HYBRID SOLAR COOKING

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ABSTRACT

In the existing traditional solar cookers, the cooking is performed near the collector which may be at an inconvenient location for cooking purposes. This paper proposes a hybrid solar cooking system where the solar energy is brought to the kitchen. The energy source is a combination of the solar thermal energy and the Liquefied Petroleum Gas (LPG) that is very common in kitchens. The solar thermal energy is transferred to the kitchen by means of a circulating fluid like oil. The transfer of solar heat is a two fold process wherein the energy from the collector is transferred first to an intermediate energy storage tank and then the energy is subsequently transferred from the tank to the cooking load. There are three parameters that are controlled in order to maximize the energy transfer from the collector to the load viz. the fluid flow rate from collector to tank, fluid flow rate from tank to load and the diameter of the pipes. The entire system is modeled using the bond graph approach. This paper discusses the implementation of such a system.

1 INTRODUCTION

India is currently the world’s fifth largest consumer of energy, accounting 3.7% of world-wide energy consumption. India faces the challenge of meeting an exponentially raising energy demand with limited conventional energy supply. According to Indian government survey-2001, 52.5% of people use firewood for cooking and LPG (Liquefied Petroleum Gas) is used by 17.5% of the population. Different energy sources for cooking have been evaluated in [1; 2] and LPG stove is found to be the most preferred cooking device in urban parts of India. Half of the world’s population is exposed to indoor air pollution, mainly the result of burning solid fuels for cooking and heating. Wood cut for cooking purpose contributes to the 16 million hectares of forest destroyed annually. The energy for cooking accounts for 36% of the total primary energy consumption. In this regards solar cookers are expected to contribute considerably towards meeting domestic cooking energy requirement in a country like India which is blessed with abundant sunshine [3].

Solar cooker is an environmental friendly and cost effective device for harnessing solar energy. The conventional box type cooker design has been studied and modified since 1980s and various designs and their characteristics have been extensively investigated [4]. Box type cooker [5] with multiple reflectors [6] is easy to build but difficult to use for cooking as it has to be done outdoor. Hot box ovens and concentrating solar cookers are cheap and effective [7]; however they are limited to cooking during clear sky periods and require the cook to work outdoors in rural areas and on roof tops in urban areas. Though parabolic cookers [8] are used for fast cooking, cooking rate cannot be controlled and it is potentially hazardous due to focusing of sun beam. In order to cook during cloudy days or night, either auxiliary source of energy is used or some kind of energy storage facility is provided. Box-type cooker with auxiliary heater inside the box is used to cook during cloudy days [9]. These types of solar cookers do not provide for interactive cooking which is prevalent in the regular cooking procedures of the Indian kitchen.

Solar cooker has not been readily accepted due to the reason that cooking has to be performed outdoor and it is completely dependent on the availability of solar insolation. For a solar cooking system to be accepted and adopted in most of the households, the following objectives have to be satisfied.

1. The cooking should be done without moving out of the kitchen,
2. A reduction in the use of conventional energy,
3. Cooking can be carried out at any time of day/night and
4. Time taken for cooking must be comparable with conventional cooking.

In order to satisfy the above mentioned objectives, a hybrid solar cooking technique has been proposed and designed wherein the solar energy is transferred to the kitchen and supplements the conventional LPG source.

Section 2 describes the proposed cooking system and its operation. Modeling and simulation using bond graph technique is explained in section 3. Hardware implementation of such a cooking system is described in section 4. Results are presented in section 5 and finally concluded in section 6.

2 HYBRID SOLAR COOKING

2.1 System Description

The block diagram of the proposed cooking system is as shown in Fig. 1. The solar thermal collector is in general placed at a high location preferably on the roof top. A cylindrical (linear) parabolic collector, a paraboloid or a concentrating collector is used to collect solar energy and increase the temperature of the fluid above 100°C. The heat exchanger is placed in the kitchen where the cooking is performed. It transfers heat from the circulating fluid to the cooking load. All other components are placed at intermediate levels according to the building re-
requirements. Pump-I is used to vary the flow rate of the fluid through the solar thermal collector. The energy extracted from the sun is stored in the buffer tank. The size of this tank is decided by the amount of energy that needs to be stored for late night or early morning cooking and amount of energy that needs to be saved from the other energy sources of the hybrid system. Whenever food has to be cooked, the stored energy is transferred to the load through the heat exchanger using pump-II, which varies the flow rate of the fluid through the heat exchanger. The auxiliary source of energy like LPG or electrical energy is used for supplementing the stored solar energy and it as well reduces the time required for cooking as compared to previously proposed cooking systems like box-type cooker. Energy required from the auxiliary source is to be optimized for the given system, availability of solar insulation at the location and the load profile. Energy required to run these two pumps are obtained either from a separate photo-voltaic (PV) panel or directly from the grid.

