EVALUATION OF EFFICIENCY FOR SOLAR COOKER USING ENERGY AND EXERGY ANALYSES

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Abstract
This paper presents the importance and usefulness of exergy analysis for evaluating and comparing solar cookers in meaningful ways. The thermodynamic considerations required for the development of rational and meaningful methodologies for the evaluation and comparison of the efficiency of the solar cookers were defined. Energy and exergy equations were also developed to obtain energy and exergy efficiencies of the solar cookers. The evaluation of the solar cookers requires a measure of efficiency, which is rational, meaningful and practical. Exergy analysis provides an alternative means of evaluating and comparing the solar cookers. Since exergy is a measure of the quality or usefulness of energy, exergy efficiency measures are more significant than energy efficiency measures, exergy analysis should be considered in the evaluation of the solar cookers.

Keywords: *Solar cooker, energy and exergy efficiency*

1. INTRODUCTION

Cooking is major necessity for people all over the world. The problem arises when fuel is either scarce or highly expensive. The problems are encountered more pronounced in most developing countries, and in particular in villages and rural areas. Cooking accounts for a major share of energy consumption in developing countries. Most of the cooking energy requirement is met by non-commercial fuels such as firewood, agricultural residues or animal dung in rural areas. The cutting of firewood causes deforestation that leads to desertification. In Turkey, almost the whole country is supplied with electricity in addition to the availability of other primary fuels such as solar energy, kerosene, natural gas and but gas. These are all used for cooking purposes. However, the problem of energy cost and its continuous increase made people, not only in rural areas and villages but also in cities, accept the use of alternative energy sources.

There is a critical need for development of alternative, appropriate, affordable methods of cooking for use in developing countries. Fortunately, Turkey is blessed with abundant solar radiation. Turkey lies (between 36° and 42°N latitudes) in the sunny belt of the world. The sunshine period of Turkey is 2 624 h/year with a maximum of 365 h/month in July and a minimum of 103 h/month in December. The main solar radiation intensity is about 3.67 kWh/m^{2}day, which is sufficient to provide adequate energy for solar thermal applications. Cumulative total of this is about 1311 kWh/m^{2}year. The amount of the solar radiation received on the all over of Turkey, in other words gross solar energy potential is 3 517 EJ/year [41]. In spite of this high potential, solar energy technologies are not now widely used, except for flat-plate solar collectors. They are only used for domestic hot water production, mostly in the sunny coastal regions. In 1998, about 3.0 million m^2 solar collectors were produced and it is predicted that total solar energy production is about 0.080 million ton of oil equivalent.

There are very favorable climatic conditions in Turkey for all solar energy applications. Thus, all solar energy applications are recommended to harness such enormous energy. Solar cookers seem to be a good substitute for cooking with firewood for widespread use in country. All kind of foods can be cooked in the solar cookers in a reasonable time. Solar cookers can be used in many areas of Turkey, especially in Southeastern Anatolia. The use of solar cookers would help in conservation of conventional fuels, such as firewood, animal dung and agricultural residues in rural areas of Turkey, and liquid petroleum gas (LPG), kerosene, electricity and coal in the urban districts. Conservation of firewood helps in preserving the ecosystems, and animal residues could be used as fertilizer, which could aid in the increase of production of agricultural products. Moreover, the use of the solar cooker would result in the reduction of the release of CO_2 into the environment. The evaluation of the solar cookers requires a measure of efficiency, which is rational, meaningful and practical. The energy efficiency of a solar cooker, the ratio of the energy gained by the solar cooker to the energy originally delivered to the solar cooker, conventionally is used to measure solar cooker efficiency. Exergy efficiency account for the temperatures associated with energy transfers to and from the solar cooker, as well as the quantities of energy transferred, and consequently provide a measure of how nearly solar cooker approach ideal efficiency. The main purposes of the present work were: (1) to apply an energy and exergy analyses for the solar cookers; (2) to develop a realistic and universal model for predicting solar cooker performance; and (3) to define the thermodynamic considerations required for the development of rational and meaningful methodologies for the evaluation and comparison of the efficiency of the solar cookers.

2. EVALUATING THE EFFICIENCY OF THE SOLAR COOKERS

The International standard procedure for testing solar cookers and reporting performance was proposed at the Third World Conference on Solar Cooking (Avinashilingam University, Coimbatore, India, 6-10 January, 1997) and revised by the committee over the following months [10]. The standard proposed by Mullick et al. [27]. is more complicated and less universal than the one being evaluated, though the characteristic curve they developed is a good predictive tool. In Europe, Grupp et al. [13] employ a test procedure that presents much useful information. The authors have investigated methodologies for evaluation and comparison of the solar cookers [9-10-13-27-31]. While many technically and economically successful solar cookers are in operation, no broadly valid basis for comparing the achieved performance of one solar cooker with that of another operating under different conditions has found general acceptance. For that reason, the work was directed toward developing simple methods for evaluating and comparing the energy and exergy efficiencies of the solar cookers. The present work deals with evaluating the efficiency of solar cookers using energy and exergy analyses.

