

## Energy Optimization and Modeling of Hybrid Solar Cooking with Heat Mass Transfer Control using Bond Graph Technique

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### ABSTRACT

In the 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 water. 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. In order to raise the temperature of the fluid, pressure regulators are used which avoids the water from boiling. The entire system is modeled using the bond graph approach. The modeled system is simulated and the results are presented.

**Keywords:** Solar cooking, Mass transfer, Hybrid solar cooking, Bond graph modeling, Flow optimization

### 1. INTRODUCTION

The energy for cooking accounts for 36% of the total primary energy consumption. The cooking energy demand in rural areas of developing countries is largely met with bio-fuels such as fuel wood, charcoal, agricultural residues and dung cakes, whereas Liquefied Petroleum Gas (LPG) or electricity is predominantly used in urban areas. Different energy sources for cooking have been evaluated in [1-3] and LPG stove is found to be the most preferred cooking device in India. Solar cookers are expected to contribute considerably towards meeting domestic cooking energy requirement in a country blessed with abundant sunshine [4].

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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 continuously since 1980s and various designs and their characteristics have been extensively investigated in [5]. Hot box ovens [6] and concentrating solar cookers are cheap and effective; however they are limited to cooking during clear sky periods. Solar cooking with energy storage using pressurized water vessel [7], phase change material [8] and box-type solar cooker with auxiliary heating [9] are proposed previously, which require the cook to work outdoors in rural areas and on roof tops in urban areas. A split-system solar cooker exists, which has its flat-plate collector outdoors and the cooking chamber inside the kitchen, with heat pipes transferring the energy between the two [10].

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 kitchens
2. A reduction in the use of conventional energy
3. Cooking can be carried out at any time of day
4. Time taken for cooking must be comparable with conventional cooking

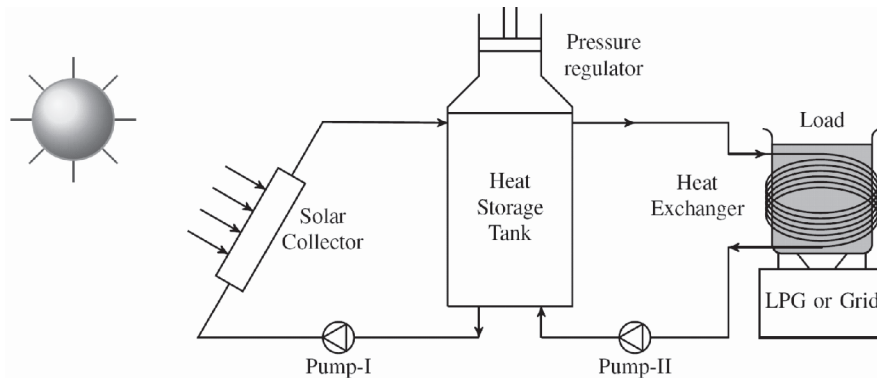
In order to satisfy the above mentioned objectives, a hybrid solar cooking technique is proposed wherein the solar energy is transferred to the kitchen and supplements the conventional LPG source. In section 2 we are describing the proposed cooking system. Modeling and simulation using bond graph technique is explained in section 3. The results are discussed in section 4 and finally concluded in section 5.

## 2. HYBRID SOLAR COOKING

### 2.1 System Description

The block diagram of the cooking system is as shown in the Fig. 1. The solar collector is in general placed at a high location preferably on the roof top. A cylindrical parabolic collector, a paraboloid or a flat plate collector is used to collect solar energy and increase the temperature of water. The heat exchanger is placed in the kitchen where the cooking is done. It transfers heat from the circulating fluid to the cooking load. All other components are placed at intermediate levels according to the building requirements. Pump-I is used to vary the flow rate of the water through the solar thermal collector. The energy extracted from the sun is stored in the buffer tank. 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. The buffer tank has an air column on top of it. As temperature increases, water density will decrease and hence it will expand in volume. A pressure regulator will vary the pressure in storage tank in order to increase the boiling point of water above the tank temperature and hence avoids water from boiling. It is possible to increase the water temperature to much above 100°C by increasing the pressure in the tank. Whenever food has to be cooked, the stored energy is transferred to the load through the heat exchanger using pump-II, which will vary 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 will as well reduce 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 insolation at the location and the load profile.