2.2 System Operation

The main goal of the proposed system is to transfer heat from the solar collector to the cooking load. There are two levels of heat transfer with intermediate energy storage in a buffer tank. The heat is first transferred from the solar collector to the storage tank. The pump-I controls the fluid flow rate $q_1$ to control the heat transfer from the collector to tank. At lower flow rates, temperature of the collector and outlet fluid is higher resulting in higher heat loss to ambient. Hence this causes lower collector heat transfer. Increasing the flow rate will not only disturb the density stratification of the fluid in the storage tank, but also requires more energy for pumping the fluid against the hydraulic resistance of the pipes, even though the heat removal factor improves. There exists an optimal flow rate for which it is possible to extract maximum energy from the collector. By dynamically varying the flow rate, maximum energy can be drawn as insolation varies. This optimal flow rate depends on many factors like solar insolation, sizing of pipe, storage tank and collector. Flow rate at which maximum power can be extracted for a given input solar insolation also depends on the characteristic of the centrifugal pump. The maximum power point tracking (MPPT) controller should sense the collected power and accordingly vary the flow rate $q_1$ to the optimal value.

If very small diameter pipes are used, then it increases the hydraulic resistance resulting in pressure drop and hence very poor performance. On the other hand if higher diameter pipes are used, surface area of the pipe increases thereby decreasing the conductive and convective thermal resistance. As a consequence, the efficiency of the system comes down due to increase in conductive and convective heat transfer coefficient between pipe and atmosphere. Thus for a given location and cooking load profile there exist an optimal pipe diameter for which energy extracted is maximal.

Power from the auxiliary source, like LPG or electrical heater is controlled according to the load requirement and availability of the stored energy and solar energy. Energy taken from this source has to be minimized so as to optimize the savings of LPG.

2.3 Maximum Power Point Tracking

Consider a closed loop setup consisting of solar concentrating collector, a fluid pump and a storage tank with thermal insulation. Rate of fluid flow is varied by changing supply voltage given to the pump. At very low flow rate, efficiency of the collector is very less as the outlet temperature is high. On the other hand, when flow rate increases, collector efficiency increases and temperature stratification in storage tank is disturbed. And more power has to be supplied to the pump to increase the flow rate. These two conflicting effects imply the existence of an optimal flow rate that gives optimal energy from sun.

In an active solar system, additional energy is spent on the pump to drive fluid through the collector in order to extract energy from sun. Hence efficiency of the system containing solar collector and pump can be expressed as given in Eq. 1 where $P_d$ is the utilized power, $P_{pump}$ is the power supplied to the pump and $P_{in}$ is the input solar power.

$$
\text{Effective Collector Efficiency} = \frac{\text{Effective Collected Power}}{\text{Input Solar Power}}
$$

$$
\eta_{coll} = \frac{P_d - P_{pump}}{P_{in}}
$$

Performance analysis is carried out for different solar insolation level. As solar insolation is reduced, the optimal flow rate shifts toward lower value. This shows that the optimal flow rate is not same for a given system. It is a function of location and solar insolation at that particular instant. Hence one has to vary the flow rate regularly in order to extract optimal energy from sun. This leads to the concept of maximum power point tracking also known as MPPT.

Second part of the heat transfer heat is from the buffer tank to the cooking load which is being placed in the kitchen. Heat energy is transferred to the load by circulating hot fluid stored in the buffer tank through a heat exchanger. Amount of the heat transferred from the buffer tank to the load depends on the mass flow rate at which fluid is being circulated. As the flow rate $q_2$ increases, amount of the energy transferred also increases. But more power has to be supplied to pump-2 to circulate the fluid against the pressure head. Rate of cooking can be controlled by keeping the flow rate at the desired level. When power supplied from the storage tank is not sufficient, auxiliary source of energy like LPG or electrical energy is used.

