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INFLUENCE OF AIR FLOW CIRCULATION AND ABSORBED THERMAL ENERGY ON CONVECTIVE HEAT TRANSFER DURING OPERATION OF MIXED-MODE SOLAR DRYER

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ABSTRACT

Thermal drying is the most common method for drying agricultural products using the heat source derived from fossil fuels or/and electricity. In many parts of developing countries, the grid-connected electricity and fossil fuels are found to be either unavailable/unreliable or too expensive for the farmer. The scarcity of fossil fuels with their rising cost of production and adverse environmental impacts emphasize the need on the utilization of solar energy as an alternative energy source, especially in the regions, where this source is abundantly available. The knowledge of convective heat transfer from absorber plate to fluid (air) is essential for computer simulation to predict thermal performance of solar dryers. For any dryer system, the air flow circulation and absorbed thermal energy are the critical variables that strongly influence convective heat transfer. For past few decades, out of various solar dryer designs tested in India and abroad, the mixed mode dryer has been extensively studied for computer simulation as well as experimental investigation. Thus for present study, the laboratory model of mixed-mode dryer is designed and constructed for experimentation under forced mode operation. Series of steady state experiments have been performed on dryer for absorbed thermal energy and mass air flow rate with a range of 300-800 W/m^2 and 0.009-0.026 kg/s respectively. The dryer with no-load has been operated, keeping inlet and outlet vents open under indoor controlled conditions. The experimental temperature data of various components of dryer is employed to determine convective heat transfer coefficient, h_{cpf}. Results of the experimental investigation indicate that increased absorbed thermal energy and air mass flow improve convective heat transfer rate. The study also reveals that greater mass flow rate beyond certain value is not recommended for the operation of dryer. In order to investigate the degree of influence of these parameters, sensitivity analysis is done. Results of analysis reveal that the air mass flow rate has relatively greater influence on hot air temperature rise.

Keywords: Convective heat transfer; mixed-mode solar dryer; forced convection; absorbed thermal energy

NOMENCLATURE

h_{cpf}	[W/m^{2o}C]	convective heat transfer coefficient from plate to air of collector-dryer assembly
h_{rpg}	[W/m^{2o}C]	radiative heat transfer coefficient from plate to glass of collector-dryer assembly
k_b	[W/m^{o}C]	thermal conductivity of bottom insulation
L_b	[m]	Length of insulation
S	[W/m^2]	absorbed thermal energy flux
$\bar{T}_p$	[^{o}C]	average temperature of plate of collector-dryer assembly
$\bar{T}_g$	[^{o}C]	average temperature of glass cover of collector-dryer assembly
$\bar{T}_f$	[^{o}C]	average temperature of hot air of collector-dryer assembly (fluid)
T_{am}	[^{o}C]	temperature of ambient air
U_b	[W/m^{2o}C]	bottom-loss coefficient of collector-dryer assembly
Special characters		
σ	[W/m^{2}K^4]	Stefan Boltzmann's constant
ϵ_p		emissivity of absorber plate
ϵ_g		emissivity of glass cover

INTRODUCTION

Drying is a simple, low-cost method to preserve food that might otherwise spoil. It reduces the moisture content of food products to a level below which deterioration does not occur and thus prevents fermentation or the growth of moulds so that they can be stored for future use. Most of the modern drying technologies available are expensive and not appropriate for a developing country, particularly in the areas where prerequisites for these, such as electricity are simply not available adequately. Therefore, it is desired to develop a simple inexpensive and more scientific method as an alternative for preservation of agricultural products. Since, energy from sun is a renewable and low pollutant source to dry agricultural products; it provides an interesting and promising alternative source. Recently drying of food product using solar dryer systems has received considerable interest among researchers in India and abroad [1-3]. They are cheaper to operate than fossil-fueled dryers, requiring no fuel, and they are more easily made with low-cost local materials. Properly designed solar dryers may provide a much-needed appropriate alternative for drying of the agricultural products in developing countries. However, all these dryers are broadly grouped into three major types as direct, indirect and mixed-mode, depending on the design arrangement of system components and mode of solar heat utilization [4-6]. The operation of these dryers is primarily based on the principle of natural or forced air circulation mode. Out of these various dryer designs tested, mixed mode solar dryer has received a considerable attention of researchers because of its faster drying rate of food product leading to overall drying cost reduction [7-9].

The knowledge of convective heat transfer coefficient from absorber plate to fluid (air) h_{cpf} is essential for computer simulation to predict the thermal performance of a dryer. It is strongly dependent on physical properties of fluid, temperature difference, air flow rate, system configuration etc. Understanding heat transfer between plate and fluid will not only help to improve the performance of drying system but also serve as performance index for comparison of various designs of dryer. The heat transfer coefficient and hence thermal performance of any solar dryer predominantly depend on mass air flow rate inside the dryer as well as absorbed solar energy. The literature review indicates that despite lot of work reported on mathematical modeling, experimental performance evaluation of various solar dryer designs, not enough information is available on the determination of convective heat transfer coefficient and its dependence on various influencing variables.

