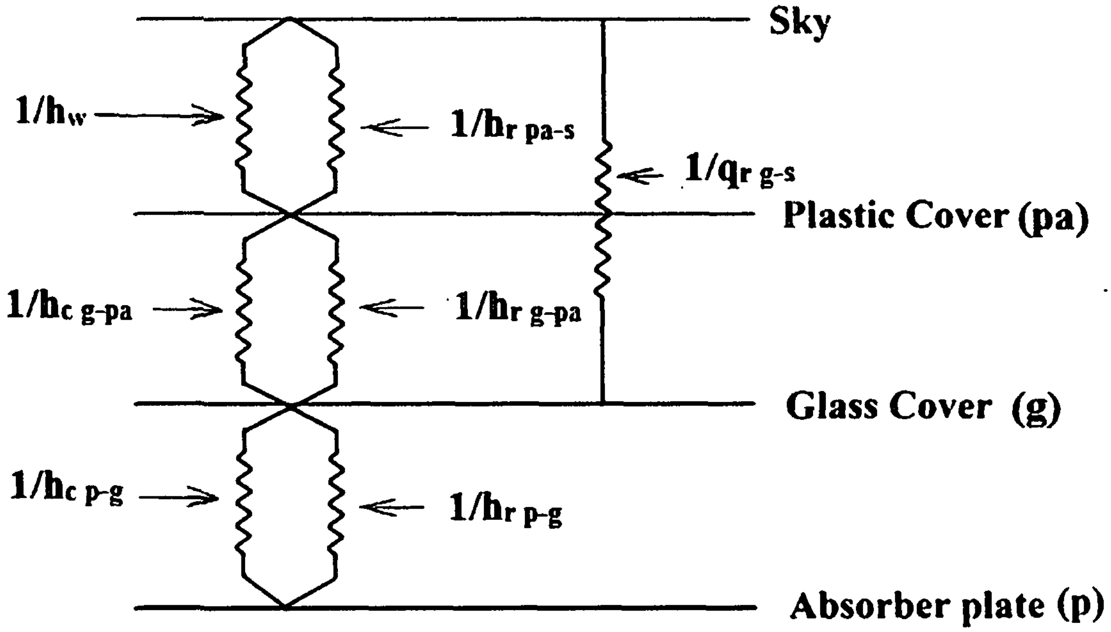

Fig. A.2.1. Schematic diagram showing different resistances for top heat loss for BC with two covers (inner one glass and outer one plastic)

So the outer cover will be partially transparent to infra-red radiation. The net radiant energy transfer directly between the glass cover (g) and sky is

$$q_{r,g-s} = \tau\varepsilon_g\sigma\left(T_g^4 - T_s^4\right)$$

(A.2.m)

where τ is the transmittance of the cover for radiation, ε_g is the emittance of the glass, T_g and T_s are the glass and the sky temperature of the system.

Let R_1 be the thermal resistance of the plastic cover and sky. So

$$R_1 = \frac{1}{h_w + h_{r,pa-s}} \quad \text{(A.2.n)}$$

Similarly R_2 be the resistance between glass cover and the plastic cover and R_2 can be expressed as

$$R_2 = \frac{1}{h_{c,g-pa} + h_{r,g-pa}} \quad \text{(A.2.p)}$$

and R_3 is the resistance between absorber plate and glass cover and can be expressed as

$$R_3 = \frac{1}{h_{c,p-g} + h_{r,p-g}} \quad \text{(A.2.q)}$$

Now equivalent resistance of R_1 and R_2 can be expressed as per the network in fig. A.2.2

$$R_2 + R_1 = \frac{1}{h_{c,g-pa} + h_{r,g-pa}} + \frac{1}{h_w + h_{r,pa-s}}$$

$$= \frac{\left(h_w + h_{r,pa-s}\right) + \left(h_c + h_r\right)}{\left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right)} \quad \text{(A.2.r)}$$

and from fig A.2.3 the equivalent resistance of (R_1+R_2) and $1/q_{r\,g-s}$ can be expressed as

$$\frac{1}{R_2 + R_1} + \frac{1}{1/q_{r,g-s}} = \frac{1}{\left(h_w + h_{r,pa-s}\right) + \left(h_{c,g-pa} + h_{r,g-pa}\right) / \left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right)} + q_{r,g-s}$$

$$= \frac{\left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right)}{\left(h_w + h_{r,pa-s}\right) + \left(h_{c,g-pa} + h_{r,g-pa}\right)} + q_{r,g-s}$$

$$= \frac{\left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right) + q_{r,g-s}\left[\left(h_{c,g-pa} + h_{r,g-pa}\right) + \left(h_w + h_{r,pa-s}\right)\right]}{\left(h_w + h_{r,pa-s}\right) + \left(h_{c,g-pa} + h_{r,g-pa}\right)}$$

