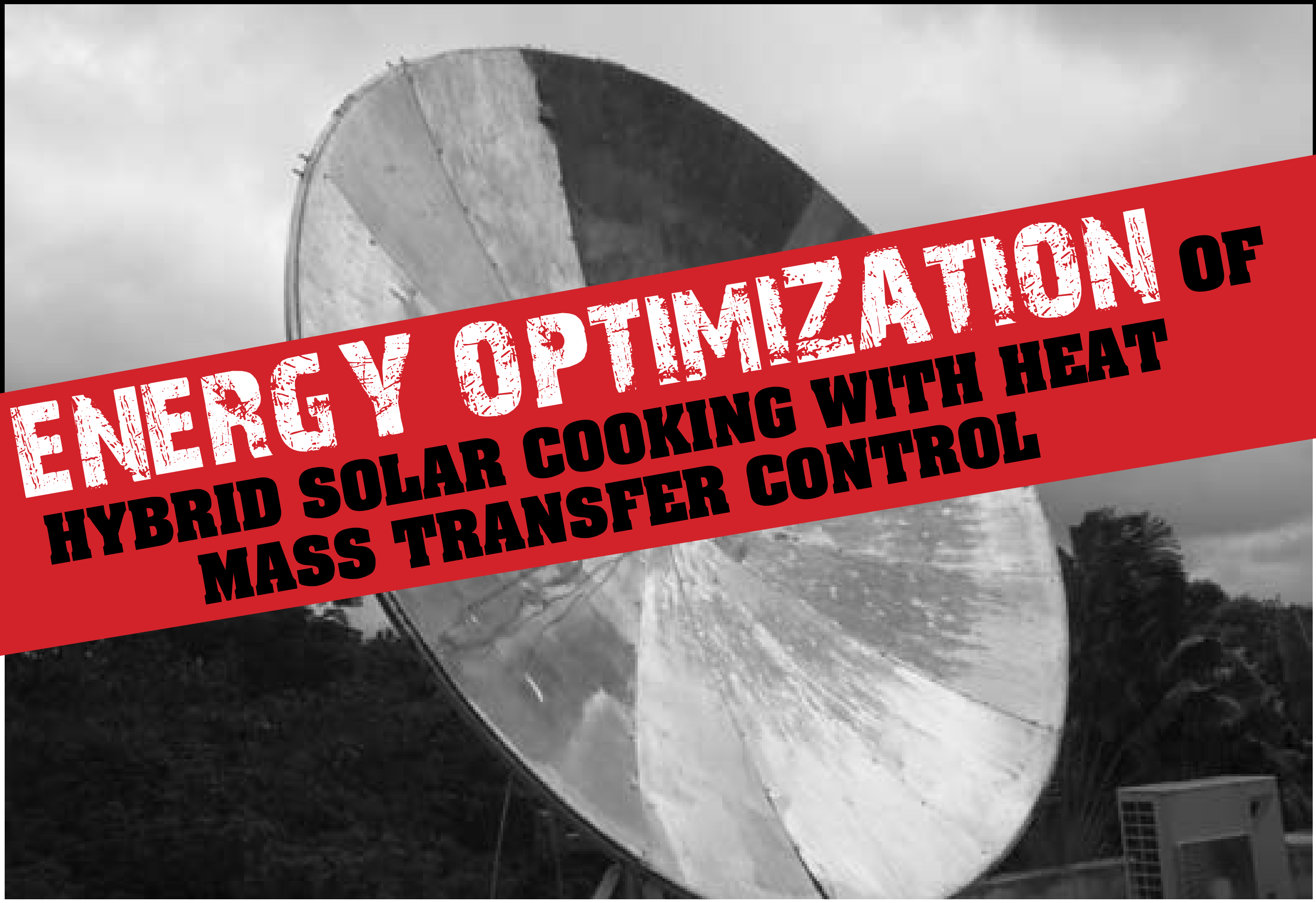

ENERGY OPTIMIZATION OF HYBRID SOLAR COOKING WITH HEAT MASS TRANSFER CONTROL

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India is currently the world's fifth largest consumer of energy, accounting for 3.7% of worldwide energy consumption. The energy for cooking accounts for 36% of the total primary energy consumption. The wood cut for cooking purpose contributes to the 16 million hectares of forest destroyed annually. The cooking energy demand in the rural areas of developing countries is largely met with biofuels such as fuel wood, charcoal, agricultural residues, and dung cakes, whereas LPG (Liquefied Petroleum Gas) and electricity are predominantly used in urban areas. Different energy sources for cooking have been evaluated and LPG stoves were found to be the most preferred cooking device in India.

According to an Indian government survey, in 2001, 52.5% of people use firewood for cooking, while LPG is used by 17.5% of the population. Half of the world's population is exposed to indoor air pollution, mainly the result of burning solid fuels for cooking and heating.

In this regard, solar cookers are expected to contribute considerably towards meeting the domestic cooking energy requirement in a country like India, which is blessed with abundant sunshine. On an average, India receives 5 kWh/day/m^2 of sunlight for more than 300 days of a year. Solar cooker is an environment-friendly and cost-effective device for harnessing solar energy.