**Fig. 1** Block diagram of the hybrid solar cooking system

## 2.2 System Operation

The central goal of the proposed system is to transfer heat from the solar collector to the 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  $\dot{q}_1$  to control the heat transfer from the collector to tank. At lower flow rates, temperature of the collector and outlet water 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 water 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 sun. By dynamically varying the flow rate, maximum energy can be drawn as insolation varies. This optimal flow rate depends on many factor 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  $\dot{q}_1$  to the optimal value.

If we use very small diameter pipes, then it increases the hydraulic resistance resulting in pressure drop and hence very poor performance. On the other hand if we go for higher diameter pipes, 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 solar energy. Energy taken from this source has to be minimized so as to optimize the savings of LPG.

### 3. MODELING AND SIMULATION

The bond graph method is applied in this paper to model the system [11-13]. A hybrid solar cooking system is a complex multi energy domain system comprising power/energy flow across several domains such as electrical, thermal, and hydraulic. 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 entire system can be represented by the bond graph model that is shown in Fig. 2 and state space equations are obtained from this by inspection [11-13]. We are giving electrical input equivalent to the solar energy available from the absorber to a  $R_1$  field, which transfers energy to thermal domain.  $C_{coil}$  represents the thermal capacitance of absorber plate. Eq. (1) shows that part of the energy from this capacitance is lost to ambient and remaining to raise the water temperature. Thermal capacitance of outlet water from the collector is represented as  $C_1$ . Dynamics of the temperature of the storage tank  $T_C$  is given in Eq. (3).  $C_{rad}$  and  $C_2$  are the thermal capacitance of the heat exchanger and the water outlet from that respectively, whose characteristic equations are given by Eqs. (4)-(5). Cooking load  $C_{load}$  is getting energy from the auxiliary source such as electrical or LPG and from the heat exchanger as seen in Eq. (6).

Flow rates  $\dot{q}_1$  and  $\dot{q}_2$  are obtained from hydraulic domain of the bond graph model. Modulated effort source  $P_1$  is the pressure across the collector which is a function of water temperature.  $P_4$  and  $P_3$  are the pressures across the storage tank and the capacitance  $C_1$  respectively, which are dependent on the temperatures  $T_{coil}$ ,  $T_{C1}$ ,  $T_C$  and density of water at that temperature. Pressure drop in pipe  $P_{pipe}$  is a function of flow rate, diameter and length of the pipe. Flow rate  $\dot{q}_1$  is decided by the characteristic of the pump used and  $P_2$ , the pressure developed by it. Resistor field  $R_{rad}$  represents the hydraulic resistance of the heat exchanger. Similarly flow rate  $\dot{q}_2$  is obtained from the Eq. (8) using temperatures of different thermal capacitances obtained from the thermal domain. State equations obtained from the bond graph model are as follows,

$$\frac{dT_{coil}}{dt} = \frac{1}{C_{coil}} \left[ \frac{V^2}{R_1} - \frac{T_{coil} - T_{amb}}{R_2} - \frac{T_{coil} - T_{C1}}{R_3} - (T_{C1} - T_C)\dot{q}_1 C_p \rho \right] \quad (1)$$

$$\frac{dT_C}{dt} = \frac{1}{C_1} \left[ \frac{T_{coil} - T_{C1}}{R_3} - \frac{T_{C1} - T_{amb}}{R_4} \right] \quad (2)$$

$$\frac{dT_C}{dt} = \frac{1}{C} \left[ (T_{C1} - T_C)\dot{q}_1 C_p \rho - (T_C - T_{C2})\dot{q}_2 C_p \rho - \frac{T_C - T_{amb}}{R_5} \right] \quad (3)$$