Exergy is defined as the maximum work, which can be produced by a stream or system in a specified environment. Increasing application and recognition of the usefulness of exergy analysis by those in industry, government and research institutes has been observed in recent years. Efficiencies based on ratios of exergy do provide rational measures of efficiency, since they can measure the approach of the efficiency of a system to the ideal [6-7-33]. In many instances, energy based performance measures can be misleading, and that exergy based performance measures provide a more realistic evaluation of thermodynamic systems in general [14].

Exergy analysis, which is based primarily on the Second Law of Thermodynamics, as compared to energy analysis, which is based on the First Law, takes into account the quality of the energy transferred. Exergy analysis is recognized by many engineers to be a powerful tool for the evaluation of the thermodynamic and economic performance of thermodynamic system in general [35-37]. Energy analysis based on the First Law of Thermodynamics is concerned only with quantity of energy use and efficiency of energy processes. Energy analysis thus ignores reductions of energy potential, which could be used productively in other physical and/or chemical process. Energy analysis alone typically is applied to selection of energy source, evaluation of scheduling alternatives, and comparison of conservation methods. Energy analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities. Thus, energy analysis is suitable for the sizing of the systems and the analysis of systems using only one form of energy [23].

The evaluation of the solar cookers requires a measure of efficiency, which is rational, meaningful and practical. The energy efficiency of a solar cooker, the ratio of the energy gained by the solar cooker to the energy originally delivered to the solar cookers, conventionally is used to measure solar cooker efficiency. The energy efficiency is inadequate as a measure of efficiency because it does not take into account all the considerations necessary in solar cookers evaluation. Energy efficiencies can only account for quantities of energy transferred, and can often be misleading high, such as in cases where heat is recovered at temperatures too low to be useful. Exergy analysis provides an alternative means of evaluating and comparing the solar cookers. Exergy efficiency is a measure of the entropy generation or exergy destruction by the system. Exergy efficiencies account for the temperatures associated with energy transfers to and from solar cookers, as well as the quantities of energy transferred, and consequently provide a measure of how nearly solar cooker approach ideal efficiency.

A number of computer models have been developed to predict the efficiency of different types of solar cookers. Das et. al. [5] simulated performance of a solar box with horizontal glazing, one reflecting mirror, and aluminum absorber plate and containing one, two or four vessels. Habeebullah et.al. [15] reported the prediction of cooking temperatures and heat-up rates for concentrating solar cookers with different wind speeds and cooking strategies. Binark and Türkmen [2] analyzed hot box-solar cooker by using the fourth-order Ruge-Kutta method. Funk and Larson [9] presented the development of model and related parametric response surface to describe the cooker design space by predicting cooking power.

Several researchers have studied the improving the efficiency of the solar cookers. Balzar et.al. [1] described a solar cooker system, which consists of a vacuum-tube collector with integrated long heat pipes directly leading to the oven plate. They obtained that the maximum temperature in a pot containing 5 L of edible oil was 252 °C. Buddhi and Sahoo [3] designed a box-type solar cooker with latent heat storage. Their results showed that it is possible to cook the food even in the evening with a solar cooker having latent heat storage. Gaur et.al. [12] made a performance study of the box-type solar cooker with special emphasis on the shape of lid of the utensils used in a solar cooker. The study revealed that the performance of a solar cooker could be improved if a utensil with a concave shape lid is used instead of a plain lid\generally provided with the solar cooker. Nahar [29] designed a double reflector hot box solar cooker with a transparent insulation material (TIM), and fabricated, tested and compared the performance with a single reflector hot box solar cooker without TIM. The efficiencies were 30.5% and 24.5% for cookers with and without a TIM respectively, during the winter season at Jodhpur. The energy saving by use of a solar cooker with TIM has been estimated to be 1485 MJ of fuel equivalent per year. Suharta et.al. [40] compared three types of solar box-cooker. Sharaf [38] revealed the concept of conical focus and explained the design of a solar cooker. The solar cooker was practically tested for grilling both white and red meat in a record time.

