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HYBRID INDIRECT SOLAR COOKER WITH LATENT HEAT STORAGE

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ABSTRACT

Solar cooking is the simplest, safest, most convenient way to cook food without consuming fuels or heating up the kitchen. All the conventional solar cooker designs have the disadvantage of inability to cook during off-shine and night hours.This disadvantage can be eliminated if the solar cooker is designed with thermal storage arrangement. In this paper, a hybrid solar cooker with evacuated tube collector and latent thermal storage unit and alternate electric heatingsource is simulated. The heat transfer fluid gets heated in the evacuated tube collector is used for cooking along with alternate electric heating source.The phase changing material takes heat from working fluid and this heat is used for cooking during off shine and night hours with the inclusion of a heat exchanger . The hot working fluid flows in upwards direction because of thermosyphon phenomena. The vacuum in the evacuated tube collector allows the tube to act both as a super greenhouse and an insulator. This design allows to cook food inside the kitchen also helpful to keep food warm till late night hours. Performance improvement can be achieved using different nanofluids as working fluid.

KEYWORDS:. Solar cooking, Evacuated tube collector(ETC), Latent heat storage.

INTRODUCTION

Energy is a thermodynamic quantity which is described as the capacity of a physical system to do work. Energy is vital for our relations with the environment, and thus the research to resolve problems related to energy is quite significant since life is directly affected by energy and its consumption. Fossil fuel based energy resources still predominate with the highest share in global energy consumption. However, clean energy generation becomes more and more crucial day by day due to the growing significance of environmental issues.Currently, renewable energy resources supply about 14 % of total world energy demand and their future potential is remarkable. Among the clean energy technologies, solar energy is recognized as one of the most promising choice since it is free and provides clean and environmentally friendly energy. The Earth receives about 3.85 million EJ of solar energy each year.Solar energy covers a wide variety of applications in order to harness this available energy resources[1].

According to Indian government survey, over 77% of rural households in the country were estimated to depend on firewood and wood chips for cooking. Over 7% used dung cake and only 9% used LPG. In urban areas, LPG was the primary source of energy in nearly 62% of households[2]. Besides the environmental and economic burden of firewood use, there are some serious health problems originate from the utilization of firewood. It is also emphasized by the World Health Organization (WHO) that 1.6 million deaths per year are caused by indoor air pollution. Therefore, there is a rising attention concerning the renewable energy options to meet the cooking requirements of people in developing countries.Utilization of solar cookers provides many advantageous like no recurring costs,high nutritional value of food, potential to reduce drudgery and high durability[1]. Also,solar cookers have many advantages, on the health, time and income of the users and on the environment.High-performance parabolic solar cookers can attain temperatures above 290^{0}C. They can be used to grill meats, stir-fry vegetables, make soup, bake bread and boil water in minutes.Conventional solar box cookers attain temperatures up to 165^{0}C.Solar cookers use no fuel which saves cost as well as reduces environmental damage caused by fuel use. Since 2.5 billion people cook on open fires using biomass fuels, solar cookers could have large economic and environmental benefits by reducing deforestation.When solar cookers are used outside,they do not contribute inside heat, potentially saving fuel costs for cooling as well. Any type of cooking may evaporate grease, oil, and other material into the air, hence there may be less cleanup.

CLASSIFICATION OF SOLAR COOKERS

Solar cooking offers an effective method of utilizing solarenergy for meeting the demand for cooking energy. A solar cooker is a device which uses the energy of direct sunlight to heat, cook or pasteurize food or drink.The available solar cookers are mainly classified into two groups.

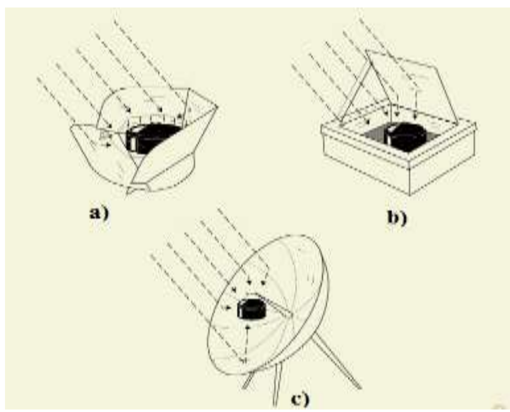
A. Solar Cookers without storage

Solar cookers without storage are classified into direct and indirect solar cookers according to the heat transfer mechanism to the cooking vessel.

i)Direct Solar Cookers

In direct type solar cookers,solar radiation is used directly in the cooking process.

