Chapter-1

Introduction

1.1 History and significance of tea

Tea is a refreshing drink. Aroma and taste of a cup of tea brings freshness to every one's mind. It is accepted as one of the highly sought after drinks in the world and has become an intrinsic part of daily life. Tea was first introduced to the society in China in 2737 BC by Emperor Shen Nong when a leaf fell accidentally in a pot of boiling water from an unknown shrub. In India, it was discovered in Assam by Robert Bruce in 1823 among the Singpho tribes. Tea plant was scientifically named as *Camellia sinensis* in 1833. India is the second largest tea producing country after China. A record 1325.05 M kg of tea was produced by India in the financial year 2018 [59]. Around 20% of the tea production is exported to other countries. The remaining amount is used for domestic purposes. India exported 201 M kg of tea in the financial year 2021-22 [15]. However, around 18% decline in the export quantity occurred in 2020 primarily due the corona virus outbreak [81]. The total area for tea plantation covers 579350 hectares of land. More than 1.5 million people are associated with the tea industry in India. It provides indirect employment in the machinery, chemicals and transportation sector in addition to being directly associated in the tea production. The tea industry contributes immensely to the overall economy of the country. Out of the total tea production in India, about 50% tea is produced in Assam [102]. The special feature of the Assam tea is recognized worldwide. Thus, it becomes crucial to emphasize on the development of this industry to sustain these benefits. Incorporation of novel and efficient machinery in the tea sector may help in achieving the goals. Moreover, tea manufacturing being an energy intensive operation, steps may be taken to involve energy conserving economic practices in the process. The process of tea manufacturing is discussed briefly below.

1.2 Tea processing

After harvest, the fresh tea leaves undergo five primary operations before the production of made tea- withering, maceration, fermentation, drying and grading or sorting. Fig. 1.1 shows the flow chart of the tea manufacturing process. Tea-leaf withering and tea drying are the operations which primarily consumes energy in tea manufacturing. Drying consumes the highest amount of thermal energy. Coal, natural gas, oil and wood are the generally used sources of thermal energy in the tea industries. The first three fuels are mainly used in Assam and the latter is used in the South Indian tea industries. The major operations of tea processing are briefly discussed as follows-

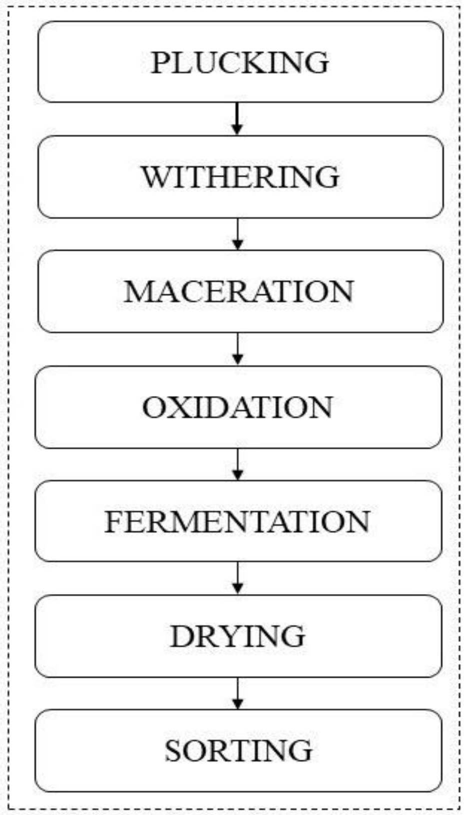

Fig. 1.1. Flow chart of a tea manufacturing process [192]

1.2.1 Withering

The standard of a typical tea shoot is two leaves and a bud having a moisture content of around 75%. Withering is a low temperature drying process just after the fresh leaves are plucked. The tea leaves are laid for (12-16) h at about 30 kg/m^2 in a withering trough over an area with a depth of about 0.20 m. Two types of withering troughs namely, open and closed troughs are used. The moisture content reaches to around (55-60) % at the end of the withering process. The moisture loss occurs at a higher rate in the beginning and slows down gradually till equilibrium is attained. Around 75% of the total air (about 2000 t) required for processing 1 t of tea is needed in the withering process [16,152]. Appropriate temperature and humidity are the major factors that decide the performance of withering and consequently the quality of made tea. Generally, the desired temperature is around 30 °C at relative humidity of (85-90) % during tea withering. Extra thermal energy in the form of heat is needed during withering in the rainy and winter seasons. This requirement is fulfilled as per availability of sources of thermal energy. In some factories, oil or gas burners are used for green tea-leaf withering operation. A typical tea withering process is shown in Fig. 1.2.