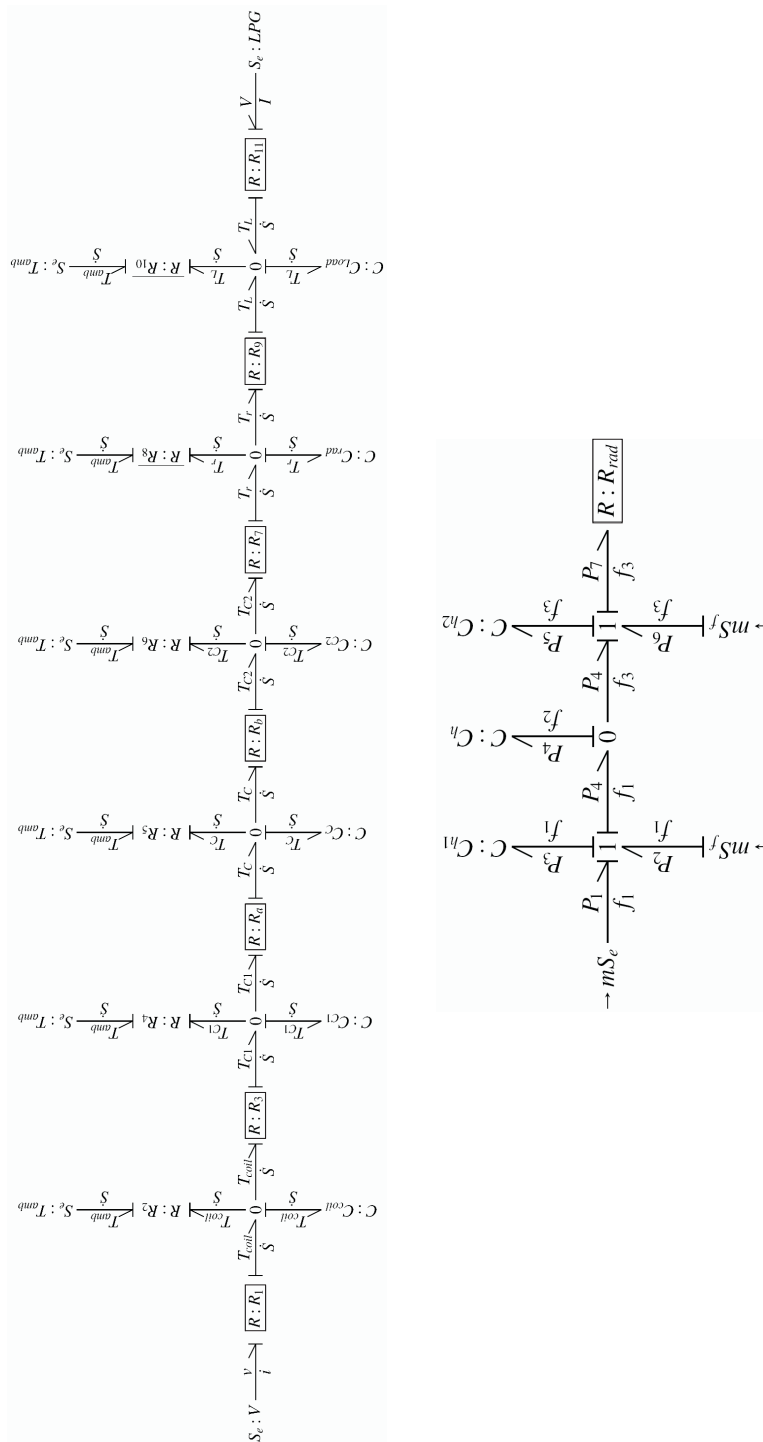


Fig. 2 Bond graph model of the system

$$\frac{dT_{C2}}{dt} = \frac{1}{C_2} \left[ (T_C - T_{C2}) \dot{q}_2 C_p \rho - \frac{T_{C2} - T_{amb}}{R_6} - \frac{T_{C2} - T_r}{R_7} \right] \quad (4)$$

$$\frac{dT_r}{dt} = \frac{i}{C_{rac}} \left[ \frac{T_{C2} - T_r}{R_7} - \frac{T_r - T_{amb}}{R_8} - \frac{T_r - T_L}{R_9} \right] \quad (5)$$

$$\frac{dT_L}{dt} = \frac{1}{C_{load}} \left[ \frac{(V_{aux})^2}{R_{11}} + \frac{T_r - T_L}{R_9} - \frac{T_L - T_{amb}}{R_{10}} \right] \quad (6)$$

$$\dot{q}_1 = \frac{1}{R_{pump1}} [P_1 + P_2 - P_3 - P_4 - P_{pipe}] \quad (7)$$

$$\dot{q}_2 = \frac{1}{R_{pump2}} [P_6 + P_4 - P_5 - P_7 - P_{pipe}] \quad (8)$$

#### 4. RESULTS

The model shown in Fig. 2 is simulated using the bond graph toolbox in MATLAB-Simulink. Simulation is carried out for different pipe diameters and the flow rate  $\dot{q}_1$  is varied by changing the voltage applied to the centrifugal pump. Input power to the system is kept constant at 625W throughout the simulation which is approximately the available solar energy incident on the collector.