2.4 Selection of pipe diameter

Performance of the cooking system is dependent on the diameter of the pipe used for circulation of the fluid. There are two conflicting effects which are dependent on diameter of the pipe.
Consider a pipe of length \( L \) having constant diameter \( D \). Pressure drop across this pipe is given by the Darcy-Weisbach formula [10] as in equation,

\[
p_{\text{pipe}} = \frac{\lambda}{D} L \rho u^2
\]  

(2)

Where, \( u \) is the velocity of the fluid in \( m/s \), \( \rho \) is the density of the fluid and \( \lambda \) is a dimensionless coefficient called the Darcy friction factor or coefficient of line hydraulic resistance, which can be found from a Moody diagram [10]. Darcy friction factor can be calculated depending on the type of the flow (laminar or turbulent). For both laminar and turbulent flow, as the diameter of the pipe decreases, pressure drop across the pipe increases. This increases the burden on the pump which is being used for the circulation. Let \( P_{\text{pump}} \) be the power requirement of the pump considering pressure drop in the pipes.

Heat energy is transferred from collector to storage tank and from storage tank to heat exchanger by circulating heat transfer liquid through pipe. Since temperature of the fluid is much higher than ambient temperature, fluid loses heat energy to ambient. Heat is lost from fluid to pipe by conduction which in turn raises the temperature of the pipe. Heat from pipe is lost to ambient through convection and radiation given by,

\[
P_{\text{loss}} = A_o \left[ h_{pa}(T_{\text{pipe}} - T_{\text{amb}}) + \sigma \varepsilon_o (T^4_{\text{pipe}} - T^4_{\text{amb}}) \right]
\]  

(3)

Where, \( A_o \) is the outer surface area of the pipe, \( h_{pa} \) is the heat transfer coefficient between pipe to ambient, \( \sigma \) is the Stefan-Boltzmann constant, \( T_{\text{pipe}} \) is the temperature of the pipe, \( T_{\text{amb}} \) is the ambient temperature and \( \varepsilon_o \) is the emissivity of the outer surface. It is observed from above equations that the heat loss to ambient is directly proportional to the surface area of the pipe. Hence the heat energy lost is higher if larger diameter pipes are used.

It is observed from the above discussions that \( P_{\text{pump}} \) varies inversely with \( D \) and \( P_{\text{loss}} \) varies directly with \( D^2 \). This implies that there exists an optimal pipe diameter for which \( P_{\text{pump}} + P_{\text{loss}} \) is minimal. For a given solar system, diameter of the pipe is selected in order to minimize the sum of these two power losses. Optimal diameter of the pipe is obtained by solving the equation,

\[
\frac{\partial P_{\text{pump}}}{\partial D} = -\frac{\partial P_{\text{loss}}}{\partial D}
\]  

(4)

3 MODELING AND SIMULATION

The bond graph method is applied to model the proposed dynamic system [11; 12; 13]. The proposed cooking system is a complex multi energy domain system comprising power/energy flow across several domains such as hydraulic, electrical and mechanical. Components like energy sources, energy dissipating elements, kinetic and static energy storage elements are connected using bonds, which represents the energy exchange. In bond graph methodology, the various physical variables in the multi-domain environment are uniformly defined as generalized power variables such as effort \( (e) \) and flow \( (f) \). The product of these two variables is the power. In the hydraulic domain, pressure is the effort variable and flow rate is the flow variable. Similarly voltage-current and temperature-entropy rate are the effort-flow pairs in the electrical and the thermal domains respectively. At the 0-junction, the flow variable from all the bonds add up to zero and each bond shares the same effort decided by the flow causal bond. Similarly efforts in all the bonds add up to zero having same flow at the 1-junction.
tical input acts like a sun emulator, which gives energy equivalent to energy obtained from the sun. Bond 1 is in electrical domain having voltage $V_{in}$ and current $I_{in}$, where as bond 2 is in thermal domain with $T_{coil}$ as effort and $S_{2}$ as flow variable. Resistance field $R_1$ represents the energy transfer between electrical and thermal domain without any entropy generation. Energy gets stored in the mass of the coil which acts as a thermal capacitance represented by $C_{coil}$. Temperature of this coil is one of the state variables in the system. Part of the energy is lost to ambient through the field $R_2$, since temperature of the coil is higher than ambient temperature.

Fluid is circulated through the coil at a rate as determined from the hydraulic model of Fig. 3. Modulated effort source $mS_{2}$ which gives the hydraulic pressure difference $P_{1}$ due to the heater coil and the outlet fluid. Another pressure source $P_{2}$ represents the pressure head developed by the pump-1. Kinetic storage element $L_{s1}$ decides the flow rate $f_{1}$ in the collector side. As density of the fluid varies with the change in temperature, pressure $P_{1}$ changes. Resistance $R_{s}$ accounts for the pressure drop in the storage tank, which is common to both collector side and load side hydraulic loops. Similar to collector side, fluid is circulated through the heat exchanger using pump-2. Flow rate $f_{2}$ is decided by the kinetic storage element $L_{s2}$. Pressure drop across the heat exchanger and the fluid outlet from that are combined together and represented as field $R_{s1}$ and $R_{s2}$.

