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EXPERIMENTAL STUDY ON HOT BOX SOLAR COOKER USING PARTICIPATING MEDIUM FOR RADIATION

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ABSTRACT- *An experimental study has been carried out to investigate the effect of participating medium in cooking chamber of a conventional hot box solar cooker. For this, carbon dioxide gas (CO_2) with atmospheric air has been used as participating medium in cooking chamber of hot box solar cooker. In order to investigate the effect participating medium in cooking chamber of a conventional hot box solar cooker, performance of one box type solar cooker having carbon dioxide gas with air as participating medium in cooking chamber has been compared with a normal identical box type solar cooker with non participating medium (air) in the cooking chamber. The increase in temperature of water in the box type solar cooker having carbon dioxide gas (CO_2) with air as participating medium for radiation in the cooking chamber has been found significant. Thus the benefit of participating medium in solar cooker has been established. Due to increased density of medium, convective mode of heat transfer has also been enhanced in the solar cooker having participating medium in its cooking chamber.*

***Keywords** -Box type solar cooker, Radiation in participating medium, Gas radiation, Carbon dioxide gas ,Water vapour.*

I. INTRODUCTION

Solar cookers are heat exchangers designed to utilise energy from sun in the process of cooking. The solar cookers can be classified mainly into three board categories, which are box type, focusing type and heat transfer type. **S**everal researchers have performed work on different designs of solar cookers and their performance improvement since the late 19th century.

1.1 Solar Radiation in Atmosphere

Solar radiation undergoes considerable attenuation as it passes through the atmosphere as a result of *absorption* and scattering. About 99 percent of the atmosphere is contained within a distance of 30 km from the earth's surface. Absorption by oxygen occurs in a narrow band about 0.76 µm. The *ozone* absorbs *ultraviolet* radiation at wavelengths below 0.3 µm almost completely, and radiation in the range 0.3–0.4 µm considerably [1]. Thus, the ozone layer in the upper regions of the atmosphere protects biological systems on earth from harmful ultraviolet radiation. Absorption in the infrared region is dominated by *water vapour* and *carbon dioxide.* The dust particles and other pollutants in the atmosphere also absorb radiation at various wavelengths. As a result of these absorptions, the solar energy reaching the *earth's surface* is weakened considerably. All of the solar radiation reaching the earth's surface falls in the wavelength band from 0.3 to 2.5 µm.

Another mechanism that attenuates solar radiation as it passes through the atmosphere is scattering (or reflection) by air molecules and the many other kinds of particles such as dust, smog, and water droplets suspended in the atmosphere.

The gas molecules and the suspended particles in the atmosphere emit radiation as well as absorbing it. The atmospheric emission is primarily due to the CO_2 and H_2O molecules and is concentrated in the regions from 5 to 8 µm and above 13 µm [1]. The absorption and emission of radiation by the elementary gases such as H_2, O_2, and N_2 at moderate temperatures are negligible, and a medium filled with these gases can be treated as a vacuum in radiation analysis. The absorption and emission of gases with *larger molecules* such as H_2O and CO_2, however, can be significant and may need to be considered when considerable amounts of such gases are present in a medium.

Ordinary glass is a very selective transmitter of solar radiation. Glass is nearly transparent to wavelengths below 2 µm thus transmits large part of incident solar energy [2]. At longer wavelengths, in the infrared, glass is virtually opaque to radiation.

1.2 Radiation in a Participating Medium

Gases that consist of monatomic molecules such as Ar and He and symmetric diatomic molecules such as N_2 and O_2 are essentially transparent to radiation, except at extremely high temperatures at which ionization occurs. Therefore, atmospheric air can be considered to be a non participating medium [1]. Gases with asymmetric molecules such as H_2O, CO_2, CO, SO_2, and hydrocarbons H_nC_m may participate in the radiation process by absorption at moderate temperatures, and by absorption and emission at high temperatures such as those encountered in combustion chambers.

Therefore, air or any other medium that contains such gases with asymmetric molecules at sufficient concentrations must be treated as a participating medium. The presence of a participating medium makes the radiation analysis complex for many reasons [1]:

- A participating medium emits and absorbs radiation throughout its entire volume. Gaseous radiation is a volumetric phenomena, and thus it depends on the size and shape of the body.
- Gases emit and absorb radiation at a number of narrow wavelength bands. While solids emit and absorb radiation over the entire spectrum. So the gray assumption is not always appropriate for a gas.
- The emission and absorption characteristics of the constituents of a gas mixture depends on the temperature, pressure, and composition of the gas mixture. Therefore, the presence of other participating gases affects the radiation characteristics of a gas.

1.3 Radiation Properties of a Participating Medium [1]

In a participating medium of thickness *L*, a spectral radiation beam of intensity $I_{\lambda,0}$ incidented on the medium, is attenuated as it propagates due to absorption. The decrease in the intensity of radiation as it passes through a layer of thickness *dx* is proportional to the intensity itself and the thickness *dx*. This is known as Beer's law, and is expressed as

$$dI_\lambda(x) = -\kappa_\lambda I_\lambda(x)dx \qquad (1)$$

where the constant of proportionality κ_λ is the spectral absorption coefficient of the medium whose unit is m^{-1} (from the requirement of dimensional homogeneity). Considerable analytical and experimental effort has been done to determine κ_λ for various gases, liquids, and solids. Analytical determinations of κ_λ require detailed quantum-mechanical calculations. Except for the simplest gases, such as atomic hydrogen, the calculations are very tedious and may require simplifying assumptions.

Separating the variables and integrating from $x = 0$ to $x = L$ gives

$$\frac{I_{\lambda,L}}{I_{\lambda,0}} = e^{-\kappa_\lambda L} \qquad (2)$$

where the absorptivity of the medium has been assumed to be independent of *x*. It is to be noted that radiation intensity decays exponentially in accordance with Beer's law.