Figure 1:



Different types of direct solar cookers a)Panel type b)Box type c) Prabolic type

a)Panel type solar cooker

Solar panel cookers may be considered the most simple type available due to their ease of construction and low-cost material. In solar panel cookers,sunlight is concentrated from above as shown in Fig. 1a. Panel cookers have a flat panel which reflects and focuses sunlight for cooking and heating. This method of solar cooking is not very desirable since it provides a limited cooking power.Solar panel cookers utilize reflective equipment in order to direct sunlight to a cooking vessel which is enclosed in a clear plastic bag.

b) Box type solar cooker

A box type solar cooker is an alternative food cooking technology with sunlight as its only energy source. Solar box cookers are the most common and inexpensive type of solar cookers. These box cookers have a very simple construction and they are made of low cost materials, which essentially consists of a black painted metallic trapezoidal tray and is usually covered with a double glass window base shown in Fig.1 b.

c) Parabolic type solar cooker

Solar parabolic cookers can reach extremely high temperatures in a very short time and unlike the panel cookers or box cookers, they do not need a special cooking vessel. However, a parabolic cooker includes risk of burning the food if left unattended for any length of time because of the concentrated power. A solar parabolic cooker simply consists of a parabolic reflector with a cooking pot which is located on the focus point of the cooker and a stand to support the cooking system as shown in Fig. 1c.A very high temperature of between 200^0C to 300^0C can be reached because of a combination of the circular design, the size and the polished aluminium.

ii) Indirect Solar Cookers

The indirect solar cooker use solar radiation to heat a thermal fluid that transports this heat to the place of cooking process.These types of solar cooker provide high thermal storage, temperature without tracking and at the same time cooking can take place in shadow or in conventional kitchen inside buildings. Due to the reversed cycle of during night and cloudy periods an effective heat transfer system is necessary to maximize the rate of heat transfer.Three types are categorized under indirect solar cookers,one which uses flat plate collector,other with evacuated tube collector and last one with concentrating type. In concentrating type of collector either parabolic or spherical shape is used to concentrate the solar radiation.

B. Solar Cookers with Storage

Cooking outdoors and impossibility of cooking food in late evening hours are the main problems associated with solar cooking systems. Therefore, thermal energy storage is essentially needed to increase the utility and reliability of the solar cookers. Solar cookers can be equipped with sensible heat storage or latent heat storage methods.

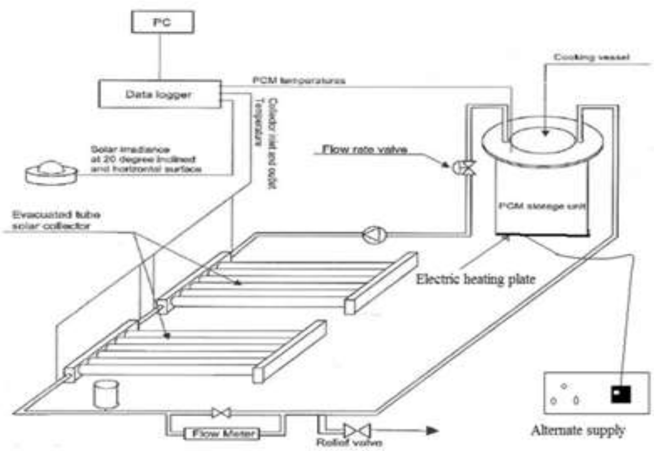
HYBRID SOLAR COOKER

Solar cookers are less useful in cloudy weather and near the poles, so an alternative cooking source is still required in these conditions.Using solar cookers may require food preparation start hours before the meal. The cooking pot is always exposed to the outdoor conditions which is also not much desirable as compared to indoor cooking.

A. Hybrid indirect solar cooker

Many designs of solar cookers have been developed by many researchers but all those were fully dependent on solar radiation availability or along with stored thermal energy. The design of a solar cooker with evacuated tube collector,latent heat storage and alternate electric heating source will be much efficient than conventional cookers since an alternate source is also applied along with the solar energy.The auxiliary source of energy like LPG or electrical heating is used for supplementing the stored or indirect solar energy.