(A.2.s)

$$R_{21s} = \frac{\left(h_w + h_{r,pa-s}\right) + \left(h_{c,g-pa} + h_{r,g-pa}\right)}{\left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right) + q_{r,g-s}\left(\left(h_{c,g-pa} + h_{r,g-pa}\right) + \left(h_w + h_{r,pa-s}\right)\right)} \quad \text{(A.2.t)}$$

Now top loss coefficient U_t can be expressed as

$$U_t = \frac{1}{R_{21s} + R_3}$$

(A.2.u)

$$= \frac{1}{\dfrac{\left(h_w + h_{r,pa-s}\right) + \left(h_{c,g-pa} + h_{r,g-pa}\right)}{\left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right) + q_{r,g-s}\left[\left(h_{c,g-pa} + h_{r,g-pa}\right)\left(h_w + h_{r,pa-s}\right)\right]} + \dfrac{1}{h_{c,p-g} + h_{r,p-g}}}$$

(A.2.v)

where, R_{21s} is the equivalent resistance of (R_1+R_2) and $1/q_{r,g-s}$

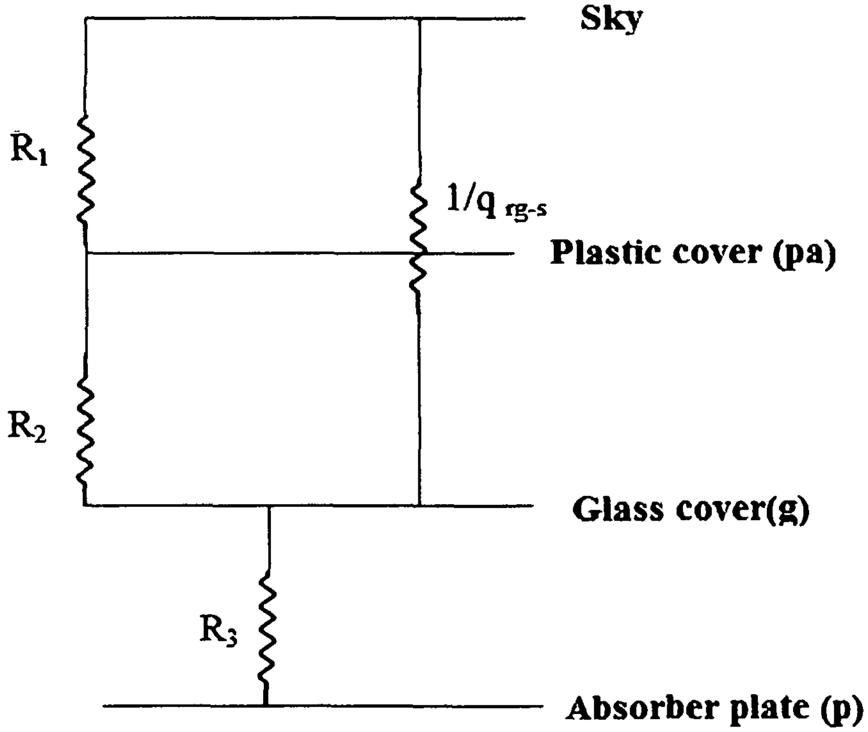

Fig. A.2.2 : Equivalent thermal circuit diagram

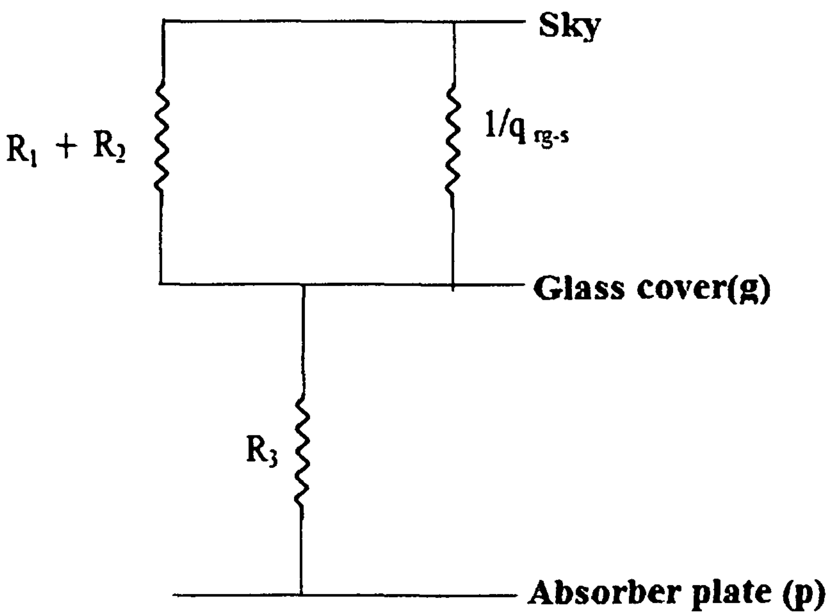

Fig.A.2.3. Equivalent circuit diagram