The spectral transmissivity of a medium can be defined as the ratio of the intensity of radiation leaving the medium to that entering the medium. That is,

$$\tau_\lambda = \frac{I_{\lambda,L}}{I_{\lambda,0}} = e^{-\kappa_\lambda L} \qquad (3)$$

τ_λ=1 when no radiation is absorbed and thus radiation intensity remains constant. Also, the spectral transmissivity of a medium represents the fraction of radiation transmitted by the medium at a given wavelength.

Radiation passing through a nonscattering (and thus nonreflecting) medium is either absorbed or transmitted. Therefore

$$\alpha_\lambda + \tau_\lambda = 1, \qquad (4)$$

and the spectral absorptivity of a medium of thickness *L* is

$$\alpha_\lambda = 1 - \tau_\lambda = 1 - e^{-\kappa_\lambda L} \qquad (5)$$

From Kirchoff's law, the spectral emissivity of the medium is

$$\varepsilon_\lambda = \alpha_\lambda = 1 - e^{-\kappa_\lambda L} \qquad (6)$$

The spectral absorptivity, transmissivity, and emissivity of a medium are dimensionless quantities, with values less than or equal to 1. The spectral absorption coefficient of a medium (and thus α_λ, ε_λ, and τ_λ) vary with wavelength, temperature, pressure, and composition.

An optically thick medium emits like a blackbody at the given wavelength. As a result, an optically thick absorbing-emitting medium with no significant scattering at a given temperature T_g can be viewed as a "black surface" at T_g since it will absorb essentially all the radiation passing through it, and it will emit the maximum possible radiation that can be emitted by a surface at T_g.

1.4 Emissivity and Absorptivity of CO_2 gas and H_2O Vapour

Absorption depends on temperature, pressure and thickness of the gas layer. Therefore, absorptivity values without specified thickness and pressure are meaningless. With gray assumption, the total emissivity and absorptivity of a gas depends on the geometry of the gas body as well as the temperature, pressure, and composition. Gases that participate in radiation exchange such as CO_2 and H_2O typically coexist with non participating gases such as N_2 and O_2, and thus radiation properties of an absorbing and emitting gas are usually reported for a mixture of the gas with non participating gases rather than the pure gas [1]. The emissivity and absorptivity of a gas component in a mixture depends primarily on its density, which is a function of temperature and partial pressure of the gas.

1.5 Applications Involving Radiation in Participating Medium

Energy transfer through hot gases in furnaces, internal combustion engines, various combustion chambers at high pressures and temperatures, rocket propulsion, and spacecraft atmospheric reentry, among others, is a very important mechanism for radiative energy transfer. Predicting the radiative properties of these radiatively participating gases, including water vapor, carbon dioxide, carbon monoxide, methane, and others constitutes a challenge in calculating energy transfer. Some recent important applications are engine combustion chambers at high pressures and temperatures, rocket propulsion, glass manufacturing, fibrous insulating layers, nuclear explosions, hypersonic shock layers, plasma generators for nuclear fusion, ablating thermal protection systems, translucent ceramics at high temperature, irradiation of biological systems, and heat transfer in porous regions. The importance of gas radiation in industrial applications was recognized for heat transfer in furnaces. Combustion products, mainly carbon dioxide and water vapor, were found to be significant emitters and absorbers of radiant energy. The energy emitted from flames arises not only from the gaseous emission but also from hot carbon (soot) particles within the flame and from suspended particulate material. Radiation can also be appreciable in engine combustion chambers, where temperatures can reach a few thousand Kelvins.

In the late 1940s it became evident that radiative transfer by absorption and reemission within the gas is a significant means of energy transfer.

II. STUDIES OF RADIATION IN PARTICIPATING MEDIA: A BRIEF REVIEW

The properties of absorbing-emitting media, particularly gases, are strongly wavelength dependent, and therefore presents a major difficulty in carrying out radiative transfer calculations. For this reason, past and present effort seeks to provide useful correlations of the properties that can give accurate results without the extreme computational requirements imposed by detailed spectral calculations.

This is an ongoing research field and new methods and improvements of existing methods continue to appear in the literature.

By the 1920s, the need for design tools that could adequately predict radiative transfer in industrial furnaces was becoming obvious.

The pioneering work by Hottel (1931, 1933) systematically developed a methodology for such applications. Hottel constructed graphs from data that were painstakingly measured and extrapolated to useful parameter ranges [2].

Edwards et al. (1967) reported experimental measurements of absorption and emission by nonisothermal CO_2 and H_2O gases. They also presented analytical formulations and calculations of radiant heat transfer using a simple nongray gas model. They found that a gray gas model cannot predict even qualitatively the experimental results, while the band model method of calculation yields results in quantitative agreement for total emission and absorption in a band [3].

Throughout the 1970s and up to the present, the search has continued for methods that could be applied broadly to multidimensional radiative transfer in enclosures, with the additional capability of handling spectral and anisotropic characteristics in absorbing-emitting-scattering media. Interest was strong in the older methods and their extensions, and some newer approaches showed promise, such as the finite-element methods. New solutions for standard problems have provided benchmarks for comparing existing and emerging methods for accuracy and ease of solution.

Radiative transfer within participating media presents some of the most mathematically challenging heat transfer problems. Various solution techniques are described in standard texts, and these often rely on either physical or mathematical approximations. Methods developed for other applications have long been appropriated for use in engineering radiative transfer. These include the Schuster-Schwarzschild [now more commonly called the two-flux model, Milne-Eddington, discrete ordinate, and diffusion methods from astrophysics; and Monte Carlo, differential, *P-N*, invariant embedding, and others from nuclear physics and engineering.

Each of the developing methods was successfully applied to simple one-dimensional gray gas problems. When they were extended to multidimensional geometries with nongray media with various boundary conditions, drawbacks emerged in. No single method is now accepted as being the best for all problems. While most of these methods enjoy some success, none of the methods has been generally accepted as being the best in all cases. A solution method that has exhibited general success is the Monte Carlo ray-tracing method.

"Direct simulation Monte Carlo" approach to radiative transfer (DSMC-R/T) exactly models the physics of radiative transfer, and can incorporate spectral material properties, nonuniform and temperature-dependent properties, and complex geometries.