System efficiency is taken as ratio of power delivered to the load to the input power and the collector efficiency is taken as ratio of collected power to the input power. The voltage applied to the centrifugal pump is initially zero, which implies that the pressure in the pipes correspond to the thermosyphon pressure. From Fig. 3, we can observe that as the flow rate increases, the collector and the system efficiency increases. At higher flow rate it decreases due to increasing requirement of power by the pump. 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.

#### 5. CONCLUSION

Hybrid solar cooking has been proposed wherein the solar energy is transferred to the kitchen and supplements the conventional LPG source. Cooking can be carried out at any time of the day with time taken comparable to conventional systems. Effects of flow rate and pipe diameter on the solar power collected and the utilized power are discussed. The bond graph approach to model the overall system has been presented in the paper.

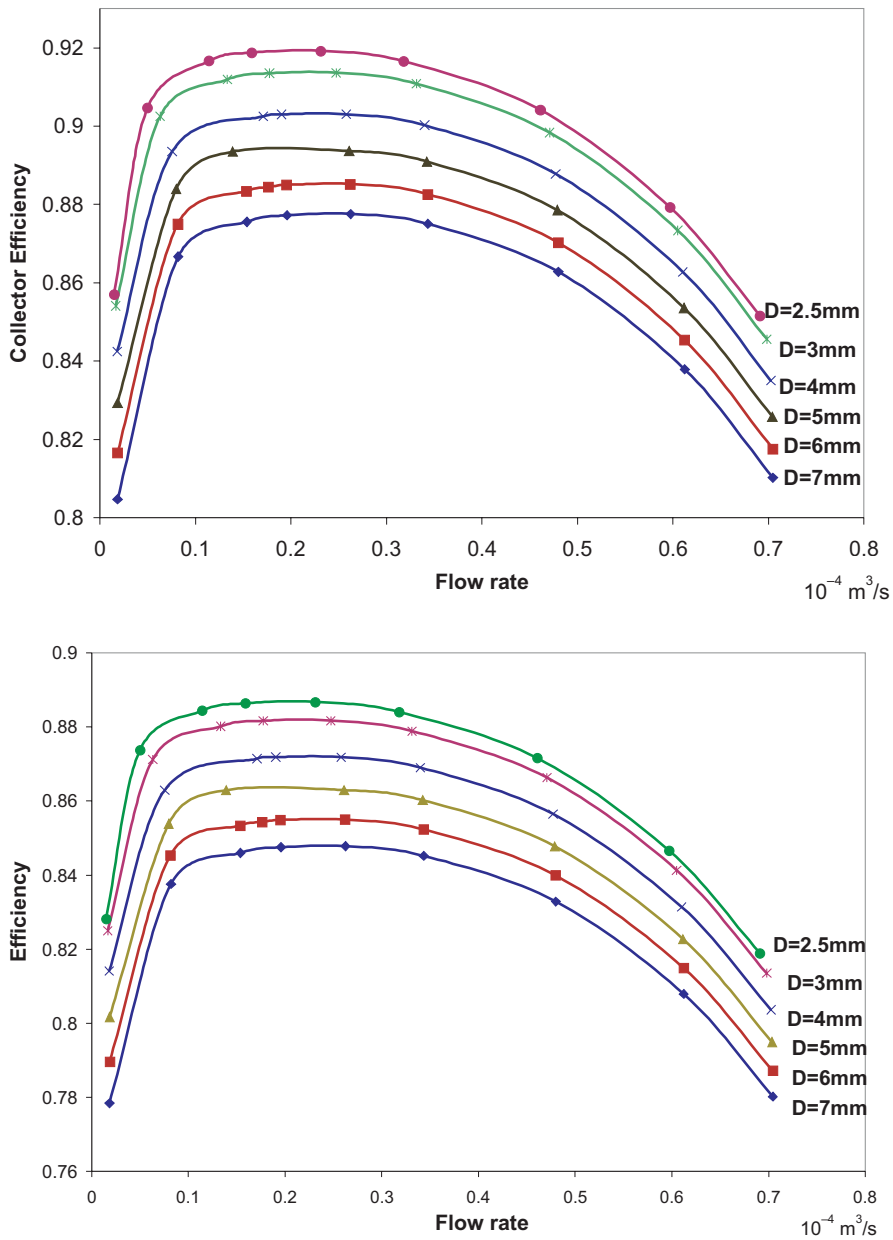


Fig. 3 Variation in collector and overall efficiency with flow rate for different pipe diameters

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