Fig. 1.2. Tea withering

In physical or artificial withering, the cell permeability changes with the moisture loss. It is a slow process and is achieved by passing air through the withering tunnel at a required temperature. There occur bio-chemical changes within the tea leaves during chemical withering. Enzymatic activity changes and breakdown of proteins to amino acids results in the aroma of tea. Further, there is a reduction in the chlorophyll content and improvement in caffeine content. Thus, proper withering of tea leaves is vital because the tea leaves become flabby with a reduction in moisture content after the process. This enhances the rolling and drying operations which in turn aids the final product [43]. There are four types of artificial withering [193]-

i) *Dry and warm air withering*: Air is heated in a furnace and a fan draws the warm air over the tea leaves in this type of physical wither. Stacked trays of about (7×5) feet, cylindrical vapour heater, pressure fan with closed exhaust, a pipe for air circulation and a winding gear comprise of the tea withering system.

ii) *Moist and warm air withering*: In this system, the warm air is combined with moisture to partially dry the tea leaves. Trays are again stacked one over the other with perforated plates incorporated at the entry point and the exit of the wilting chamber. The exhaust air is passed via conduit pipes fitted near the inlet and outlet. A fan is again connected for recirculation of the exhaust air in the withering chamber.

iii) *Vacuum withering*: Trays made of galvanized iron are kept serially in an air-tight compartment to spread the tea leaves. An air pump is connected with a valve box which regulates the vacuum inside the chamber through pipes. The leaves in this case are exposed to vacuum for the withering process.

iv) *Waste heat system*: The waste air is drawn through the withering chamber with the help of exhaust fans or blast fans in this type of withering. The fan size decides the elevation of the ceiling cloth. Again, the length of the withering chamber decides the quantity of fans required for the purpose. The velocities of the fans are responsible for determining the power required to operate them.

The moist air system of tea withering is mostly employed in the tea industries of Northeast India due to the climatic conditions in the region [153].

1.2.2 Maceration

The maceration process helps to aid chemical reactions in the already withered leaves. The tea shoots with varied tenderness get significantly deformed during rolling operation. During the gradual breakage of leaf, the epidermis gets torn up, cells and cuticles are crumpled with an increase in the intercellular space. This mechanical rupture of tea shoots results in the creation of particles of different shapes and dimensions based on the method employed and the level of cell impairment.

Normally, two methods of maceration are applied- Orthodox and Crush-Tear-Curl (CTC). The leaves are ruptured manually in the Orthodox method. On the other hand, the tea leaves are crushed, torn and curled with the help of two rollers in a CTC machine [6]. A conventional CTC machine is shown in Fig. 1.3.

Fig. 1.3. A CTC machine for maceration

1.2.3 Fermentation

The primary characteristics of tea like colour, aroma and flavor are developed during the process of fermentation. The macerated tea or *dhool* at a thickness of (0.4-0.7) m is laid down at a temperature of around 27 °C in a fermentation room as shown in Fig. 1.4. The fermentation process takes (1-4) h to complete depending on the type of maceration and the variety of tea required. The degradation of enzymes, polyphenols, lipids and carotenoids take place leading to the formation of compounds like theaflavins and thearubigins which in turn are accountable for the colouring of tea. In the orthodox method, natural fermentation is practiced. The *dhool* is placed in thin layers on tables or perforated aluminum stacked trays. The environment is kept moistened by using humidifiers. Drum or continuous fermentation is done in CTC method. The macerated leaves are put in a rotating drum in this system where blowers supply the oxidation air. This type of fermentation is quicker than the natural one [118].