In present study, the laboratory model of mixed mode solar dryer has been designed and constructed to perform steady state no-load experiments for forced air circulation. Experiments with dryer in no-load condition are preferred to provide the consistent results since the load tests are often influenced by type, composition and moisture content of food product. The dryer with inlet-outlet vents open is operated under indoor simulated condition for a wide range of absorbed thermal energy and air mass flow rate of 300-800 W/m^2 and 0.009 to 0.026 kg/s respectively. The indoor experimentation provides more reliable steady state results compared to those obtained for variable outdoor climatic conditions. In this case, the heating by solar energy has been simulated by number of electric heating plates fixed beneath the absorber plate.

PROPOSED METHODOLOGY FOR DETERMINING CONVECTIVE HEAT TRANSFER COEFFICIENT, h_{cpf}

In a mixed mode dryer, the food product in drying chamber receives heated air from solar air collector as well as direct heat from exposure to solar radiation. Since for this dryer, the collector-dryer assembly with inlet and outlet vents open is uniformly exposed to incident solar radiation, it can be considered as a single unit operation approximating to that of solar air collector. The proposed computation methodology therefore, involves consideration of temperature variation effect of various drying chamber components (plate, glass cover, hot air) in addition to that of air collector. For instance, the average temperatures of absorber plate, glass cover and hot air of collector-dryer assembly operating as a single air heating unit are computed from average of individual measured temperature data of each component of solar air collector and dryer chamber. The governing steady state heat balance over collector-dryer absorber plate is applied for determination of h_{cpf}.

Under steady state condition, the electrical energy flux applied to absorber plates of collector and dryer chamber of mixed mode dryer is equal to upward heat transfer from absorber plate to air of collector-dryer assembly. Thus, heat balance on the collector-dryer plate under steady state condition is given as:

$$S = U_b(\bar{T}_p - T_{am}) + h_{cpf}(\bar{T}_p - \bar{T}_f) + h_{rpg}(\bar{T}_p - \bar{T}_g) \quad (1)$$

Rearranging the Eq. (1), one gets:

$$h_{cpf} = \frac{S - U_b(\bar{T}_p - T_{am}) - h_{rpg}(\bar{T}_p - \bar{T}_g)}{(\bar{T}_p - \bar{T}_f)} \quad (2)$$

In Eq. (1), S is the absorbed thermal energy flux; U_b is the bottom heat loss coefficient; the h_{rpg} is the radiative heat transfer coefficient between absorber plate and glass cover of collector-dryer assembly.

The bottom heat transfer coefficient, U_b can be obtained as:

$$U_b = \frac{k_b}{L_b} \quad (3)$$

The radiative heat transfer coefficient between absorber plate and glass cover, h_{rpg} is computed using the following standard relation [10]:

$$h_{rpg} = \frac{\sigma(\bar{T}_p^2 + \bar{T}_g^2)(\bar{T}_p + \bar{T}_g)}{\left[\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1\right]} \quad (4)$$

where $\overline{T_p}$, $\overline{T_g}$, $\overline{T_f}$ and T_{am} represent the average temperatures of absorber plate, glass cover, hot air of collector-dryer assembly and ambient air respectively. ε_p and ε_g represent the emissivity of absorber plate and glass cover respectively. σ is the Stefan-Boltzmann's constant.

EXPERIMENTAL ARRANGEMENT

In the present experimental investigation, the laboratory model of mixed-mode solar dryer has been constructed and tested. It comprises two separate units namely solar air heater for heating the incoming ambient air and drying chamber for drying the food product. An inclined flat-plate solar air collector is connected in series to a drying chamber with glass cover on the top allowing solar radiation to impinge directly on food product (Fig. 1). The air heated across collector plate is fed to drying chamber. The collector-dryer assembly is made of matt black painted 22 gauge (0.643 mm thickness) aluminum sheet. The fibre glass insulation is provided to the bottom and sides of the dryer to minimize the thermal losses through conduction. The whole assembly is encased in a thick wooden frame with an outer aluminum foil cover to protect it from weather conditions. In order to make the dryer system air leak-proof, the rubber gasket is used beneath each glass cover of air collector and drying chamber. The arrangement for wire mesh tray is made inside the dryer chamber for keeping food product to be dried. The collector-dryer assembly is supported by a mild steel angle frame. In order to measure the temperature of various components of dryer namely dryer plate, glass cover, hot air etc. several calibrated thermocouples have been fixed at various locations. Two opposite rectangular openings each of size 0.45 × 0.02 m at collector inlet and dryer outlet are made for air circulation.

In indoor experimentation, the heating of dryer absorber surface from solar radiation is simulated by the electric heater plates placed below it. The electric heating of dryer/collector absorber plate resembles to practical situation when there is symmetrical heating from the overhead sun. The independent set of nine heater plates each sizing 0.05x0.9m and 0.05x0.4m with total wattage of 500W and 250W has been fitted beneath absorber plates of air collector and drying chamber respectively to obtain uniform heating across absorber plates.