Some approaches using Monte Carlo or nonrandom ray-tracing approaches apply one or more approximations or simplifications that can greatly reduce computation time at the expense of accuracy. Where the approximations are justified-for example, when material properties are imperfectly known-these methods may be preferable to DSMC-R/T. However, if spectral or nonuniform properties are present, as is the case for many real problems, DSMC-R/T must be used for accurate solution.

The Monte Carlo method simulates radiative transfer by tracking the histories **of** a number of rays that represent energy bundles or photons traveling through the medium. The rays experience interactions with the medium (emission, scattering, and absorption) and the boundary (emission, reflection, and absorption for opaque boundaries). These simulations produce statistical estimates **of** parameters describing radiative transfer in the medium and interactions with the boundary. Monte Carlo suffers from two factors: The statistical nature of the results it produces, and the large computation times sometimes necessary to obtain the precision and accuracy required for engineering applications [4].

III. OBJECTIVES

The study of energy transfer through media that can absorb, emit, and scatter radiation has received increased attention. This interest stems from the complicated and interesting phenomena associated with nuclear explosions, hypersonic shock layers, rocket propulsion, plasma generators for nuclear fusion, and ablating systems. Energy transfer through hot gases in furnaces, internal combustion engines, various combustion chambers at high pressures and temperatures, rocket propulsion, and spacecraft atmospheric reentry is a very important mechanism for radiative energy transfer. Predicting the radiative properties of these radiatively participating gases, including water vapor, carbon dioxide, carbon monoxide, methane, and others constitutes a challenge.

No evidence about the use of participating media in hot box solar cooker has been found in the literature survey. So an experimental study can be conducted to see the effect of participating medium in cooking chamber of a conventional hot box solar cooker. Hence, the objective of the present experimental study, to be carried out as per BIS 13429:2000 [5] and recommendations of other investigators, is to investigate the effect of participating medium in cooking chamber of a conventional hot box solar cooker.

IV. EXPERIMENTAL METHODOLOGY

4.1 Experimental Setup

4.1.1 Solar cooker

The two identical box type solar cookers used in the study are shown in Fig. 1. As per claim of supplier, solar cooker has been fabricated to meet the standards prescribed by BIS for solar cookers. It is approved by Agro Industries Corporation Limited and Rajasthan Renewable Energy Corporation Limited (Formerly REDA). Two identical box type solar cookers have been used in the study.

Each cooker consists of a 0.6 m X 0.6 m X 0.22 m box made of GI sheet with a mat black painted trapezoidal tray of (43 cm X 43 cm at bottom, 50 cm X 50 cm at top and 12 cm height) made of 28 SWG thick GI sheet. Four cooking vessels/ pots can be kept inside it. Aluminium pots with mat black painted on outside of size 170 mm diameter and 65 mm height have been used in the study.

The total absorber area is 0.382 m^2; the bottom surface of the tray is 0.185 m^2 in area.

The cover plate is double glazed. Spacing between inner and outer glazings (4 mm thick each) is about 15 mm. The glazing area is L_g X W = 498 mm X 498 mm. Provision on the side is made to keep the cover plate at inclined position for loading and unloading of the cooking pots.

A plane mirror (reflector) is hinged at the side of box to increase the solar irradiation on glazing. Mirrors are free from bubbles and waviness. The reflecting area of mirror is 506 mm X 506 mm which is greater than the glazing area. Provision on the sides is made to keep the mirror in any inclined position. There is a provision to keep the mirror in any inclined position.

The solar radiation falls upon the glazing directly and indirectly after reflection from mirror. The maximum projected area of glazing is known as aperture area. The maximum projected area of mirror is known as reflector area. The sum of aperture area and reflector area is termed as intercept area. The ratio of intercept area to the aperture area is known as concentration ratio (ASAE) [6].

Joint between glazing and absorber tray is sealed by polyurethane foam. The space between the absorber tray and outer sheet of box is filled with glass wool insulation on all sides and bottom. Thermal resistance R (=δ/k) of about 40 mm thick glass wool (thermal conductivity = 0.06 $Wm^{-1}K^{-1}$ at 380 K) is about 0.66 m^2KW^{-1}. However BIS recommends a minimum value of 0.96 m^2KW^{-1} at 100 ˚C.

4.1.2 Experimental devices

The experimental study has been made by recording temperature rise of the water in the vessel with a calibrated HTC digital K type thermocouple (Ni Cr / Ni Al Alloy). The temperature probe of the thermocouple has been placed in the cooking vessels with measuring tip of the thermocouple submerged in the water. Thermocouple wires have been sealed using epoxy resin to make the vessel vapour tight. The ambient temperature has also been measured by a thermometer.

The solar irradiance on the horizontal plane has been measured using a Tenmars solar power meter TM-206 (solarimeter) calibrated against a precision pyranometer available in IIT Jodhpur.

4.2 Design of Experiment

In order to investigate the effect of participating medium in cooking chamber of a conventional hot box solar cooker, carbon dioxide gas with atmosperic air has been used as participating medium in cooking chamber of hot box solar cooker. For yielding carbon dioxide gas in the cooking chamber of box type solar cooker, sodium bicarbonate has been reacted with hydrochloric acid in a beaker kept in cooking chamber of box type solar cooker.

$$\mathbf{NaHCO_3 + HCl \text{ ---------> } NaCl + H_2O + CO_2(g)}$$

A direct comparison of temperature rise of a known quantity of water in two identical conventional pots directly kept on absorber tray of one solar cooker with temperature rise of same quantity of water in two identical pots in another solar cooker with CO_2 gas in the cooking chamber. At first, resemblance of both solar cookers used in the study has been tried to establish in identical conditions. After that, in all experiments one solar cooker has been kept in its normal form while another solar cooker has been kept with provision of CO_2 gas in its cooking chamber.

For provision of CO_2 gas in the cooking chamber of box type solar cooker, a glass beaker with a certain amount of sodium bicarbonate (baking soda) has been kept in the cooking chamber on absorber tray centrally in front side. In that beaker hydrochloric acid (HCl) can be added to obtain the carbon dioxide gas (CO_2).