The conventional box type cooker design has been studied and modified since the 1980s and various designs and their characteristics have been extensively investigated. Box type cooker with multiple reflectors are 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. 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 are used for fast cooking, the cooking rate cannot be controlled, and it is potentially hazardous due to the focusing of sun beam. 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 by the Indians due to the reason that cooking has to be done outdoor and it is completely dependent on the availability of solar insolaton.

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. It should reduce the use of conventional energy.
3. Cooking can be carried out at any time of day/night.
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.

System description and operation

The block diagram of the proposed cooking system is shown in Figure 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. 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 fluid through the solar thermal collector.

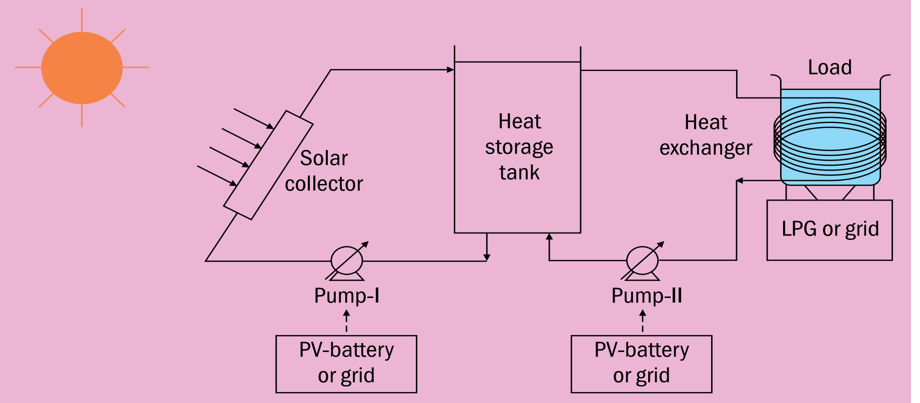

Figure 1 Block schematic of the hybrid solar cooking system

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 the amount of energy that needs to be saved from 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. This also reduces the time required for cooking, as compared to the previously proposed cooking systems like box-type cookers. Energy required from the auxiliary source is to be optimized for the given system based on the availability of solar insolation at the location and the load profile.

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. Pump-I controls the fluid flow rate q1 to control the heat transfer from the collector to tank. At lower flow rates, the 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 necessitate 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, and sizing of pipe, storage tank, and collector. The 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 MPPT (maximum power point tracking) controller should sense the collected power and accordingly vary the flow rate q1 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 we go for higher diameter pipes, surface area of the pipe increases, which decreases the conductive and convective thermal resistance. As a consequence, the efficiency of the system comes down

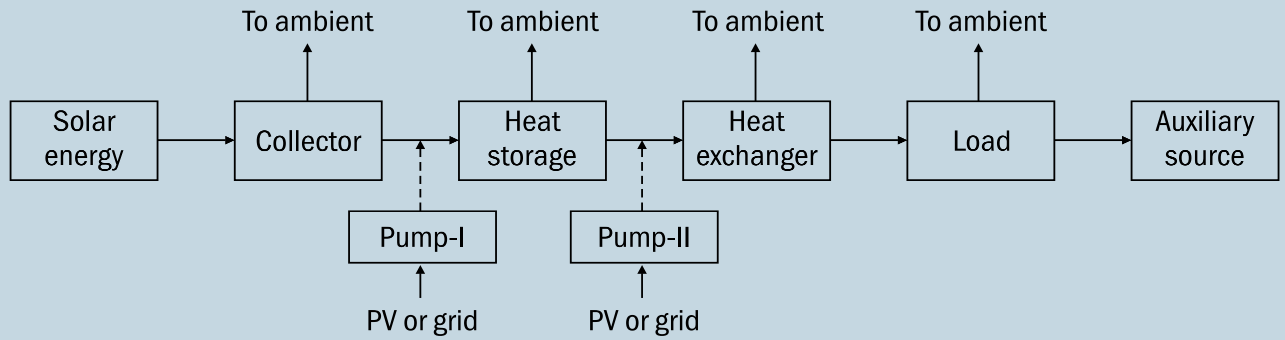

Figure 2 Energy flow diagram of the system

due to increase in conductive and convective heat transfer coefficient between the pipe and the atmosphere. Thus, for a given location and cooking load profile, there exists 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.

Figure 2 shows the energy flow in the described cooking system. Solar thermal collector absorbs solar energy, which is used to heat up the fluid. During this process, part of the energy is lost to ambient and the remaining energy is stored in the heat storage tank as buffer. The heat transferred from solar energy to the storage tank is dependent on the flow rate of the circulating fluid. This heat transfer rate is controlled by using a hydraulic pump. Energy is transferred from the storage tank to the load through the heat exchanger. This flow of energy is controlled by the flow rate of fluid through the heat exchanger. Energy requirement for the load, in addition to solar energy, is provided by the auxiliary source of energy like LPG or electrical energy. The load temperature requirements of typical Indian households is as follows.