Referring to Fig. 2, $C_{s}$ represents the thermal capacitance of the heat storage tank including the fluid in the inlet pipe to the heater. Thermal capacitance of the fluid in the outlet pipe from the heater is represented as $C_{s1}$. Entropy flow rate through the field $R_{3}$ accounts for the energy transferred from coil to $C_{s1}$. Outlet pipe fluid is modeled as thermal capacitance as it can store energy by a raise in the temperature. Energy is transferred from $C_{s1}$ to $C_{s}$ through the field $R_{5}$. Flow rate $f_{1}$ as determined from the hydraulic model of Fig. 3, decides the energy transferred from the coil to the buffer. From the fluid in the outlet pipe to the heater, $C_{s}$ and the storage tank $C$, part of the entropy flows to ambient through the fields $R_{6}$ and $R_{3}$ respectively.

Circulation of fluid on load side transfers energy to the load through the heat exchanger. $C_{s2}$ represents the thermal capacitance of the fluid in outlet pipe from the heat exchanger. Entropy flow rate through the field $R_{8}$ transfers energy from the heat storage tank to $C_{s2}$. From $C_{s2}$ part of the energy is lost to ambient through the field $R_{9}$ and remaining is transferred to the load through $R_{7}$. Whenever this energy is not sufficient for cooking, remaining energy requirement is fulfilled using auxiliary source of energy. The energy from $V_{aux}$, which is fed through the field $R_{9}$, represents the auxiliary source.

From the model, non-linear state equations are obtained, which help in characterizing dynamics of the system. A laboratory of the cooking system is built and different parameters of the bond graph model [14] are estimated for this setup. Using these parameters, this model is simulated and validated experimentally. Effects of the flow rate and the pipe diameter on the solar power collected and the utilized power can be explained. This mathematical model can be used for both analysis and synthesis of a heat transfer system for cooking.

4 IMPLEMENTATION

The block diagram of the experimental setup for the solar cooking system is as shown in Fig. 4. Paraboloid dish concentrator is used to focus sun rays onto the receiver. Polished/anodized aluminium sheets are used as reflecting material. A linear actuator is fixed to the paraboloid with a lever system in such a way that when actuator moves to and fro, the paraboloid is rotated in east-west direction. Using an accelerometer sensor which is fixed on the paraboloid, the tilt angle is sensed. Early in the morning, the concentrator is fixed towards the sun manually. The sensor considers this as the reference angle and tracks at the constant angular rate of 15° angle per hour.

A coil made of copper tube is placed at the focus of the parabola in order to receive the heat. Servo-therm oil is circulated through the collector to absorb the heat energy from sun. Stainless steel pipes with glass wool insulation over that is used for circulation of the oil from the collector to the tank. Thermocouples (TC) are placed to measure temperature of oil entering and leaving the receiver. A rotary pump is used to circulate oil through the receiver and put back into the heat storage tank. The pump is driven by a permanent magnet DC (PMDC) motor, which is controlled by a variable voltage power supply. Heat storage tank is made of stainless steel material with good thermal insulation around that for better retention of heat. Flow rate of the fluid is measured using flow meter specially designed for very low flow measurement.

On the load-side, hot oil from top of the heat storage tank is taken directly to kitchen through thermally insulated stainless steel tube. Heat is transferred from the oil at higher temperature to cooking load using heat exchanger. Helical shaped coil made of copper is wound around the cooking vessel with thermal insulation around it to constrain the heat within the heat exchanger. Oil leaving the heat exchanger is pumped back from the kitchen to the buffer tank using another similar pump-motor drive. Mass flow rate on the load-side is measured using a flow meter. Thermocouples (TC) are placed at different places as shown in Fig. 4.
5 RESULTS

Figure 5. Variation in effective collector with flow rate for different pipe diameters