Figure 2:



Proposed hybrid solar cooker

Energy required from the auxiliary source is to be optimized for the given system,solar insolation at the location and the load profile. Evacuated tube solar cookers are essentially a vacuum sealed between two layers of glass. The vacuum allows the tube to act both as a super greenhouse and an insulator. The schematic diagram of an ETC with a PCM storage unit is shown in Fig. 2. It consists of an ETC,a closed loop pumping line containing water as the heat transfer fluid (HTF), a PCM storage unit, cooking unit,pump, relief valve, flow meter and a stainless steel tube,heat exchanger.Thermal storage unit provides facility of cooking food at night also. The proposed indirect hybrid solar cooking unit consists of an evacuated tube collector, thermal storage tank, heat exchanger,alternate electric supply respectively. The heat was supplied by heat transfer fluid to thermal storage unit by natural convection process. In this system supply of energy was two way, firstly energy supplied by the heat transfer fluid to the cooking pot and secondly energy supplied by electrical means. This system provides the facility of using electricity and solar energy according to the temperature available at the cooking pot.The temperature at different points can be monitored using temperature sensors.The temperature thus obtained can be set as the input to compare with a reference value set in the data logger say a PIC micro-controller through a simple program.The hybrid cooking unit was very useful and will have great advantage. The performance of this cooking unit can be controlled effectively by varying the fluid flow rate from collector to thermal storage unit and from thermal storage unit to the heat exchanger.

B. ***Modeling Equations***

The solar cooker can be modelled by considering all the inputs,losses and outputs.The input to the solar cooker is purely from sunlight and the electric supply will be actuated only if the solar power is not sufficient. So for normal analysis,here considering only the solar power input to the collector and the stored heat energy in PCM material as a result of this. Also the temperature distribution of the PCM material surrounding the cooking pot is also assumed to be constant for analysis.

Incoming radiation on collector, $S = I.A$ (1)

where :

I=Total incoming radiation(W/m^2)

A= Net absorber area of tubes(m^2)

After losses,

Total absorbed solar power , $G = (\alpha\tau)\int_0^t I_s \, dt$ (2)

where:

α = Absorptivity of the surface,τ = Transmittivity of the surface,I_S = solar irradiance at some angle inclined from the horizontal surface (W/m^2),t = time period of incidence (hour)

*Let f*1 be fraction indicating the ratio of the total stored heat in PCM to total absorbed radiation

$$f_1 = \frac{Q_{PCM\,stored}}{G} \quad (3)$$

where :

Q_{PCM} stored is the total heat stored in the PCM storage material (kW)

$$Q_{PCMstored} = m\left[C_p(T_m - T_i) + L\,m + C_p\left(T_f - T_m\right)\right] \quad (4)$$

where :

T_i is the initial temperature (^{0}C),T_m is the melting temperature (^{0}C),T_f is the final temperature (^{0}C),m is the mass of heat storage medium (kg),C_p is the specific heat (kJ/kg ^{0}C),L is the latent heat of fusion of PCM material (kJ/kg)

Mass of PCM, $m = V_i\,\rho_{PCM}$ (5)

where :

m= mass of PCM material (kg),Vi = Volume of PCM material (m^3),ρ_{pcm} = Density of PCM material(kg/m^3)

Let f_2 be the fraction defined as the ratio of the total stored heat in the PCM ($Q_{PCMstored}$)to the total heat gain by the heat transfer fluid ($Q_{HTFstored}$)

$$f_2 = \frac{Q_{PCM\,stored}}{Q_{HTF\,stored}} \quad (6)$$

where :

$Q_{HTFstored}$ is the total heat gain by the heat transfer fluid given by

$$Q_{HTF\,stored} = MC_{HTF}\int_0^t (T_{out} - T_{in})dt \quad (7)$$

where :