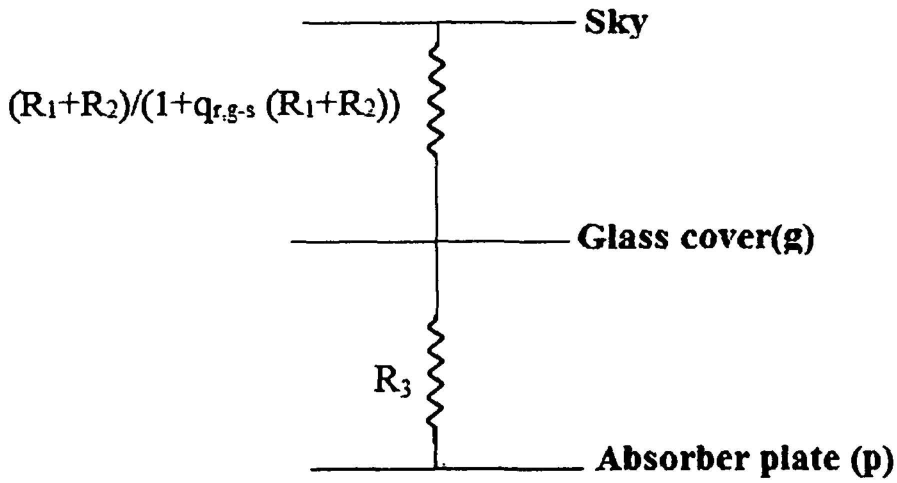

Fig.A.2.4. Equivalent circuit diagram

Now the heat balance equation of the system can be expressed as:

$$\dot{Q}'' = h_{c,p-g}\left(T_{pm} - T_g\right) + \frac{\sigma\left(T^4{}_{pm} - T^4{}_g\right)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1\right)} \tag{A.2.w}$$

$$= h_{c,g-pa}\left(T_g - T_{pa}\right) + \frac{\sigma\left(T_g^4 - T_{pa}^4\right)}{\left(\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_{pa}} - 1\right)} + q_{r,g-s} \tag{A.2.x}$$

$$= h_w\left(T_{pa} - T_s\right) + \sigma\varepsilon_{pa}\left(T_{pa}^4 - T_s^4\right) + q_{r,g-s} \tag{A.2.y}$$

where,

$$q_{r,g-s} = \tau\varepsilon_g\sigma\left(T_g^4 - T_s^4\right) \tag{A.2.z}$$

The radiative heat transfer coefficient between the absorber plate and glass cover (g) can be written as:

$$h_{r,p-g} = \frac{(T_p + T_g)(T_p^2 + T_g^2)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1} \qquad \text{(A.2.aa)}$$