Since no evidence about the use of participating media in hot box solar cooker has been found in the literature survey, it is difficult to decide amount of CO_2 required. Amount of sodium bicarbonate and hydrochloric acid to be reacted and thus amount of CO_2 yielded, has been decided by trial basis, starting from 25 gram sodium bicarbonate and 10 ml of hydrochloric acid.

4.3 Experimental Procedure

The experimental study has been made by recording temperature rise of the water in the vessel with a thermocouple. Schematic representation of experimental setup is shown in Figs. 1 (a) and 1 (b). The temperature probe of the thermocouple has been placed in the cooking vessels with measuring tip of the thermocouple submerged in the water above 10 mm from pot bottom. Thermocouple wires have been sealed using epoxy resin to make the vessel vapour tight. The ambient temperature has also been measured by the thermocouple.

The solar irradiance on the horizontal plane has been measured using a solarimeter. The tests were conducted in still air (wind velocity less than 1.0 m/s).

All components and instruments were checked for proper functioning. A measured quantity (1400 cc that is 700 cc in each pot) of the water was filled in the pots in each solar cooker.

The tests were started in the morning between 9 AM and 10 AM IST. Solar irradiance and temperatures have been measured at 10 min interval in the beginning. This interval was reduced to 5 min after the water temperature reached about 80˚C. The upper limit of the water temperature for the time period analysed cannot be taken as 100˚C (the boiling point at atmospheric pressure) because the rate of variation of water temperature approaches zero as the water temperature approaches 100˚C. Therefore, the upper limit of sensible heating (T_{w2}) has been fixed in the temperature range 90˚C – 95˚C (Mullick et al., 1987) [7]. The data recording was continued until the water temperature reached about 95°C as per suggestion of BIS [5].

The tilt of the reflector was varied every 30 minutes so that the reflected radiation does not fall outside the glazing and covers the glazing completely. The cooker was also tracked every 30 min.

In order to investigate the effect participating medium in cooking chamber of a conventional hot box solar cooker, performance of one box type solar cooker having carbon dioxide gas with air as participating medium in cooking chamber has been compared with a normal identical box type solar cooker with non participating medium (air) in the cooking chamber.

Since no evidence about the use of participating media in hot box solar cooker has been found in the literature survey, amount of CO_2 (that is amount of sodium bicarbonate and hydrochloric acid to be reacted) has been decided by trial method, starting from 25 gram sodium bicarbonate and 10 ml of hydrochloric acid.

After establishing resemblance of both solar cookers, all experiments have been conducted by keeping one solar cooker in its normal condition and another solar cooker with provision of CO_2 gas in its cooking chamber.

For provision of CO_2 gas in the cooking chamber of box type solar cooker, a glass beaker with a certain amount of sodium bicarbonate (baking soda) has been kept in the cooking chamber on absorber tray centrally in front side. In that beaker hydrochloric acid (HCl) can be poured/ added to obtain the carbon dioxide gas (CO_2) as shown in Fig. 1 (b).

To reduce effects of uncertainty and errors, the experiments have been repeated two or three times.

The tests were conducted at Department of Mechanical Engineering, Faculty of Engineering & Technology, Jodhpur National University, Jodhpur (India). Jodhpur is located at 26.25˚N latitude, 73.03˚E longitude and 235 m elevation of sea level.

4.3.1 Load Test (Sensible Heating Test)

The solar cooker has been tested by measuring the rise in temperature of a known quantity of water in the cooking vessels with time.

Cooking pots have been filled with 1400 CC of water, which works out to be about 6.2 litres of water per m^2 of the glass area. This is in the range suggested by BIS for standard conditions for load of 8 kg of water / m^2 of aperture area. Equal quantity of water at ambient temperature has been used in the two cooking pots in both the solar cookers and they are of the same size in the tests.

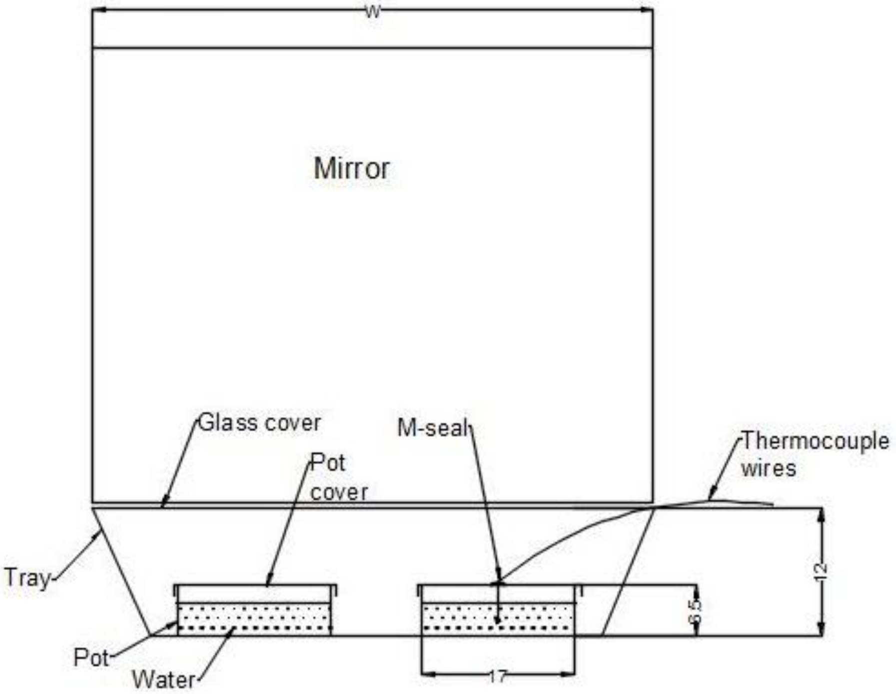

Fig. 1 (a) Schematic diagram of solar cooker 1 having non participating medium (air) in the cooking chamber in experimental set up (all dimensions are in cm).