M is the flow rate of heat transfer fluid,C_{HTF} is the specific heat of heat transfer fluid in kJ/kg ^{0}C,Tout is the heat transfer fluid temperature at the outlet of the ETSC (^{0}C),Tin is the heat transfer fluid temperature at the inlet of the ETSC (^{0}C).Finally fraction (f_3) is the ratio of the total heat gain by the PCM material (Q_{PCM} stored) to the solar irradiance (G), and is defined as

$$f_3 = \frac{Q_{PCM\,stored}}{G} \tag{8}$$

To have the food temperature at the solidifying point of the PCM at 6.00 PM, the energy released by the PCM and food should be equal to the energy loss from the cooker,

$$M_f C_W \left(T_f - T_m\right) + mC_p(T_{PCM} - T_m) + Lm = U_L A(T_f - T_a)\Delta t \tag{9}$$

where :
M_f is the mass of cooking food (kg),C_w is the specific heat of water (kJ/kg ^{0}C),T_f is the food temperature during cooking process (^{0}C),T_m is the melting temperature of PCM (^{0}C),m is the mass of PCM (kg),T_{PCM} is the PCM temperature (^{0}C),L is the latent heat of fusion of PCM material (kJ/kg),T_a is the average ambient temperature (^{0}C),Δt is the time interval in hours,U_L is the heat loss coefficient of cooker (W/m^2 ^{0}C)
Overall efficiency will be the ratio of all inputs and heat content in cooking vessel,

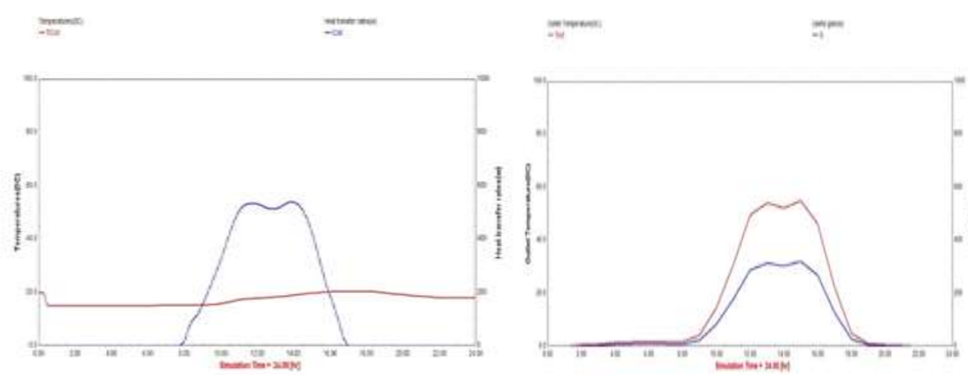
$$\text{Overall } efficiency,\ \eta = \frac{M_f C_W (T_f - T_m)}{G} \tag{10}$$

1. SIMULATION STUDY

A. Solar Cooker Simulation

First of all a normal conventional solar cooker which works only when there is sun shine is simulated using software TRNSYS.Then a hybrid solar cooker consists of an evacuated tube collector,latent heat storage,cooking vessel,pumps and flow rate control is also simulated at the same ambient temperature conditions. The ambient temperature was set at 35^{0}C in both cases. Simulations were done for both for analysing their heat gain and increase in temperature.Conventional solar cooker component models the thermal performance of a theoretical flat plate collector with no heat storage. The entire collector array might consist of collectors connected in series and in parallel. The thermal performance of the entire collector array is decided by the number of modules in series and also the characteristics of every module. This model provides for the theoretical analyses of a flat plate collector. The incident solar radiation is around 500 W/m^2 in both cases,shown in Fig. 3a.The outlet temperature for the month of May is analysed using TRNSYS simulation which is shown in Fig. 3b.
Normal solar cooker characteristics are almost similar to a solar collector which is a default component available in TRNSYS. Hottel-Whillier steady-state model is employed for evaluating the thermal performance. The collector that has an area of 1 m^2 is simulated with water as the heat transfer fluid. From Fig.3b we can understand that a conventional solar cooker can give output temperature of about 60^{0}C during sun shine hours,the useful heat gain is also plotted in it and it is around 350 W. In conventional system,there is no auxiliary sources of heating other than solar radiation. So the output will be purely dependent upon the availability of solar radiation and it is clear from the characteristics of conventional system of solar cooking.