Fig. 1.4. Natural fermentation of tea

1.2.4 Drying

The process of removing moisture from the fermented tea leaves is termed as drying. At the end of this process, the moisture level comes down to 3% in the product. About 1.5 to 2.5 kg of moisture is removed in the drying process for every one kg of made tea. The colour of the tea becomes blackish from the reddish tone. All the chemical reactions occurring in fermentation cease during drying. The drying medium used is generally the hot air coming from the furnace or a mixture of air and flue gas. The drying process is highly thermal energy intensive. Factors like inlet and exhaust temperatures, feed rate of fermented tea leaves, quantity of air and drying time affect the tea drying operation. Basically, two types of dryers are used in the process- conventional dryer (Fig. 1.5) and vibro-fluidized bed dryer (Fig. 1.6). These are illustrated briefly below-

i) *Conventional dryer*: This double firing type of dryer is an endless chain pressure type one. It is normally used in the factories of Northeast India. The drying and exhaust temperatures are maintained around 100 °C and 55 °C respectively for case-hardening of fermented tea and to cease stewing. It is recommended to keep the exhaust temperature at 52 °C for economic and quality purposes. The initial temperature for double firing is within

93.3 °C to 104 °C. For CTC tea, the appropriate temperature for second drying is between 77 °C to 82.2 °C whereas it ranges between 71 °C to 77 °C for orthodox type [1]. This depends on the moisture content after the first drying is done. The drying is completed in this type of dryer within 40 minutes. A conventional dryer is preferable if only the quality aspect is considered. However, there has been a switch over to vibro-fluidized bed dryer to attain a better drying efficiency.

Fig. 1.5. A conventional dryer

ii) *Vibro-Fluidized bed dryer*: These dryers comprise of three to five zones having mixed or cross flow mode of operation along with a cooling section. Initially the pressure drop is proportionate to the flow rate as the fluid passes upwards through a granular bed. The frictional drag becomes comparable to the noticeable weight of the particles at a higher air velocity, thus causing the bed to expand. This phase is known as the commencement of fluidization. It is called fluidized bed when the particles start floating in an air stream after separating from one another at more increased velocity. A better appearance of the tea is obtained in fluidized drying as particle to particle hold is minimum because of the fluid cushion surrounding each particle.

In vibro-fluidized dryers, the fermented tea leaves are laden on a grid-plate in the drying compartment. The chamber is fully closed at the top and provided with two arrangements of centrifugal fans. These two sets are used for re-firing and collection of dust. There is a plenum chamber under the bed in which the air pressure is balanced. Flow control dampers are incorporated to regulate the flow of hot air. The high moisture level of the incoming fermented leaves is reduced by allowing a heavy amount of hot air for quick evaporation. The bulk density of the product decreases due to this rapid moisture loss causing it to deviate from the feed. The final product is discarded to the cooling chamber after complete drying to prevent case-hardening or stewing. The appropriate inlet temperature ranges from (140-150) °C in the vibro-fluidized bed dryer. The exhaust temperature is recommended to be within 71.1 °C to 76.7 °C [1].

Fig. 1.6. A fluidized bed dryer

1.2.5 Sorting and packaging

Sorting or grading is the final stage in tea processing. In this process, the final dried product is separated into different sizes and classified according to their types. Packing is done once sufficient amount of each grade have been sorted. Earlier, sorting was done manually in order to remove bigger leaves and unwanted matter. Grading was known as sifting in the past. However, both these processes are carried out simultaneously nowadays and hence are merged into one single step in black tea manufacturing. After the sorting is done, the final product is packed in foil lined paper sacks to serve as a moisture barrier [50]. The processes of sorting and packaging of tea are shown in Figures 1.7 and 1.8.

Fig. 1.7. A Sorting machine

Fig. 1.8. Packaging of tea

1.2.6 Manufacturing of some other types of tea

i) *Green tea*

- Plucking: To maintain premium quality, only the top two leaves and a bud are harvested.
- Steaming or Pan-Firing: Right after being picked, leaves undergo steaming or pan-firing to halt oxidation. Steaming preserves the green hue and the fresh taste of the leaves.
- Rolling: Leaves are steamed and then rolled to give them shape and release juices, which enhances their flavour.
- Drying: Rolled tea leaves are dried either using hot air or heated pans to decrease moisture content and stabilize the tea. This drying method is quicker compared to that of black tea in order to maintain the green color.
- Sorting and Grading: Green tea leaves undergo a sorting and grading process similar to that of black tea.
- Packaging: The end product is packaged to prevent exposure to moisture and light, thus preserving its quality [211].

ii) Oolong tea

- Withering: Leaves are exposed to direct sunlight for withering before being moved indoors to decrease moisture levels.
- Bruising: Leaves undergo agitation or tumbling to bruise their edges, initiating partial oxidation, resulting in a blend of green and brown leaves.
- Oxidation: Bruised leaves are allowed to undergo partial oxidation, usually ranging from 20% to 80%. The degree of oxidation contributes to the

distinctive flavour of oolong tea, which falls between that of green and black tea.