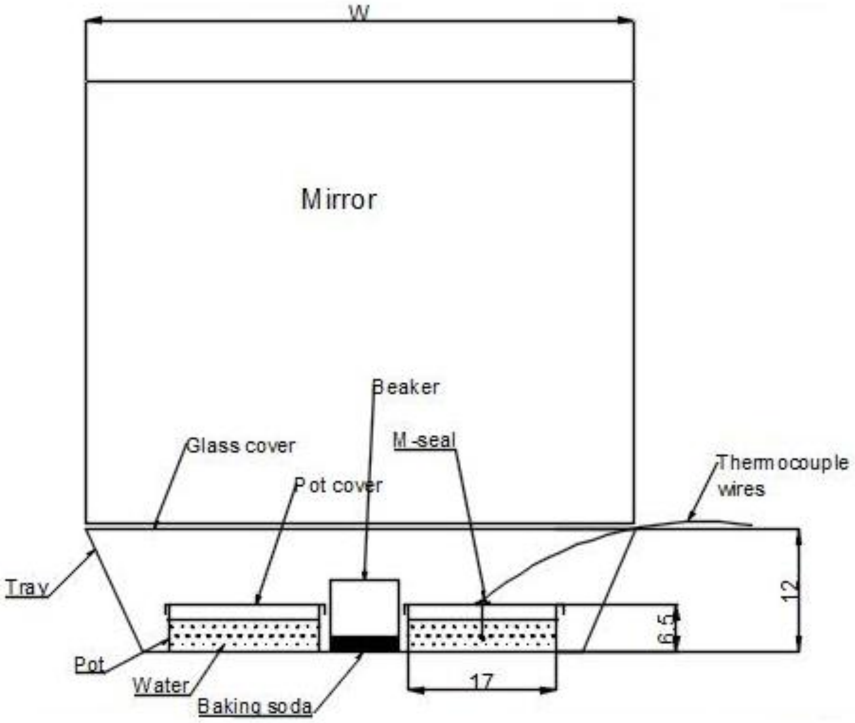

Fig. 1 (b) Schematic diagram of solar cooker 2 having participating medium (CO_2 with air) in the cooking chamber in experimental set up (all dimensions are in cm).

4.3.2 Expeimental Data

Ideally the experiment must be conducted in a clear weather but sometimes there were intermittent clouds and the diffuse radiation was observed to be 20-30%. The solar radiation exceeded 600 W/m^2 (which is the recommendation of all standards including BIS [5], [6], [8], [9]) most of the time after 10 am except during the short periods of cloudy conditions on some days of experiment. The tests were conducted in still air (wind velocity less than 1.0 m/s). The ambient temperature T_a varied from a 30 ^{o}C in the morning to a maximum of 38˚C in the afternoon. The opening area of hot box solar cooker varies by about 10% because of the adjustment of the tilt of the mirror.

V. RESULT AND DISCUSSION

5.1 Introduction

To investigate the effect of participating medium in cooking chamber of a conventional hot box solar cooker, an experimental study has been carried out.

Performance of one box type solar cooker having carbon dioxide gas with air as participating medium in cooking chamber has been compared with a normal identical box type solar cooker without having participating medium for radiation in its cooking chamber.

5.2 Standardisation of Both Identical Solar Cookers (Establishing Resemblance of Cookers)

Initially both the construction wise identical solar cookers have been tested for their similar performance in similar conditions. It can be seen from Fig. 2 that performance of both solar cookers is similar. Temperature of water in pot of solar cooker 2 remains equal to temperature of water in pot of solar cooker 1 at all time. It can be claimed that both the solar cookers used in the study are identical in all respect. Hence both cookers can be used to see the effect of one particular modification which is use of participating medium for radiation, here.

5.3 Effect of Participating Medium in Box Type Solar Cooker

Carbon dioxide gas (CO_2) with atmospheric air has been used as participating medium in cooking chamber of one box type solar cooker. For provision of CO_2 gas in the cooking chamber of box type solar cooker, a glass beaker with a certain amount of sodium bicarbonate (baking soda) has been kept in the cooking chamber on absorber tray centrally in front side. In that beaker hydrochloric acid (HCl) can be added to obtain the carbon dioxide gas (CO_2). Amount of sodium bicarbonate (baking soda) and hydrochloric acid (HCl) to be reacted, and thus amount of carbon dioxide gas (CO_2), has been decided by trial method, starting from 25 gram sodium bicarbonate and 10 ml of hydrochloric acid.

5.3.1 10 ml HCl added to 25 gram $NaHCO_3$ after 10 minutes from starting of experiment

In first trial 10 ml HCl has been added to 25 gram $NaHCO_3$ after 10 minutes from starting of experiment in solar cooker 2.

From Fig. 3, it can be seen that temperature of water in pot of solar cooker 2 lags by 3 ºC behind temperature of water in pot of solar cooker 1 when temperature of water of solar cooker 1 reaches 87 ºC . After that, temperature of water in pot of solar cooker 2 lags by 2 ºC behind temperature of water in pot of solar cooker 1 when temperature of water of solar cooker 1 crosses 87 ºC .

Initial lagging of temperature in solar cooker 2 is due to loss in convective heat transfer to pot contents. When glass cover was opened to add hydrochloric acid to the beaker containing 25 gram sodium bicarbonate (baking soda) kept on the absorber tray, developing convective air currents got disturbed resulting in the loss of heat transfer to the pot. After some time, this lagging of temperature began to reduce which may be credited to role of carbon dioxide gas as participating medium, produced after reaction of baking soda and HCl.

Hence in this trial, indication of enhanced heat transfer to pot contents due to carbon dioxide gas as participating medium has been achieved.

5.3.2 30 ml HCl added to 60 gram $NaHCO_3$ after 10 minutes from starting of experiment

Since in first trial (10 ml HCl added to 25 gram $NaHCO_3$ after 10 minutes from starting of experiment), indication of enhanced heat transfer to pot contents due to carbon dioxide gas as participating medium has been achieved, it has been decided to increase the yield of carbon dioxide (CO_2).