The radiative heat transfer coefficient between glass cover to plastic cover can be written as:

$$h_{r,g-pa} = \frac{\varepsilon_g \sigma \left[T_g^4 (1 - \rho_{pa}) - \varepsilon_{pa} T_{pa}^4\right]}{(1 - \rho_g \rho_{pa})(T_g - T_{pa})} \qquad \text{(A.2.ab)}$$

The radiative heat transfer coefficient between plastic to sky can be written as

$$h_{r,pa-s} = \varepsilon_{pa} \frac{\sigma (T_{pa} + T_s)(T_{pa}^2 + T_s^2)(T_{pa} - T_s)}{T_{pa} - T_a} \qquad \text{(A.2.ac)}$$

where, ρ is the reflectance and the subscript pa, g, s represent plastic, glass and sky. The other variables are same as mentioned in section A.2.1.

The losses through the absorber plate to sky have been shown in (Fig.A.2.1). The final losses in the case of outer cover, made of plastic will be more than the losses through the two glass cover system as plastic cover allows IR radiation to pass to the sky or ambient. A computer program in C has been developed to find out losses through two transparent cover systems solving the simultaneous equations A.2.t-v numerically. Some of the computed values have been shown in Table A.2.2.

A.2.3.Results and discussions:

To solve the above equations to find U_t i.e., top loss coefficient the values considered for computation purposes are given in the Table A.2.1. A computer program in C is developed and by solving the equation for two cover system one having glass (inner one) and the other plastic (outer one), top heat loss coefficient (U_t) is computed. The values are given in Table A.2.2. U_t is computed by varying the emissivity of absorber plate. From the calculation it is found that U_t is more for plastic cover because one radiative component of heat is transferred to sky from glass cover 1 as shown in figA.2.1. as plastic cover allows to pass IR radiation to sky without blocking. The surface temperature of inner glass cover as well as plastic cover (T_{c1}, T_{c2}) is also calculated. If absorber plate temperature is 200 °C and ε_p is 0.75, then inner glass cover temperature is 129.16 °C and outer plastic cover temperature is 54.4 °C and top loss coefficient is 6.95 W/m^2 which is more than the loss through the two glass cover.

An analysis of detailed numerical data may help to use the analytical equation A.2.n by having empirical relation for glass cover temp. T_g and the plastic cover temp. T_{pa} as it has been done for two glass cover systems discussed in section A.2.1.

Table: A.2.1: Values of variables used in Programming

Variable/Constant	Value	Variable/Constant	Value
σ	$5.67 X 10^{-8}$	t_g	0.003
ε_g	0.88	k_g	1.05
ε_{pa}	0.86	h_w	5
ρ_c	0.09	k_p	0.4
ρ_{pa}	0.35	τ	0.92
ε_p	0.25	th_{pa}	0.001
sp	0.025	t_a	30 °C

Table A.2.2: Values of ε_p, T_{c1}, T_{c2}, U_t

ε_p	T_{c1}(°C)	T_{c2}(°C)	U_t
0.75	129.16	54.4	6.9529
0.85	129.67	53.34	7.5545
0.95	129.84	52.33	8.1474

A.2.4. Conclusions:

An attempt is made to estimate the top heat loss coefficient of box type cooker, through two cover systems with outer cover made of plastic. From the analysis it is found that the top loss is more in case of plastic cover. Considering other aspect of plastic material like less weight, portability, less initial cost etc. it may be one of the useful alternative to make the BC more popular, but a detailed analysis is required for this.