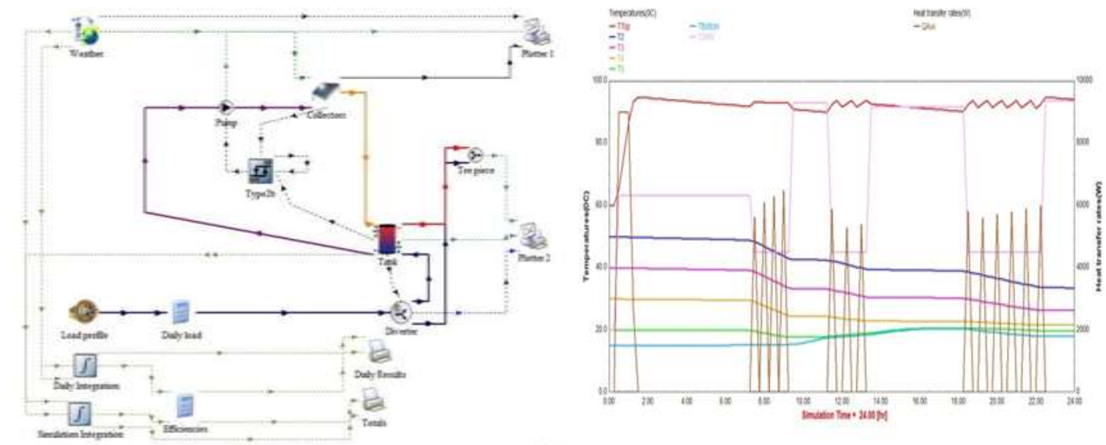
Figure 3:



a)Solar radiation and inlet temperature ***b) Heat gain and outlet temperature of conventional solar cooker***

The simulation model of a hybrid solar cooker is shown in Fig. 4a. It is similar to the basic solar water heater with slight modifications including the provision for auxiliary heating and latent heat storage. Here also water is used as the heat transfer fluid. Simulation time was set for 24hours with same input conditions for both solar cookers,conventional and hybrid. The heat gain at the cooking pot is determined by the difference in inlet and outlet temperatures.In proposed hybrid solar cooking system,the cooking vessel temperature is maintained constant by providing auxiliary heating at the cooking pot.

Figure 4:



a)Simulation model of hybrid cooker in TRNSYS ***b) Temperature distributions,cookingpot temperature and auxiliary heating of hybrid cooker***

The outlet temperature of collector is improved in hybrid system by means of properly controlling the outlet flow rate so that it can reach upto about 50^0C. The cooking pot temperature attained is almost 95^0C in hybrid solar cooker and thus the overall efficiency can be improved. Fig. 4b gives the output characteristics of the hybrid solar cooker obtained in TRNSYS where T_{top} represents the final cooking vessel temperature which is constant throughout the day,that is it is independent of sun shine availability.T_2,T_3,T_4,T_5 and T_{bottom} are the temperatures at different locations around the pot which is surrounded by heat storage material erythyritol which has the ability to store at 119.8^0C. Whenever the actual temperature of cooking vessel falls below a fixed value,say 50^0C the auxiliary heating source(Q_{aux}) will provide sufficient heat to maintain the cooking vessel temperature at 95^0C.

CONCLUSION

Hybrid solar cooking can be a promising technology for cooking of variety of food stuffs for a developing country like India, wherever solar power is plentiful.The hybrid solar cooker is an alternate to rectify the disadvantages of conventional solar cooker and use of maximum accessible solar radiation along with alternate sources. A hybrid cooker with PCM storage and electric heating source was able to store thermal energy in the form of latent heat and sensible heat throughout the daytime and release the same after the sunshine hours. This stored energy will maintain the cooking temperature around 95^0C, therefore, extended the period of cooking during night as well.

The simulation study shows that a hybrid solar cooker can be effectively used for fast and off shine cooking purposes. Increased cooking temperature helps the food stuff to reduce the cooking time which is one of the important positive point. Furthermore, the cooking food is protected from direct sun's radiation, infestation by insects and contamination by dust particles. As a result, the product quality is also high compared to conventional cooker which is exposed.For further improvement of the hybrid cooker, we can use nanofluids as heat transfer fluids instead of water.Nanofluids are having very high values of thermal conductivities over water which can help the cooker efficiency to have better values. Also we can extend the cooker to work as a dryer as well if proper shading techniques are adopted.

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