For increasing the yield of CO_2, 30 ml HCl has been added to 60 gram $NaHCO_3$ after 10 minutes from starting of experiment in solar cooker 1. From Fig. 4, it can be seen that temperature of water in pot of solar cooker 2 leads by 4 ºC over temperature of water in pot of solar cooker 1 when temperature of water of solar cooker 2 crosses 90 ºC .

Initial lagging has not been observed during this repetition though glass cover has also been opened during experiment to add HCl. This may be due to (i) lesser temperature inside the solar cooker (temperature of water recorded 36 ºC at the time of opening glass cover as compared to 40 ºC and 45 ºC in previous cases), hence lesser developing air currents, (ii) lesser wind velocity nearby to cooker and (iii) lesser opening time duration hence developing convective air currents could not get disturbed.

The increase in temperature of water in the box type solar cooker having carbon dioxide gas (CO_2) with air as participating medium for radiation in the cooking chamber is significant and establishes the benefit of participating medium.

5.3.3 30 ml HCl added to 60 gram $NaHCO_3$ initially just before the starting of experiment

To avoid the opening of glass cover during experiment, 30 ml HCl has been added to 60 gram $NaHCO_3$ initially just before the starting of experiment. The same trial has been repeated with reversing the solar cookers.

From Fig. 5, it can be seen that temperature of water in pot of solar cooker having carbon dioxide gas (CO_2) with air as participating medium leads by 1 ºC over temperature of water in pot of solar cooker with non participating medium (atmospheric air) when temperature of water reaches around 90 ºC .

The lead of temperature is marginal in this case. This is due to the slow formation of CO_2 gas. When HCl is added to $NaHCO_3$ at room temperature condition, it requires continuous stirring of the solution to obtain CO_2 faster, which cannot be done in cooking chamber of solar cooker. High diffuse radiation during these tests is also a reason of marginal gain.

5.4 Enhanced Convective Heat Transfer

The heat to the conventional cooking vessel and its contents (water in the present study) flows by conduction through the bottom of the vessel from heated absorber tray, though there exists a thermal contact resistance between the bottom of the vessel and absorber tray surface. Heat flows by convection from the heated absorber tray to vessel's side walls. Heat also flows from the heated cover/ lid of vessel to the contents of the vessel by conduction through the side walls of the vessel though there is a thermal contact resistance because of uncertain contact between the lid and vessel's side surface. The contribution of radiative heat transfer to cooking vessel is not direct but the absorber tray and vessel's lid are heated by radiation.

When 30 ml HCl has been added to 60 gram $NaHCO_3$ after 10 minutes from starting of experiment that is at some elevated temperature, the increase in temperature of water in the box type solar cooker having carbon dioxide gas (CO_2) with air as participating medium for radiation in the cooking chamber has been found significant. Thus the benefit of participating medium in solar cooker has been established.

$$NaHCO_3 + HCl \text{ ---------> } NaCl + H_2O + CO_2(g)$$

From the balanced equation it can be seen that 1 mole of $NaHCO_3$ produces 1 mole of CO_2.

When 60.00 grams of $NaHCO_3$ is used,

$$\text{Moles of } NaHCO_3 = \frac{\text{grams}}{\text{molecular mass}} = \frac{60.00 \text{ g}}{84.01 \text{ g/mole}} = 0.7142 \text{ moles}$$

Since the $NaHCO_3$: CO_2 mole ratio is 1:1, then 0.7142 moles of $NaHCO_3$ would form 0.7142 moles of CO_2. The mass of this amount of CO_2 would be:

grams of CO_2 = n X molecular mass = 0.7142 mol X 44 g/mol = 31.4248 grams of CO_2.
Thus the theoretical yield of CO_2 expected is 31.4248 grams.

Since the $NaHCO_3$: H_2O mole ratio is 1:1, then 0.7142 moles of $NaHCO_3$ would form 0.7142 moles of H_2O. The mass of this amount of H_2O would be:

grams of H_2O = n X molecular mass = 0.7142 mol X 18 g/mol =12.8556 grams of H_2O.
Thus the theoretical yield of H_2O expected is 12.8556 grams.

Since the volume of the cooking chamber is approximately 0.26 m^3, mass of the enclosed air in the cooking chamber is 31.3128 gram (assuming density of air as 1.2 kg/ m^3)

Thus the total mass of the gas mixture in the cooking chamber that is mass of air, CO_2 and H_2O vapour will be 75.5932 gram, and density of the gas mixture will be 2.9 kg/ m^3,which is around 2.5 times more than the density of air.

Due to increased density of medium , convective mode of heat transfer has also been enhanced in the solar cooker having participating medium in its cooking chamber. It is an established fact that contribution of convective mode of heat transfer to cooking vessel in conventional hot box solar cooker is very strong.

5.5 Challenges in the Study of Radiation in Participating Media

Two major difficulties make the study of radiation transfer in absorbing, emitting, and scattering media quite challenging. The first difficulty is the spatial variation in radiative properties throughout the medium; absorption, emission, and scattering can occur at all locations within the medium at different strengths depending on the concentration of gases and local temperature variations. A complete solution for energy exchange requires knowing the radiation intensity, temperature, and physical properties throughout the medium. The mathematics describing the radiative field is inherently complex. A second difficulty is that spectral effects are often much more pronounced in gases, translucent solids, and translucent liquids than for solid surfaces, and a detailed spectrally dependent analysis may be required. Most of the simplifications introduced for solving radiation problems in gases and other translucent materials are aimed at decreasing one or both of these complexities.

The properties of absorbing-emitting media, particularly gases, are strongly wavelength dependent, and therefore presents a major difficulty in carrying out radiative transfer calculations. For this reason, past and present effort seeks to provide useful correlations of the properties that can give accurate results without the extreme computational requirements imposed by detailed spectral calculations.

This is an ongoing research field and new methods and improvements of existing methods continue to appear in the literature.

There are many factors of uncertainties in the experiments involving leakage of hot air from the cooking chamber. To reduce effects of uncertainty and errors, the experiments have been repeated two or three times. Repeatability of the results has been verified.

Since in all tests, a temperature of 90-95°C of water has been achieved in around two hours easily, no need has been experienced to conduct various tests to evaluate the performance of solar cooker.