Table 1 Temperature set points for cooking

Temperature in °C	*Application*
65	Keeping liquids hot
85	Simmering of food
95	Boiling of food
116	Steam pressure cooker
175	Deep frying

The proposed system is a complex multi-energy domain system comprising of energy flow across several domains such as thermal, electrical, and hydraulic. The entire system is modelled using the bond graph approach with seamless integration of the power flow in these domains. It is simulated and the results are validated experimentally.

Design

Hybrid solar cooking system is being setup to supply the energy requirement of a canteen near CEDT (Centre for Electronic Design and Technology) at IISc (Indian Institute of Science), Bangalore. Paraboloid solar concentrator is used to raise the temperature of servotherm oil, which is used as heat transferring fluid. Anodized aluminium sheets are used to reflect sunlight on to the receiver, which is fixed at the focus of the paraboloid, as shown in Figure 4. Linear actuator controls the angle of tilt made by the paraboloid in order to track the Sun continuously.

A stainless steel pipe with thermal insulation is used to carry hot fluid from heat storage tank to the receiver and back to the buffer tank. The buffer tank is made up of stainless steel and thermally insulated using mineral wool. Servotherm oil is circulated through the concentrator using a rotary gear pump. On the load side circulation, hot oil is circulated from the heat buffer through the heat exchanger using another pump. Temperature sensors are placed at different points to measure the temperature. Flow rate of the collector side and the load side circulation is measured using two flow meters. Figure 3, 4, and 5 show the experimental setup of the cooking system.

(a) buffer tank, (b) buffer-collector pump, (c) buffer-load pump, (d) heat exchanger, (e) flow meter

Figure 3 Experimental setup of the cooking system

Figure 4 Solar parabolic collector

Figure 6 Lab prototype of the solar cooking system

Results and discussions

Experiments have been carried out on a small-scale laboratory prototype as shown in figure 6. The temperature at different parts of the system is measured. Experimental results are compared with the simulation results within 5% error. Effective collector efficiency and overall system efficiency is calculated for different flow rates and different pipe diameters from the bond graph model as shown in figure 7 and 8.

Figure 5 Experimental setup

Estimated energy savings

In a typical Indian household of five members, one LPG cylinder lasts approximately a month. One LPG cylinder containing 14 kg of LPG contains 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 5kWh/m^2/day, the amount of energy incident on the surface for a month of 30 days is 471kWh. Considering the collection efficiency as 20% (typical), about 90kWh is available every month. Thus, the LPG should last twice as long if used with the proposed system.

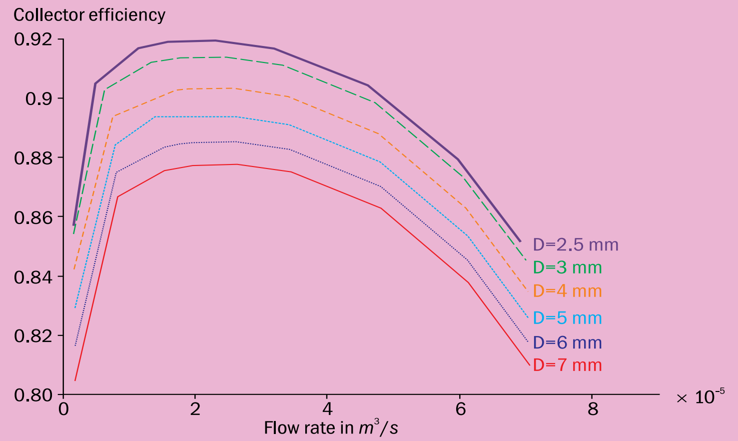

Figure 7 Variation in effective collector efficiency

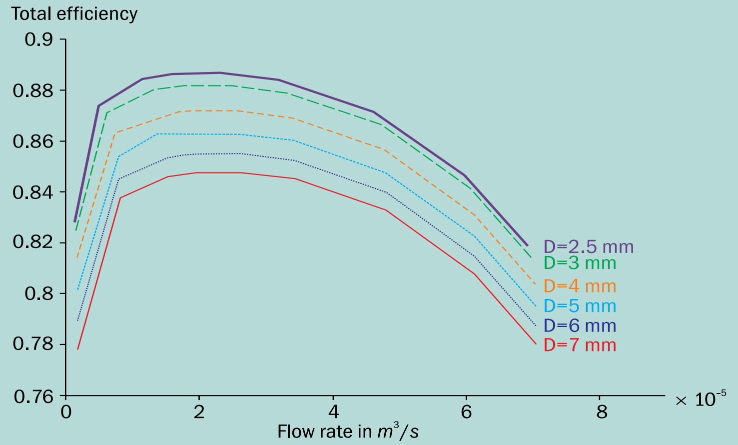

Figure 8 Variation in overall efficiency

Conclusion

The hybrid solar cooking device has been designed to bring solar energy directly to the kitchen. Using heat storage buffer, cooking can be carried out at any time of the day or night. The user need not have to completely depend on solar insolation, as the remaining energy is supplied by conventional source of energy like LPG or electrical.