- Fixing: The oxidation process is stopped by either pan-firing or steaming the leaves.
- Rolling: Processed leaves are rolled to mold their shape and intensify flavour.
- Drying: The rolled leaves undergo drying to decrease moisture content and stabilize the tea.
- Sorting and Grading: Comparable sorting and grading procedures are employed, akin to those used for other types of tea.
- Packaging: The final oolong tea is packaged to maintain its distinct qualities [211].

iii) White tea

- Plucking: Only the freshest buds and leaves are harvested.
- Withering: Leaves are allowed to wilt under natural sunlight or in controlled indoor environments.
- Drying: The withered leaves undergo minimal processing to retain their delicate flavour and aroma, typically dried at low temperatures.
- Sorting and Grading: The leaves undergo sorting and grading according to their quality.
- Packaging: The fragile white tea leaves are meticulously packaged to prevent any harm and maintain their freshness [211].

1.3 Energy utilization and environmental impact in tea manufacturing

The process of tea manufacturing involves many energy intensive operations as each stage requires different mechanical and electrical equipment. Three types of energy are used- thermal, electrical and human. The thermal energy consumed is more in the processes of tea-leaf wilting and drying. Though less, electrical energy is an essential requirement in nearly all the steps of tea processing. About 30% of the total cost in tea production is constituted by the overall energy costs. For the production of one kg tea, the ranges of thermal and electrical energy requirements are respectively (16.02-24.62) MJ and (1.44-2.52) MJ. The tea industries in South India use firewood, coal and furnace oil as the sources of thermal energy. Whereas, the industries in Northeast India mainly depend on coal, natural gas and oil for the fulfillment of the energy requirements. The yearly consumption of fuel can be summarized as approximately 1.3 lakh t of coal, 7.8 lakh t of firewood, 642 M liters of oil and (2.4×10^9) GJ of electricity [26].

The process of tea withering depends on the production plan. An indirect thermal energy supply will not suffice to a tea factory where the handling of tea leaves is comparatively large in quantity. Such facilities are seen in the Vietnamese and Sri Lankan tea industries where heaters are provided exclusively for the withering process. In India, the specific consumption of thermal energy in withering for the processing of Orthodox tea is 3.74 MJ/kg and that for CTC tea is 2.12 MJ/kg of made tea. Tea drying consumes a large amount of energy during its operation. The approximate energy consumption rates in oil-fired, coal-fired and gas-fired burners are respectively 23.88 MJ/kg, 43.72 MJ/kg and 27.49 MJ/kg of made tea. Due to less efficient dryers, there has been excess consumption of thermal energy in the process. About 47% of the total thermal energy supplied is utilized during wilting and drying operations in the Indian tea factories [26].

The use of the conventional thermal energy resources in tea processing cause many environmental hazards. Pollutants like CO, CO_2, SO_2, NO_x, hydrocarbons, fly ash particles emerging from combustion of fossil fuels pose threat to the environment in the form of greenhouse gas emissions. Suspended particle matter emission due to combustion of coal is found in the range of (160-800) ppm. This level is reported to be higher than the critical value near the combustion space. During combustion, the amount of respirable particle matter having sizes less than 10 µm in air is found as 47.26 $\mu g/m^3$. Though this value is lesser than the permissible limit for industries (100 $\mu g/m^3$), the continuous emission of such matter is hazardous in the long run for tea industrial work. The NO_3 values ranged between (1-10) ppm. Further, the concentration of SO_2 in air is reported as 465.184 $\mu g/m^3$ which is higher than the permitted limit [26].