Programming for calculation of top heat losse for box type cooker taking two cover, inner one glass and outer one plastic.

```
#include <stdio.h>
#include <math.h>
#include <conio.h>
#define pi 3.1416
#define max 180
#define sgm 5.67*pow(10,-8)
#define ec .88
#define g 9.81
#define b 45
#define tg .003
#define kg 1.05
void main()
{
    float sp,sp12,tpm,ta,v,tb,ts,k,tc1,tc1k,tc2k,tak,ratas,ratas1,ut3,ut4,ut34,ut5;
    float tc2,hpc1,hw,tsky,tpmk,ktap1,rcsb,y,x,rcsb2,qt,ap,r12,ut1,ut2,ut12,a,b1,c1,c2;
    float
    neu,nul,pr,tap1,tap2,neu2,pr2,ktap2,hp12,nul2,r3a,r23,ta1p,ta2p,fin,fiout,tc1kn,tc2k
    n;
    float fin1;
    float hrc12,hrc2a,hrpc1,ut,us,ub,ul,ki,bith,sab,sal,asp,ep,st,utci,utc,tc1k1,tc2k1;
    float
    tap1k,tap2k,tc2k2,qrps,tau,utp,epa,rauc,raup,fiout1,tp,kp,r23a,r23c,tc1k11,tc2k11,th
    p;
    clrscr();
    hw=5;
    tau=.92;
    kp=.4;
    thp=.001;
    epa=.86;
    rauc=.09;
    ta=30;
```

```
sp=.025;
raup=.35;
tak=ta+273.16;
tsky=tak;
tpm=200;
do
{
    ep=.25;
    do
    {
    tc1=(tpm+ta)/2;
    tc2=(tc1+ta)/2;
    tc1k=tc1+273.16;
    tc2k=tc2+273.16;
    tpmk=tpm+273.16,
    printf(" tc1k   tc2k    fiout    fiout1   fin   fin1    ut     tpmk \n");
    printf("--------------------------------------------------------------------\n");
    do

        tap1=(tpmk+tc1k)/2;
        ktap1=0.1783*pow(tap1,.8706);
        neu=0.0008*pow(tap1,1.7235);
        pr=6*pow(10,-7)*pow(tap1,2)-.0006*tap1+.8331;
        x=(pi*b)/max;
        y=cos(x);
        rcsb=((g*(1/tap1)*(tpmk-tc1k)*pow(sp,3)*pr*y)/(neu*neu*pow(10,-12)));
        if (rcsb>9.23*pow(10,4))
        nul=0.157*pow(rcsb,.285);
        else if(rcsb>5900)
        nul=0.229*pow(rcsb,.252);
        else if(rcsb>1708)
        nul=(1+1.446*(1-(1708/rcsb)));
        else
```

```
nul=1;
hpc1=((nul*ktap1*pow(10,-3))/sp);
tap2=((tc1k+tc2k)/2);
ktap2=0.1783*pow(tap2,.8706);
neu2=0.0008*pow(tap2,1.7235);
pr2=6*pow(10,-7)*pow(tap2,2)-.0006*tap2+.8331;
rcsb2=((g*(1/tap2)*(tc1k-tc2k)*pow(sp,3)*pr2*y)/(neu2*neu2*pow(10,-
12)));
if (rcsb2>9.23*pow(10,4))
nul2=0.157*pow(rcsb,.285);
else if(rcsb2>5900)
nul2=0.229*pow(rcsb2,.252);
else if(rcsb2>1708)
nul2=(1+1.446*(1-(1708/rcsb2)));
else
nul2=1;
hp12=((nul2*ktap2)/(sp*pow(10,3)));
hrpc1=sgm*(pow(tpmk,2)+pow(tc1k,2))*(tpmk+tc1k)/((1/ep)+(1/ec)-1);
hrc12=ec*sgm*((1-raup)*pow(tc1k,4)-epa*pow(tc2k,4))/((1-
raup*rauc)*(tc1k-tc2k));
hrc2a=epa*sgm*(pow(tc2k,2)+pow(tak,2))*(tc2k+tsky);
r12=1/(hpc1+hrpc1);
r23=1/(hp12+hrc12);
r3a=(1/(hw+hrc2a));
r23a=r23+r3a;
qrc1-s=(tau*ep*sgm*(pow(tc1k,4)-pow(tsky,4)))/(tc1k-tak);
ut=(1+qrc1-s*r23a)/(r23a+r12*(1+qrps*r23a));
tc1kn=tpmk-ut*(tpmk-tak)*r12;
tc2kn=tc1kn-ut*(tpmk-tak)*(r23/(1+r23*qrps));
fiout=(r23a*ut)/(1+r23a*qrps);
r23c=r23/(1+r23*qrps);
fin=r12/(r12+r23c);
fiout1=(tc1kn-tak)/(tpmk-tak);
```

```
            fin1=(tpmk-tc1kn)/(tpmk-tc2kn);
            printf("%6.4f %6.4f        %6.4f     %6.4f    %6.4f    %6.4f    %6.4f %6.4f
            \n",tc1k,tc2k,fiout,fiout1,fin,fin1,ut,tpmk);
            tc1k11=tc1k;
            tc2k11=tc2k;
            tc1k=tc1kn;
            tc2k=tc2kn;
            }
        while(fabs(tc1k11-tc1kn)>=.001 &&(fabs(tc2kn-tc2k11)>=.001));
        ep=ep+0.1;
        printf("ep=  %f\n",ep);
        }
    while(ep<=.97);
    tpm=tpm+20;
    printf("tpmk=  %f\n",tpmk);
    }
while (tpm<=222);
getch();
}
```