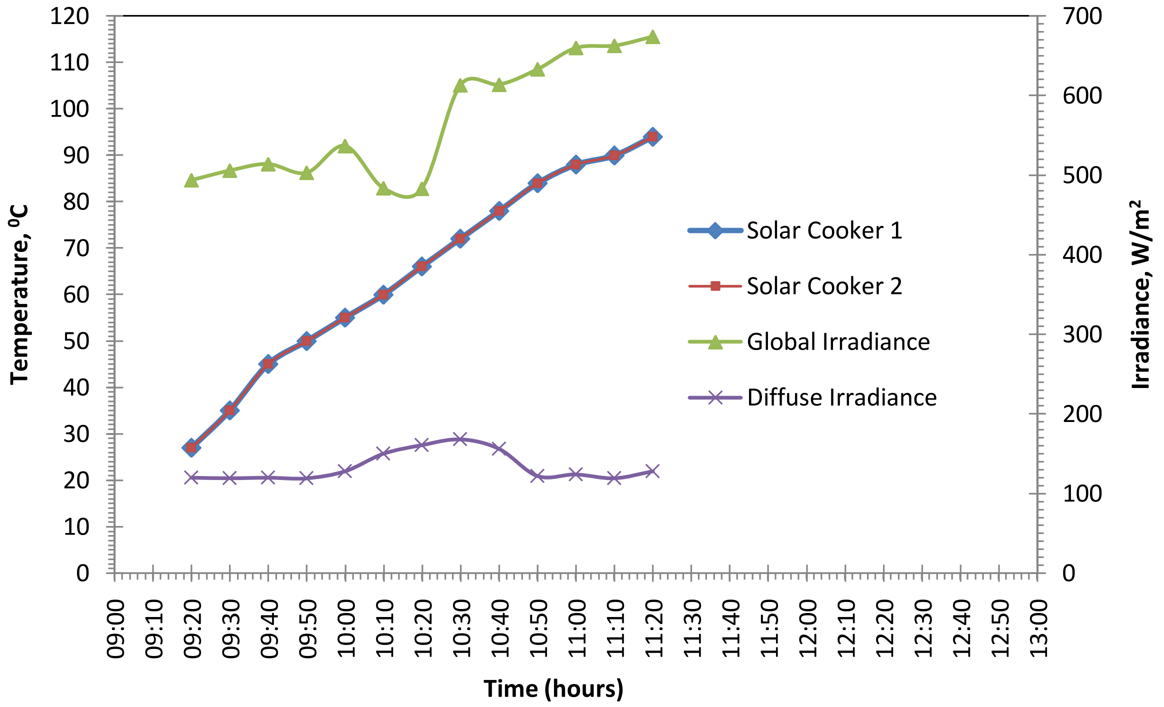

Fig. 2 Standardisation of both solar cookers.

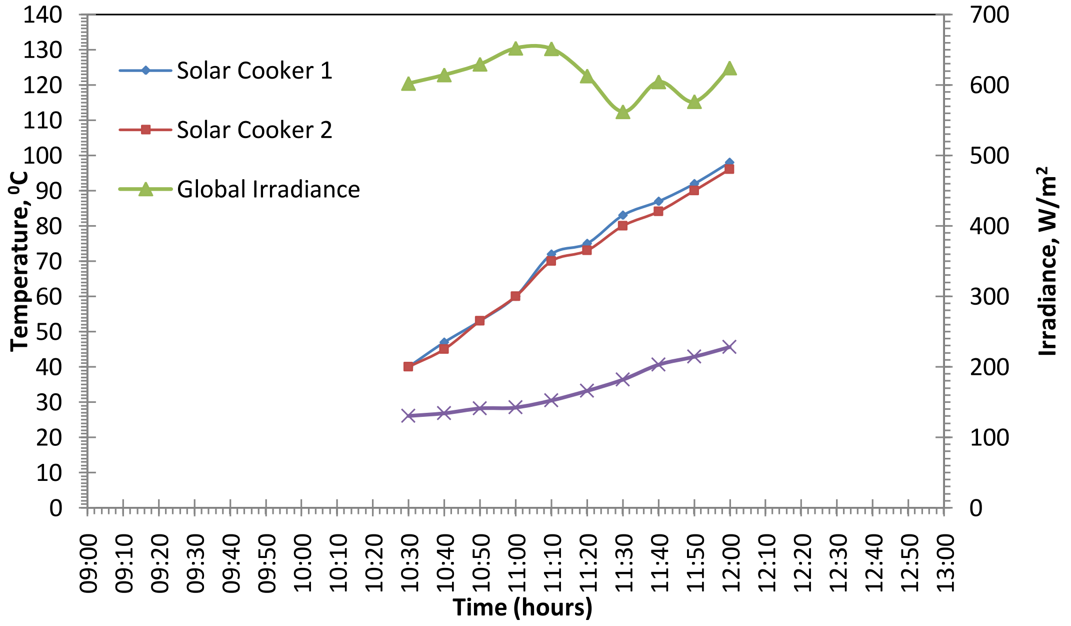

Fig. 3 10 ml HCl added to 25 gram $NaHCO_3$ after 10 minutes from starting of experiment in solar cooker 2.