The continuous usage of these conventional energy resources in the tea industries is not fruitful both in cost as well as the environmental aspects. It is high time that the fuel types and techniques are altered by the tea manufacturers. For the prospective green technology, renewable energy resources are readily available which may be consumed to encounter the energy mandate. One such economically and environmentally sound source is the solar energy. Implementation of solar thermal collectors or solar air heaters in the tea factories would definitely serve the purpose. A brief discussion on solar air heaters is given below.

1.4 Solar air heater

A solar air heater (SAH) is a special type of heat exchanger that absorbs solar irradiation and enhances air temperature with a certain thermal efficacy. A typical SAH heater comprises of a see-through cover, a base plate, an absorber plate and a collector box along with proper insulations in all sides.

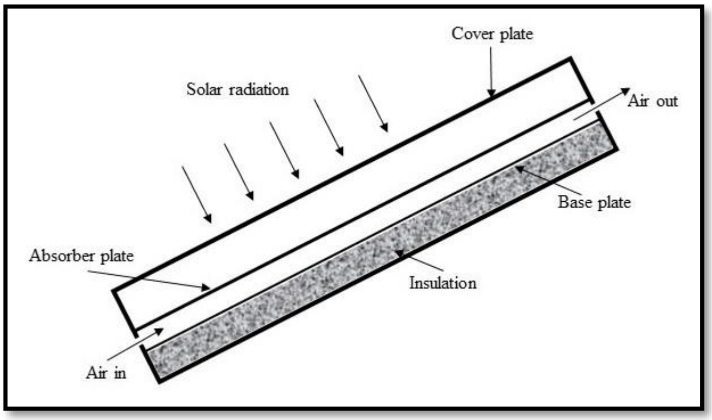

Fig. 1.9. Schematic illustration of a simple SAH

The schematic illustration of a typical SAH is depicted in Fig. 1.9. The cover plate of the SAH is made of a material through which the solar radiation is free to pass into the absorber. Generally, glass covers or plastic sheets of thickness (4-5) mm are used for the purpose. Keeping a space beneath the cover plate, the absorber plate is placed which is a metal sheet of thickness (1-2) mm. The absorber plate is coated with specific black colour so that it absorbs the radiation to the maximum extent. The base plate which is again a metal sheet is positioned beneath the absorber in the collector box. Sufficient insulation is provided on the edges and bottom of the SAH to minimize the heat losses [65].

1.4.1 Working principle of a solar air heater

A conventional SAH works on a simple principle. The absorber plate traps the solar irradiation coming through the cover plate for which there is an increase in the absorber plate’s temperature. Adequate amount of the heat gets transmitted to the air over the plate and the remainder is lost to the ambience through convection and conduction mode through the top, back and edges of the collector box. The air circulation inside the heater is with the aid of electric blower or buoyancy effect depending on the type of SAH. The rate of heat transmission from the absorber to the air decides the performance of the heater. The thermal performance as well as the rate of heat transfer can be improved by modifying the design of the air heater absorber plate [65].

1.4.2 Classification of solar air heaters

The SAHs are broadly categorized into two types-

i) *Non-porous collectors*: The air stream flows over both the sides of the absorber plate and not through it. Convective losses occur if the air flows above the absorber surface. It is therefore preferred to use those in which the air flows beneath the absorber plate. There are also some non-porous collectors where an air stream is used to cool down the absorber plate which passes through both the sides of the plate. The efficiency of such air heaters are less due to the low rate of heat transfer in between the air and plate. The use of V-corrugated plate or coarsening the absorber surface may enhance the thermal enactment of the air heater [65].

ii) *Porous collectors*: These types of SAHs consist of porous absorber plates. The plates may be constructed using split metal, crushed glass, transpired honeycomb structures, porous broken bottle bed and overlaid glass plate. However, the overall efficiency in these air heaters is again less due to too many obstructions in the air flow which in turn require more energy. The benefits obtained from the solar energy absorbed gets nullified due to the high usage of electrical energy in the form of blowers [65].

1.4.3 Solar troughs

Solar troughs offer an efficient way to harness solar energy for drying agricultural and industrial products. These systems are specifically designed to optimize the capture and use of solar radiation, presenting an environmentally friendly and cost-efficient drying solution. An in-depth analysis of different solar trough designs utilized in experimental drying setups is given below [65]-

i) Parabolic Trough Solar Collector (PTSC):

- Design: It features a parabolic reflector that focuses sunlight onto a receiver tube positioned along the focal line of the parabola.
- Operation: The focused solar energy heats a working fluid inside the receiver tube, which can be utilized right away or stored for later use.
- Applications: Generally used for drying fruits, vegetables, grains and spices. The high concentration of solar energy enables efficient and rapid drying.

ii) V-Groove Solar Trough

- Design: Includes a V-shaped reflective surface that directs sunlight onto a central absorber plate.