2.1. Energy Efficiency of Solar Cooker

Energy analysis based on the First Law of Thermodynamics is concerned only with quantity of energy use and efficiency of energy processes. Energy analysis thus ignores reductions of energy potential, which could be used productively in other physical and/or chemical process. Energy analysis alone typically is applied to selection of energy source, evaluation of scheduling alternatives, and comparison of conservation methods. Energy analysis can provide sound management guidance in those applications in which usage effectiveness depends solely on energy quantities. Thus, energy analysis is suitable for the sizing and analyzing of the systems using only one form of energy [23].

To perform energy and exergy analyses of the solar cookers, the quantities of input and output of energy and exergy must be evaluated. If kinetic and potential energy terms are considered negligible, for the steady-state flow process during a finite time interval, the overall energy balance of the solar cooker can be written as:

Energy Input = Energy Output +Energy Loss

Energy input to the solar cooker is he total solar energy incident upon plane of the solar cooker per unit time per unit area. Thus, energy input to the solar cooker can be calculated as follows:

$$E_i = I_t.A_{sc} \qquad (1)$$

where; E_i is the energy input to the solar cooker in W; I_t is the total solar energy incident upon plane of the solar air heater per unit time per unit area in W/m^2; and A_{sc} is the surface area of the solar air heater.

In the energy and exergy analyses of the solar cooker, the energy gained by the solar cooker (cooking power) is considered as the energy output from the solar cooker. Calculation of the energy output from the solar cooker is based on the change in water temperature, mass of the water and specific heat capacity of the water. Cookers are to have 7 kg water/m^2 intercept area distributed evenly between the pots supplied with the cooker. Intercept area is defined as the sum of the reflector and aperture areas projected onto the plane perpendicular to direct beam radiation [10]. The change in water temperature for each 10 min-interval is multiplied by the mass and specific heat capacity of the water. Then, dividing this value by the 600 s contained in a 10 min-interval, the energy output of the solar cooker is obtained in Watts (Equation (2)).

$$E_o = \frac{m_w c_{pw}(T_{wf} - T_{wi})}{\Delta t} \qquad (2)$$

where; E_o is the energy output of the solar cooker in W; m_w is the mass of the water in kg; c_{pw} is the specific heat of the water in J/kg K; T_{wi} and T_{wf} are initial and final temperatures of the water in K; and t is the time in s.

Energy efficiency of the solar cooker can be defined as the ratio of energy output to energy input of the solar cooker. Energy efficiency of the solar cooker (η; %) is calculated from the following equation:

$$\eta = \frac{Energy\ output}{Energy\ input} = \frac{E_o}{E_i} = \frac{\lfloor m_w c_{pw}(T_{wf} - T_{wi}) \rfloor / \Delta t}{I_t.A_{sc}} \qquad (3)$$

2.2. Exergy Efficiency of Solar Cooker

Exergy analysis, which is based primarily on the Second Law of Thermodynamics, as compared to energy analysis, which is based on the First Law, takes into account the quality of the energy transferred. Exergy analysis is recognized by many engineers to be a powerful tool for the evaluation of the thermodynamic and economic performance of thermodynamic system in general [33]. Exergy analysis, derived from both the First and Second Laws of Thermodynamics, includes a consideration of energy quality or capability, which permits evaluation of the most effective, not just most efficient, use of energy potential. Since higher quality energy is usually more costly, exergy analysis also can provide insights to cost effectiveness. Exergy analysis involves conducting an accounting of irreversibility gains or energy capability reductions associated with such changes as temperature degradation, elevation or head loss and composition changes. Exergy analysis is based on the separate quantification and accounting for usable energy, called exergy or availability, and usable energy, called irreversibility [23].

Exergy analysis involves the examination of the exergy at different points in a series of energy conversion steps, and determination of meaningful efficiencies and of the steps having the largest losses [35]. Exergy analysis involves the evaluation of the inputs, outputs, accumulations and consumptions of exergy for a system. It is also the most complex to apply because appropriate values of the temperature and pressure of the environment, and chemical potentials for several species in the reference environment, must be selected; and efficiencies must be carefully defined [34]. For the steady-state flow process during a finite time interval, the overall exergy balance of the solar cooker can be written as follows:

Exergy Input = Exergy Output +Exergy Loss + Irreversibility

Solar irradiance consists of direct beam irradiance and diffuse irradiance. The latter is created by scattering processes in the atmosphere. The beam radiation is contained within the solid angle subtended by the solar disk. The majority is of concentrating cookers use only beam irradiance and very little diffuse component. But even on clear day, the diffuse irradiance can represent 20 percent of the total irradiance [42]. The availability of the terrestrial solar radiation obtained by superposition of the availabilities of two lumped sources, a direct beam source and diffuse source. The availability (exergy) of a solar flux with both beam and diffuse components can be represented by superposition as [30]:

$$\Xi_i = I_b\left[1 - 4T_o/3T_s\right] + I_d\left[1 - 4T_o/3T_s^*\right] \quad \text{.......(4)}$$

where: Ξ_i is the exergy of solar radiation) in W/m^2; I_b is the beam radiation in W/m^2; I_d is the direct radiation in W/m^2; T_o is the outside temperature in K; T_s is the sun temperature in K; and T^*_s is the effective diffuse radiation temperature in K.

