Abstract

Traditional biomass cook stove have been a popular device used for cooking by millions of people. Despite of its shortcomings corresponding to lower thermal efficiency and indoor air pollution, it is still prevalent among a major chunk of people due to its favorable features matching to cooking habits, and availability of low cost and abundant biomass fuel. There are efforts to improve its thermal efficiency and there are different varieties of improved cook stoves. Still, heat lost to its body is not appropriately addressed. In this study, attempt is made to see the prospect of recovery of lost heat and its conversion into electricity. Quantitatively, the electricity produced appears small, but considering the number of stoves distributed among the population and critical requirement of electricity for smaller devices like illumination and mobile charging, this approach appears to be significant.

A systematic study to understand the amount of thermal energy received and dissipated in a stove was made using a standard government approved improved fixed clay made biomass cook stove. Experiments were conducted to understand the thermo-physical property of the stove material and the temperature distribution in the stove body. The heat received and dissipated in the stove body was worked out using heat transfer analysis. In the present study, thermoelectric generator (TEG) was used as the technology to capture the heat lost and convert it into electricity. Thermoelectric Generator (TEG) is a technological device that works on the principle of Seebeck effect, whereby electricity is produced with respect to temperature difference across it i.e. between TEG hot surface and TEG cold surface. However, the integration of such technology requires research involving performance testing in laboratory, field, in addition to economic analysis. Keeping in view of this, the investigation was carried out with the following objectives: (i) to develop a thermoelectric generator (TEG) system for recovery of waste heat as electricity from fixed clay stove, (ii) to investigate the technical feasibility of TEG integrated fixed clay cook stove (TIFICS) in a typical rural area through field testing, and (iii) to analyze the economic benefits and TIFICS promotion policy.

An improved fixed clay cook stove, *Sukhad*, was selected based on its merit of converting fuel into useful energy and ensuring a clean indoor environment. The thermo-physical properties (viz. specific heat, density, thermal conductivity and thermal diffusivity) and temperature distribution inside the combustion chamber (CC) of the stove was determined using standard experimental set up. Based on the temperature distribution profile, the location of TEG was identified. TEG assembly for electricity conversion from waste heat of the stove consisted of three components viz., (i) heat collector, (ii) TEG module and (iii) heat sink. The TEG assembly was conceptualized in such a manner that TEG module was sandwiched between the heat collector and heat sink. The hot side of TEG module was attached with the heat collector whereas heat sink was attached to the cold side of TEG module. The maximum available temperature and the amount of recoverable thermal energy on the CC inner wall was used for the design of heat collector. Three materials (copper, aluminum, and stainless steel) were compared in terms of thermal conductivity, strength of material and cost. The best material out of the selected materials was selected for heat collector plate. There are different variants of TEG in terms of physical dimension, thermoelectric material, operational temperature range, power output, and cost. Based on the requirement of the present investigation, a TEG module was selected. The next aspect was thetechnique of generating a cold junction on the cold side of the TEG module. Four cooling technologies (natural convection mode of air, natural convection mode of water, forced convection mode of air and forced convection mode of water) were compared based on thermal resistance of heat flow, external power consumption, maximum achievable fluid (air/water) temperature and usefulness of dissipated heat. The best cooling technology was selected for heat sink. The heat sink for cooling the cold side of TEG was developed and the assembly for mounting the TEG assembly comprising of heat collector, TEG module and heat sink was fabricated.

The assembly was then integrated with the fixed clay cook stove and tests were conducted for three modes of performance testing, viz. (i) matched load, (ii) illumination, and (ii) battery charging. The electricity production in the form of illumination and battery charging during stove operation was possible. The temperature difference between the hot and cold side of TEG module under a typical cook stove operation was recorded in the ranges between 1.1ºC and 231.2ºC which produced electricity up to 2.7W at load voltage of 4.03V and current of

0.67A. Additional thermal energy output of 1 kW as hot water (i.e. heat dissipation into heat sink) for ten hours of stove operation was observed which makes TIFICS a cogeneration system.

Laboratory results were adequate to prove the feasibility of generation of electricity for illumination and battery charging. However, the working of TEG integrated fixed clay stove (TIFICS) under field condition with interaction by the users was also required. Five TIFICS were installed in a typical rural area based on the assessment of their need and tests were being conducted up to 450h. Technical, social and cultural issues were being identified. Overall, based on the field test results which was in line of the laboratory results, it was found that TIFICS was a technically feasible solution for rural area where electricity supply is either not available or not reliable. In the context of Sustainable Development Goals (SDG), TIFICS was able to address and support eight of the 17 goals on reduction of poverty, reduction of hunger, gender equality, promote education, improve health, ensuring clean and affordable energy access, protect climate and protect life on land.

From the data generated during the field test and the prevailing rates of economic parameters, an economic analysis was made to understand the cost of the system as well as the users' cost. Economic analysis in terms levelized cost of cooking a meal (LCCM), firewood savings, and kerosene savings was evaluated. With a realistic environment in a rural set up, LCCM of TIFICS, traditional biomass cook stove and LPG stove was assessed and found that LCCM of TIFICS was lower in comparison to traditional biomass cook stove but higher in comparison to LPG stove. However, with increasing rate in fuel costs. LCCM of TIFICS was equal to LPG stove. TIFICS was identified as a favorable option in the selected area considering the additional beneficial features of onsite electricity generation, clean cooking environment and thermal energy output in the form of hot water. Further the associated benefits can hugely impact in household's existing expenditure behavior on energy sources.

In order to channelize the benefits of the technical know-how generated in the present research work, the integration of appropriate policy framework along with business plan in the existing governmental policies of clean cooking, rural electrification, and LED lighting through different rural development schemes was desired. Appropriate financial institutions and entrepreneurial organizations were identified which can help boost promotion of TIFICS.

In a typical rural Indian condition, TIFICS was capable to address, fulfill and support the national mandates on clean cooking and power for all. The feasibility of TIFICS will also have relevance to other regions particularly in South East Asia and Sub Saharan Africa where majority of population are still facing the hardship of poor cooking devices and lack of access to electricity. With appropriate policy drivers within national mandates, the promotion of TIFICS can be ensured.