- Operation: The V-groove design boosts the collection of solar radiation, increasing the efficiency of heat transfer to the absorber plate and, in turn, to the drying air.
- Applications: Ideal for drying agricultural products such as herbs, nuts and seeds, where moderate temperatures and consistent drying are crucial.

iii) Flat Plate Collector with Reflective Trough

- Design: Integrates a flat plate collector with side reflectors arranged in a trough shape to direct extra sunlight onto the flat plate.
- Operation: The reflectors amplify the solar radiation reaching the flat plate, thereby improving the thermal efficiency of the system.
- Applications: Efficient for drying delicate products like tea leaves, coffee beans and others that necessitate gentle drying methods to maintain quality.

iv) Double-Pass Solar Air Heater with Trough Reflector

- Design: Utilizes a double-pass solar air heater configuration, where air flows over and beneath the absorber plate, complemented by trough reflectors to focus sunlight onto the plate.
- Operation: The double-pass configuration extends the duration of contact between the air and the heated surface, thus enhancing heat transfer and drying efficiency.
- Applications: Ideally used for drying grains, fish, and meat, particularly where elevated air temperatures and effective moisture extraction are paramount.
- Compound Parabolic Concentrator (CPC)
- Design: Utilizes a compound parabolic reflector to focus sunlight onto a reduced absorber area.
- Operation: This design enables the capture of diffuse sunlight, ensuring effectiveness even in partly cloudy conditions. The concentrated energy boosts the drying process.
- Applications: Ideal for drying high-value crops such as medicinal herbs, where precise regulation of drying conditions is crucial.

v) Semi-Cylindrical Solar Trough

- Design: It includes a semi-cylindrical reflector that redirects sunlight onto a tubular or flat absorber placed along the central axis of the trough.

- Operation: The semi-cylindrical design guarantees continuous concentration of sunlight on the absorber throughout the day, thus ensuring consistent drying temperatures.
- Applications: Suitable for drying fruits, vegetables and other products that require uniform exposure to steady temperatures.

vi) Conical Solar Concentrator

- Design: Employs a conical reflector to concentrate sunlight onto a central absorber plate or tube.
- Operation: The conical structure enables effective concentration of solar energy, delivering elevated temperatures for swift drying.
- Applications: Ideal for drying biomass, wastewater sludge and other industrial materials that demand high-temperature drying processes.

vii) Hybrid Solar Trough Systems

- Design: Integrates solar troughs with supplementary heating systems to ensure uninterrupted drying operations regardless of solar availability.
- Operation: The hybrid system ensures steady drying conditions by utilizing solar energy when it is accessible and seamlessly transitioning to auxiliary heating during periods of limited solar radiation.
- Applications: Adaptable for various products including agricultural goods, industrial by-products and food items.

1.4.4 Artificial roughness elements in solar air heaters

Artificial roughness elements are crucial in improving the thermal efficiency of solar air heaters (SAHs). This significance can be underscored through several key points [65]:

i) Improved heat transfer:

- Increased surface area: Roughness elements such as corrugated surfaces and
- Al-cans expand the effective surface area in contact with the air, thereby boosting convective heat transfer.
- Turbulent flow creation: These elements induce turbulence in the airflow, interrupting the laminar sublayer that forms near the absorber plate. This turbulent flow enhances air mixing, thereby increasing heat transfer rates.

ii) Improved thermal performance:

- Higher Heat Transfer Coefficient: The inclusion of roughness elements boosts the heat transfer coefficient, resulting in improved thermal performance of the SAH.
- Effective Temperature Control: Enhanced heat transfer ensures that the desired temperature range for processes such as tea withering is maintained more efficiently and consistently.

iii) Energy efficiency:

- Reduced Energy Consumption: By improving the heat transfer, roughness elements decrease the amount of energy required to achieve the desired heating, thereby making the system more energy proficient.
- Lower Operational Costs: Greater efficiency leads to lower operational costs over time, as less energy is needed to reach and retain target temperatures.

iv) Sustainability:

- Using Recycled Materials: Using materials like aluminum cans not only enhances performance but also promotes sustainability through recycling.
- Reduced Carbon Footprint: Improved efficiency and decreased energy usage help diminish the carbon footprint, rendering SAHs with roughness elements an eco-friendly choice.