The Petela [32] expression for the available energy flux, which has the widest acceptability, can be used to calculate the exergy of solar radiation as the exergy input to the solar cooker

$$\Xi_i = \dot{I}\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] \quad \text{.......(5)}$$

where; T_a is the ambient temperature in K. The sun's black body temperature of 5762 K results in a solar spectrum concentrated primarily in the 0.3-3.0 μm wavelength band [21]. Although the surface temperature of the sun (T_s) can be varied on the earth' surface due to the spectral distribution, the value of 5800 K has been considered for the T_s.

The thermal exergy at temperature T is:

$$\in = \int_{T_o}^{T} m.c_p\left(1 - \frac{T_o}{T}\right)dQ \quad \text{.......(6)}$$

This equation can be applied for non-isothermal processes. Thus, the thermal exergy content of water Ξ_w at temperature T_i can be calculated by the following equation:

$$\in_w (T_i) = m_w.c_{pw}\left[(T_{wi} - T_o) - T_o \ln\frac{T_{wi}}{T_o}\right] \quad \text{.......(7)}$$

When the temperature of the water is increased to temperature T_f, exergy is:

$$\Xi_o = m_w c_{pw}\left[(T_{wf} - T_{wi}) - T_o \ln\frac{T_{wf}}{T_{wi}}\right] \Big/ \Delta t \quad \text{.......(8)}$$

Exergy efficiency is formed as a ratio of the exergy transfer rate associated with the output to the exergy transfer rate associated with the necessary input [20]. An exergy efficiency of the solar cooker can be defined as the ratio of the exergy gained by the solar cooker (exergy output) to the exergy of the solar radiation (exergy input).

$$\Psi = \frac{\textit{Exergy output}}{\textit{Exergy input}} = \frac{\dot{\Xi}_o}{\dot{\Xi}_i} = \frac{m_w c_{pw}\left[(T_{wf} - T_{wi}) - T_o \ln\frac{T_{wf}}{T_{wi}}\right] \Big/ \Delta t}{\dot{I}\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right] A_{sc}} \quad \text{.......(10)}$$

3. CONCLUSIONS

This theoretical study was conducted to develop an energy and exergy evaluation method for predicting solar cooker performance. Exergy analysis is a useful tool for evaluating the relative performance of different designs of the solar cookers. The following are the conclusions drawn from the present study:

(1) In frame of present study two formulas were developed: one for determining the energy efficiency of a solar cooker, and the other to find out its exergy efficiency.

(2) An energy and exergy balance for the solar cooker was carried out. Exergy analysis is more convenient than the energy analysis for predicting the efficiency of the solar cookers. It is concluded that exergy is more effective and more efficient tool for the performance analysis of the solar cookers.

(3) The use of solar energy for heating and cooking applications has gained an increasing acceptance during the last years. The main problem is related with the selection and sizing or the more appropriate, passive or active technology for the specific application. The use of solar cookers would help in conservation of conventional fuels, such as firewood and agricultural waste in rural areas of Turkey. Conservation of firewood helps in preserving the ecosystems. Moreover, the use of the solar cooker would result in the reduction of the release of CO_2 into the environment. Sustainable development could be fostered and standards of living in a society that is currently desperately dependant on fuel wood can be improved.

(4) Further modifications to the solar cookers will be directed at reducing the size and weight, to making it handier and easier to carry. Research directed toward improving the efficiency of the solar cookers could be useful. Development and low cost containment and direct heat technology could significantly reduce the cost of cooking technology with solar energy.

(5) The optimisation of the design and exploitation of the solar cookers can be made by means of the exergy analysis. When optimising the thermodynamic efficiency of a solar cooker, both design and operational parameters must be considered. More investigation is required to define the optimum efficiency of the solar cookers.

(6) Future studies should focus on modelling the efficiency of the solar cookers. Such experimental studies will be very useful to optimise the management of the solar cookers. The economics and thermal efficiency of each new system must be carefully evaluated in a total system context. Further experiments will be elaborated to check the cooking efficiency and to find out the maximum efficiency.

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