Symbols used in programming and equations:

ε_c:emissivity of glass

e_p: emissivity of absorber plate.

t_g: thickness of glass

k_g : conductivity of glass.

k_p : conductivity of plastic.

th_p : thickness of plastic.

tau: transmissivity of plastic (Teflon).

e_{pa}: emissivity of plastic.

rauc: reflectance of plastic.

t_a: ambient temperature, °C.

tak: ambient temperature in Kelvin.

tpm : absorber plate temperature, in °C.

tpmk: absorber plate temperature, in Kelvin.

sp: gap between the cover plate.

ktap1: thermal conductivity at temperature tap1.

hpc1: convective heat transfer coefficient between absorber plate and cover plate 1.

hp12: convective heat transfer coefficient between cover plate 1and 2.

hrpc1: radiative heat transfer coefficient between absorber plate and absorber plate and cover plate 1.

hrc12: radiative heat transfer coefficient between cover plate 1 and 2.

hrc2a: radiative heat transfer coefficient cover plate 2 and ambient.

$1/qrc_1$-s: ressitance between cover plate 1 and ambient.

tc1k: temperature of the cover plate 1, Kelvin.

tc2k: temperature of the cover plate 2 (here plastic), Kelvin.

tc1kn: new temperature of cover plate 1 (after iteration), Kelvin.

tc2kn: new temperature cover plate 2 (after iteration), Kelvin.

σ: Stefen-Boltzmann constant.

ε_g : emissivity of glass

ε_{pa} : emissivity of plastic

ε_p : emissivity of plate

ρ_c: reflectance of glass

β : slope

ρ_{pa}: reflectance of plastic

τ : transmittance,

s_p: Space between glass cover and plastic cover, meter.

h_w: wind heat transfer coefficient. (W/m^2K)

k : thermal conductivity of air, (W/mK)

k_p : thermal conductivity of plastic. (W/mK)

k_g : thermal conductivity of glass. (W/mK)

th_{pa}: thickness of plastic, meter

t_g : thickness of glass, meter.

L_{12} : air gap spacing between absorber plate and glass cover, meter.

L_{23} : air gap spacing between absorber plate and glass cover, meter.

Nu: Nusselt number (hc12l)/k

P_r: Prandtle Number

R= heat transfer resistance (K/W)

Ra' = Rayleigh number,

T_{m12}= arithmetic mean temperature between absorber plate and cover plate1 (K)

T_{m23}= arithmetic mean temperature between cover plate1 and cover plate 2 (K)

T_{c1}, T_{c2} = temperatures attained by the two covers,

T_{sky} = effective temperature of the sky with which the radiative exchange takes place,

ε_p = emissivity of the absorber plate for long wave length radiation,

ε_c= emissivity of the covers for the long wavelength radiation.

q_t = rate at which heat is lost from the top,

References:

[1] Njomo, D. Techno- economic analysis of plastic cover solar air heater, Energy Conversion and Management 36(10), 1023-1029, 1995.

[2] Jannot,Y., Coulibaly, Y., Radiative heat transfer in a solar air heater covered with a plastic film, Solar Energy 60(1), 35-40, 1997.

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Appendix-III

The existing thermal performance parameters (TPPs) and test procedure for their determination:

Appendix-III

The existing thermal performance parameters (TPPs) and test procedure for their determination:

3.A. Mullick *et al.* [1]

The TPPs considered for PCC by Mullick *et al* are optical efficiency factor, $F'\eta_o$ and over all heat loss factor, $F'U_L$

Two tests were recommended by Mullick *et al* to obtain the above mentioned TPPs. The first test was a water heating test under clear sunshine. The second test was water cooling test performed in absence of sunlight The second test was performed to determine $F'U_L$. By taking the value of $F'U_L$ and analyzing the results of first test, $F'\eta o$ was calculated.