Different parameters of the cooking system are obtained experimentally from the lab prototype system. These estimated parameters are used in the bond graph simulation. The system has been modeled and simulated in Matlab-Simulink. Simulation is carried out for different flow rates on the collector side keeping the input power at 625W. Effective collected power is the power collected from the solar collector excluding the power spent for circulation of fluid. Effective collector efficiency \( \eta_{coll} \) is calculated for different flow rates by varying the input voltage to the pump-1 and plotted as shown in Fig. 5. The voltage applied to pump-1 is initially zero, which implies that the pressure in the pipes correspond to the thermosyphon pressure. As the flow rate increases, heat loss to the ambient is reduced improving efficiency of the collector. But above some flow rate, one needs to spend more energy for the circulation against pressure drops. Simulation is carried out for different diameters of the pipe. At optimal flow rate, there is about 6% increase in efficiency as compared to thermosyphon flow rate. As diameter of the pipe is decreased, the efficiency curve moves up. This is due to the decrease in the pipe exposure area which presents a higher thermal resistance for the entropy flow to the ambient. Similarly overall efficiency of the system is plotted against the flow rate for different pipe diameters as shown in Fig. 6.

5.1 Estimated energy savings

In a typical Indian household of five members, one LPG cylinder lasts approximately 1 month. One LPG cylinder containing 14 kg of LPG implying about 170 kWh of energy. Thus in a month 170 kWh of energy is utilized for cooking purposes by a typical Indian household. A 1m radius paraboloid has a cross section area of around 3.14 m\(^2\) presented to the sun. At an average irradiance of 5 kWh/m\(^2\)/day, the amount of energy incident on the surface for a month of 30 days is 471 kWh. Considering the overall conversion efficiency as 20% (typical), about 90 kWh is available every month. Thus the LPG should last twice as long if used with the proposed system.

6 CONCLUSION

Hybrid solar cooking has been proposed wherein the solar energy is transferred to the kitchen and supplements the conventional cooking source like LPG. Energy is stored in the heat storage tank so that cooking can be done at any time of the day and time taken for cooking is comparable with the conventional method. Control over the rate of cooking is possible with the proposed cooking technique. The concept of maximum power point tracking has been discussed where flow rate of fluid is continuously changed according to the available insolation in order to maximize the energy collected from sun. Practical implementation of such a system has been explained. Entire system is modeled using bond graph technique and effects of flow rate and pipe diameter on the solar power collected and the utilized power are discussed in this paper.

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NOMENCLATURE

\( A_o \) Outer surface area of the pipe \( [m^2] \)
\( C_{c1} \) Thermal capacitance of fluid outlet from heat storage tank \( [J/K] \)
\( C_{c2} \) Thermal capacitance of fluid outlet from heat exchanger \( [J/K] \)
\( C_c \) Thermal capacitance of heat storage tank \( [J/K] \)
\( C_{coll} \) Thermal capacitance of collector \( [J/K] \)
\( C_{Load} \) Thermal capacitance of load \( [J/K] \)
\( D \) Diameter of the pipe \( [m] \)
\( h_{psu} \) heat transfer coefficient between pipe to ambient \( [W/m^2K] \)
\( I_{aux} \) Equivalent input current from auxiliary source \( [A] \)
\( I_{in} \) Equivalent input current from solar energy \( [A] \)
\( L \) Length of the pipe \( [m] \)
\( P_{in} \) Input solar power \( [W] \)
\( P_{loss} \) Power loss to ambient from the pipe \( [W] \)
\( P_{pipe} \) Pressure drop across the pipe \( [Pa] \)
\( P_{pump} \) Power supplied to the pump \( [W] \)
\( P_u \) Utilized power \( [W] \)
\( q_1 \) Flow rate on collector side \( [m^3/s] \)
\( q_2 \) Flow rate on load side \( [m^3/s] \)
\( R \) Thermal coefficient between two thermal capacitances \( [K/W] \)
\( T_{amb} \) Ambient temperature \( [K] \)
\( T_{c1} \) Temperature of thermal capacitance \( C_{c1} \) [K]
\( T_{c2} \) Temperature of thermal capacitance \( C_{c2} \) [K]
\( T_c \) Temperature of thermal capacitance \( C_c \) [K]
\( T_{coil} \) Temperature of collector [K]
\( T_L \) Temperature of load [K]
\( T_{pipe} \) Temperature of the pipe [K]
\( u \) Velocity of the fluid [m/s]
\( V_{in} \) Input voltage equivalent to solar energy [V]
\( V_{aux} \) Input voltage equivalent to auxiliary source [V]
\( \dot{q}_1 \) Flow rate on the collector side [m\(^3\)/s]
\( \dot{q}_2 \) Flow rate on the load side [m\(^3\)/s]
\( \eta_{coll} \) Effective collector efficiency
\( \lambda \) Darcy friction factor
\( \rho \) Density of the fluid

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