1.4.5 Different types of artificial roughness elements

Different types of artificial roughness elements in SAHs are disussed below [65]-

i) Transverse Ribs:

- Design: Small ribs placed perpendicular to the airflow at regular intervals.
- Effect: They disturb the boundary layer, generating turbulence and improving heat transfer.

ii) V-Shaped Ribs:

- Design: V-shaped ribs arranged in different configurations, such as facing upstream or downstream.
- Effect: The V-shape encourages superior airflow disruption and mixing in comparison to transverse ribs.

iii) Helical Ribs:

- Design: Ribs positioned in a spiral pattern along the surface.
- Effect: These cause spiral flow, boosting air mixing and enhancing heat transfer.

iv) Dimpled Surfaces:

- Design: Surfaces featuring regularly spaced dimples or indentations.
- Effect: Dimples generate localized turbulence, improving heat transfer without significantly raising pressure drop.

v) Wavy or Corrugated Surfaces:

- Design: Surfaces with a wavy or corrugated design.
- Effect: The corrugations boost surface area and induce turbulence, thereby enhancing heat transfer efficiency.

vi) Wire Meshes and Screens:

- Design: Fine wire meshes positioned on the absorber plate.
- Effect: They augment surface roughness and disturb airflow, thereby improving heat transfer.

vii) Perforated Plates:

- Design: Plates featuring evenly spaced holes or perforations.
- Effect: The perforations generate jets of air that blend with the primary flow, boosting turbulence and heat transfer.

viii) Aluminum Cans:

- Design: Trimmed and flattened or organized in a particular configuration on the absorber plate.
- Effect: They offer expanded surface area and provoke turbulence, thereby enhancing heat transfer. Additionally, their high thermal conductivity contributes to the improved performance.

ix) Staggered Baffles:

- Design: Baffles positioned in a staggered configuration along the path of airflow.
- Effect: They disrupt the airflow repeatedly, generating turbulence and improving heat transfer.

x) Multi-Geometry Roughness Elements:

- Design: Various shapes and geometries (such as ribs and dimples) combined on a single surface.
- Effect: The collective impact of various roughness elements can result in even more significant enhancements in heat transfer.

1.5 Background of the study

Tea production is considered as the backbone of the overall development of the society and economy of Assam. The tea manufacturing procedure is overall an energy consuming process. Nearly 30% of the overall cost of tea processing is constituted by the expense of energy consumed. Around 30 kcal of energy is required to dry freshly harvested tea leaves for producing a spoon of tea. This releases about 17 g carbon dioxide into the atmosphere [26]. Therefore, the low energy efficiency has become a very important matter to be addressed. The operations of tea withering and drying consumes the maximum amount of thermal energy required during tea production. The need for conventional energy resources like coal, natural gas, oil is increasing in the tea factories of the region with enhanced green leaf production. To curb the requirement, renewable energy resources like solar and biomass may be employed. In the field of tea drying, literature provides certain experimental studies on such utilization of renewable energy in different regions along with Assam. Drying of tea was carried out by using a downdraft gasifier with locally available biomasses [50]. There was a decrease in the fuel cost by using bamboo as feed in tea drying [147]. Also, microwave drying was tested for Assam CTC tea samples [74]. As withering too is a crucial energy consuming step in tea processing, the focus should also be given on the energy management in this process. The specific energy consumption in this partial drying process sums up to around 6.48 MJ/kg of made tea. It has become essential that the energy issues are addressed for this unit operation. An environmentally and economically sound alternative may be employed to serve the purpose. Implementation of solar thermal energy by maintaining the desired parameters of temperature and relative humidity is a viable option for tackling the problem. The technique of using solar air heaters for tea withering for the local variety of tea in Assam is not yet experimented. Therefore, an illustrative study in the tea withering aspect with the intervention of solar thermal energy is taken up as the primary objective of the work.