Water heating and cooling tests were performed on a paraboloidal mirror concentrating cooker with aperture area 0 58 m^2 An aluminum pot with outer surface area of 0.08 m^2 was taken to heat 1 litre of distilled water up to 90- 95 °C. The pot was kept on the focus of the concentrating cooker The concentrator was adjusted in such a manner that bright spot falls on the bottom of the pot near the edge. During sensible heating test, no adjustment of concentrator was required as the water in the cooking pot boils before bright spot reaches the diametrically opposite edge When water temperature reaches 90-95°C the concentrator was shaded The water temperature was noted down after regular interval of time and cooling curve was obtained by plotting these data Both heating and cooling curves are plotted as shown in Fig III a From this cooling curve time constant τ_o is determined. By putting the value of τ_o, $(MC)'_w$, and A_t in equation (III.b) the value of $F'U_L$ is found out. Then from equation (III.d) the value of $F'\eta_o$ is determined

The time, τ_t, required for sensible heating of water under given insolation and ambient temperature is

$$\tau_t = -\frac{(MC)'_w}{A_t F' U_L} \ln\left[\frac{(T_w - T_a)}{(T_{wo} - T_a)}\right] \tag{III.aa}$$

$$\tau_0 = (MC)'_w / A_t F' U_L \tag{III.ab}$$

$$\tau = -\tau_0 \ln\left[\frac{F'\eta_0 - \frac{F'U_L}{C}\left(\frac{T_{w2} - T_a}{G_b}\right)}{F'\eta_0 - \frac{F'U_L}{C}\left(\frac{T_{w1} - T_a}{G_b}\right)}\right] \tag{III.ac}$$

$$F'\eta_0 = \frac{F'U_L}{C}\left[\frac{\left(\frac{T_{w2} - T_a}{G_b}\right) - \left(\frac{T_{w1} - T_a}{G_b}\right) e^{-\tau/\tau_0}}{1 - e^{-\tau/\tau_0}}\right] \tag{III.ad}$$

where, A_t is the surface area of the pot, F' is the heat exchange efficiency factor, U_L is the overall heat loss factor of the pot and T_a is the ambient air temperature, $(MC)_w$ is the product of mass of water taken and its specific heat capacity. $(MC)'_w$ also includes the heat capacity of the pot.

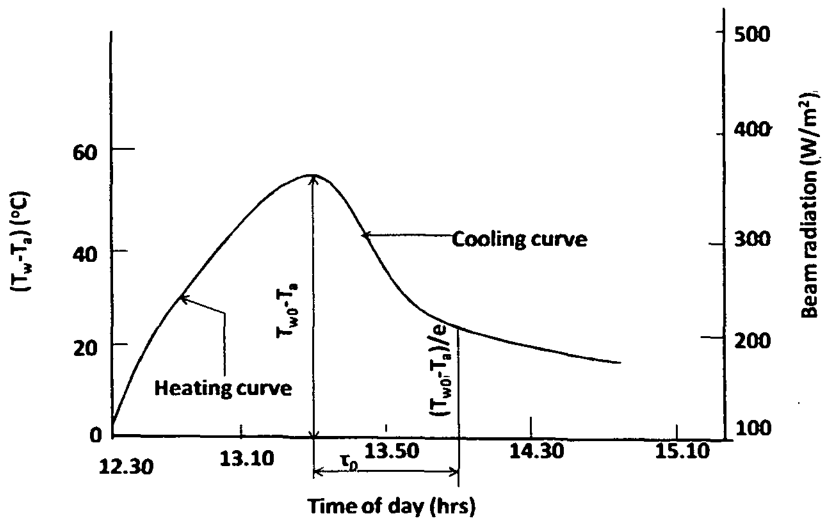

Fig.III.a: Heating and cooling curve of water [1]

The performance parameter (PPs) proposed by the author and their values were given in Table III.1

3.B. Khalifa *et al.* [2]

A new oven type cooker was designed and developed. In this an oven type receiver was placed in the focus of the spiral concentrator. The different type of TPPs selected here were efficiencies like oven efficiency, Cooker efficiency, Optical efficiency etc. These TPPs were computed by computer simulation method. To check the correctness of the simulation process, experiments were performed. Heating tests were performed by using water and oil. Actual cooking operation was also performed to check the accuracy of the simulation process proposed by them. From the study they found that new design may provide better results and results obtained from simulation process were in practical consistency with experimental process.