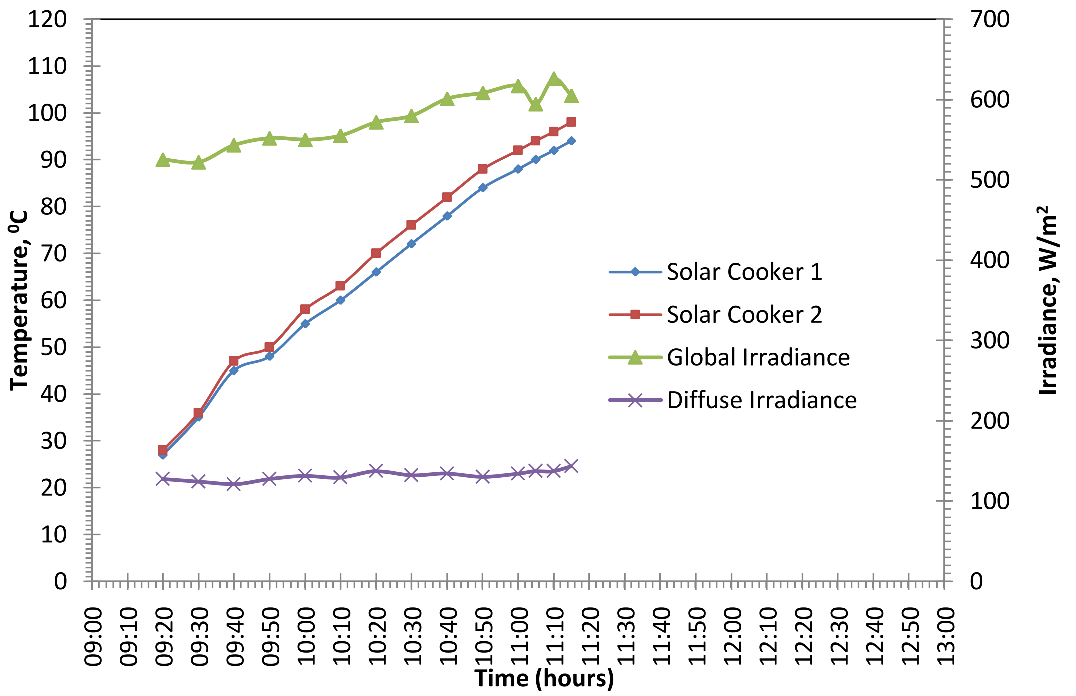

Fig. 4 30 ml HCl added to 60 gram $NaHCO_3$ after 10 minutes from starting of experiment in solar cooker 2.

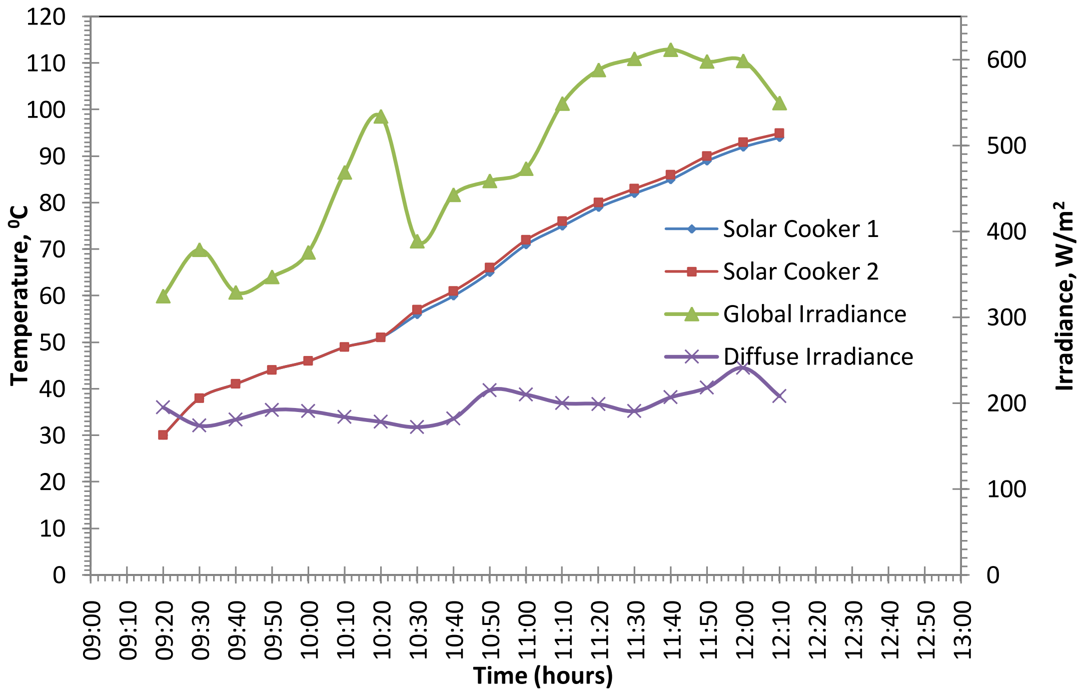

Fig. 5 30 ml HCl added to 60 gram $NaHCO_3$ initially just before the starting of experiment in solar cooker 2.

VI. CONCLUSIONS AND RECOMMENDATIONS

An experimental study has been carried out to investigate the effect of participating medium in cooking chamber of a conventional hot box solar cooker. For this, carbon dioxide gas (CO_2) with atmosp heric air has been used as participating medium in cooking chamber of hot box solar cooker.

No evidence about the use of participating media in hot box solar cooker has been found in the literature survey. Perhaps this is the first study of this type, not only for the solar cookers but also for the other solar devices.

The increase in temperature of water in the box type solar cooker having carbon dioxide gas (CO_2) with air as participating medium for radiation in the cooking chamber has been found significant. Thus the benefit of participating medium in solar cooker has been established.

The main findings of the study are:

1. The increase in temperature of water in the box type solar cooker having carbon dioxide gas (CO_2) with air as participating medium for radiation in the cooking chamber has been found significant. Thus the benefit of participating medium in solar cooker has been established.
2. No evidence about the use of participating media in hot box solar cooker has been found in the literature survey. Perhaps this is the first study of this type, not only for the solar cookers but also for the other solar thermal devices.
3. Carbon dioxide (CO_2) gas can also be formed by reaction of baking soda (sodium bicarbonate) with vinegar (acetic acid, sirka). Baking soda (sodium bicarbonate) and vinegar (acetic acid, sirka) are not costly and usually found in house wife's kitchen. It can be recommended that around 50-60 gram of baking soda with certain amount of vinegar can be kept in a small bowl with cooking pot in the cooking chamber of box type solar cooker.
4. Due to increased density of medium , convective mode of heat transfer has also been enhanced in the solar cooker having participating medium in its cooking chamber. It is an established fact that contribution of convective mode of heat transfer to cooking vessel in conventional hot box solar cooker is very strong.

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