The new solar cooker heats the pot kept in a hot box from bottom or from side and bottom depending on season and cooking is not affected by speed of the wind.

To simulate the thermal behavior of the oven a mathematical model was developed. For developing the model three elements, the cooking pot, the glazing and food inside the pot were considered. The food receives the energy from the pot by convection process. Part of this energy is used to raise the internal energy of the food and rest is lost to ambient through top of the pot.

The pot itself was heated by the beam radiation received from the spiral concentrator. The part of the absorbed heat is transferred to the food and remaining portion is lost by process of convection and radiation through glass and sides of the oven. Internal energy of the pot is increased due to absorption of heat. Glass receives energy by convection and radiation from the receiving surface of the pot. It absorbs part of the beam radiation transmitted to the pot. Some part of the energy received by the glass is lost and remaining portion is used to increase the internal energy of the glass. For Heat loss and heat gain, first order differential equations are formed for each element (i.e., for pot, food and glass). A fourth order Runge –Kutta algorithm was used for numerical solution of set of equations formed for the three elements.

The first TPP, the instantaneous oven efficiency was defined as the ratio of the rate heat added to the fluid at a certain instant of time to the corresponding concentrated solar energy reaching the oven from the concentrator.

$$\eta_{i,o} = q_f / Q_{s,in} \tag{III.ba}$$

Where $\eta_{i,o}$ is the instantaneous oven efficiency, q_f is the rate of heat added to the fluid, and $Q_{s,in}$ solar energy from the concentrator to the oven.

The second TPP, the overall oven efficiency is defined as

$$\eta_o = \int_0^t q_f dt \bigg/ \int_0^t Q_{s,in} dt \tag{III.bb}$$

The nomenclature is same as stated in above.

The third TPP the overall cooker efficiency, η_c is given by

$$\eta_c = \int_0^t q_f dt \Big/ \int_0^t \overline{G}_b A_{pa} dt \qquad \text{(III.bc)}$$

where $\overline{G}_b$ is the beam radiation, A_{pa} is the projected area of concentrator in m^2 and t is the time period.

Oil and water were taken as working fluid for heating purpose. The instantaneous oven efficiency drops as the temperature of the fluid increases for both the fluid. For water the oven efficiency was greater than the cooker efficiency. For oil, maximum oven efficiency depended on maximum temperature of the oil used.

The predicted results were compared with experimental results and found that boiling time for water found from simulation is less than the results obtained from experiments.

The performance parameters (PPs) and their values as reported by Khalifa et al were given in Table-III.1

3. C. Patel *et al.* [3]

Three concentrating type cooker of different model were tested by Patel *et al.* The first cooker was German design made by an Indian company IME Co. Valsad. The cooker was a paraboloidal concentrating cooker. The cooking pot was kept at the focus of the concentrator. The second one was Philippine cooker. The concentrator was Fresnel type. The third one was Chinese type having foldable Fresnel concentrator.

Three tests namely stagnation temperature test, water heating test and cooking test were performed in these three cookers and performance of these cookers were studied.

The stagnation test was carried out under no load condition and maximum temperature attained by these cookers was measured..

Water heating test was done to evaluate the thermal performance of these cookers at different temperatures. The maximum temperature fixed was 90°C. Some of the parameters during test were measured were heating time and efficiency.

The performance parameters (PPs) and their values reported given in Table-III.1.

Table- III.1: Performance parameter

Reference	PP	Reported range of PP
Mullick et al.[1]	$F'\eta_o$,	0.447-0.454
	$F'U_L$	17.2 W/m^{2o}C
Khalifa et al[2]	η_c	33.1% (Water) 18.6-29.6% (olive oil)
	η_o	68.3% (Water) 38.4-61.0 (olive oil)
Patel et al[3]	η_{th}	35-42%

References:

[1] Mullick, S.C, *et al.*, Thermal test procedure for a paraboloid concentrator solar cooker. Solar Energy 46(3), 139-144, 1991

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