In order to perform experiments under forced convection mode, the electric motor (0.5 hp, three phase, and 1440 rpm) with centrifugal fan has been used to circulate air inside collector-dryer assembly (Fig. 1). A divergent rectangular duct made from galvanized iron sheet of 20 gauge (0.812 mm) connecting the motor-fan assembly is provided at the entry of air heater to provide uniform air circulation over absorber surface. To regulate air flow rate, the frequency variable AC drive with adjusting knob is used.

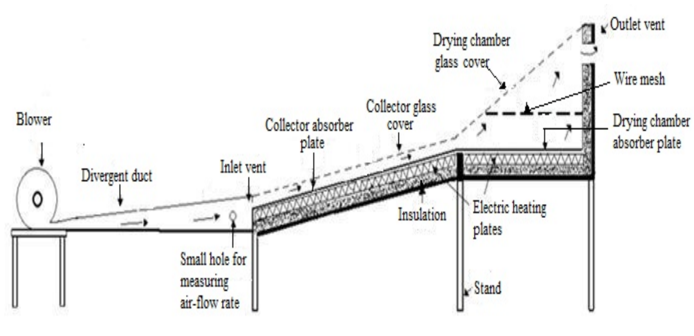

Figure 1 Sectional view of forced convection mixed-mode solar dryer

EXPERIMENTAL PROCEDURE

For experimental investigation, the dryer was operated under no load indoor condition with inlet-outlet vent open for constant input electric energy supplied to heater plates through servo-stabilizer. The electric supply to absorber plates of air collector and drying chamber of mixed mode dryer was independently regulated. The wattage of power input to these absorber plates was so adjusted through variac as to obtain the same amount of power input per unit area of plate. This arrangement permits to simulate outdoor condition of receiving the same amount of solar radiation incident on collector-dryer assembly from overhead sun. Steady state was assumed to have reached when there is negligible variation in temperature measurement of various components of dryer for about 20 minute duration. The steady state for each test run was obtained in about 4 to 5 hours. The temperatures of various components of collector-dryer assembly were measured by pre-calibrated chrome-alumel thermocouples connected to micro-voltmeter (accuracy ±0.1°C). Six thermocouples (two each on absorber, glass cover and air passage) and four thermocouples (one each on plate, top cover and two in air passage) were fixed inside air heater and drying chamber respectively. One additional thermocouple was used to measure ambient air temperature. The power input to electric heater plates was measured by calibrated digital wattmeter (accuracy ± 1.0%). The experiments were repeated for different power input varying from 300 to 800 W/m^2 of dryer/collector absorber plate and air mass flow rate ranging from 0.009 to 0.026 kg/s. The portable air velocity transmitter (Lufft, Germany) operated with power supply of 24VAC/DC was used to measure the flow rate at the inlet of solar collector-dryer assembly by inserting the probe inside a small opening made in duct (accuracy within ± 0.2 m/s).

RESULTS AND DISSCUSSION

The average temperature data of various components of solar collector-dryer assembly is used to compute the convective heat transfer coefficient from Eqs. (2-4) for different absorbed energy and air flow condition. The results of convective heat transfer coefficient, h_{cpf} variation with absorbed energy and air mass flow rate are illustrated in Fig. 2. As can be seen, h_{cpf} increases with the absorbed energy and air mass flow rate. It can be observed that for a given mass flow rate, h_{cpf} increases rapidly up to certain absorbed energy level and thereafter there is a marginal rise. The reason of such behavior may be due to increasing thermal losses due to greater temperature difference of hot air and ambient air. Increasing absorbed energy for a given air flow rate causes higher hot air temperature which in turn enhances heat transfer coefficient, as expected. It can be further noticed that the air mass flow rate has also considerable influence on $h_{cpf.}$ For a given absorbed energy of 500 W/m^2, air mass flow of 0.026 kg/s enhances heat transfer by 65-70% compared to that of 0.009 kg/s, as Reynolds number significantly increases.

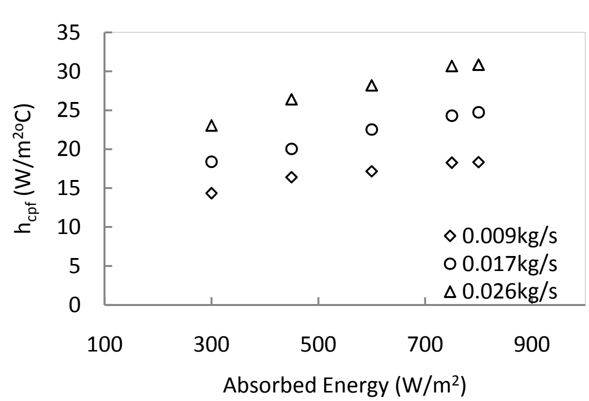

Figure 2 Variation of h_{cpf} with absorbed thermal energy and air mass flow rate

The present study also indicates that there is direct correlation between absorbed energy and rise in temperature difference between absorber plate and air, ($\overline{T_p}$ - $\overline{T_f}$). The variation of ($\overline{T_p}$ - $\overline{T_f}$) with absorbed thermal energy for different mass flow rate is depicted in Fig. 3. As can be seen, for any air mass flow rate, the ($\overline{T_p}$ - $\overline{T_f}$) varies almost linearly with absorbed energy.

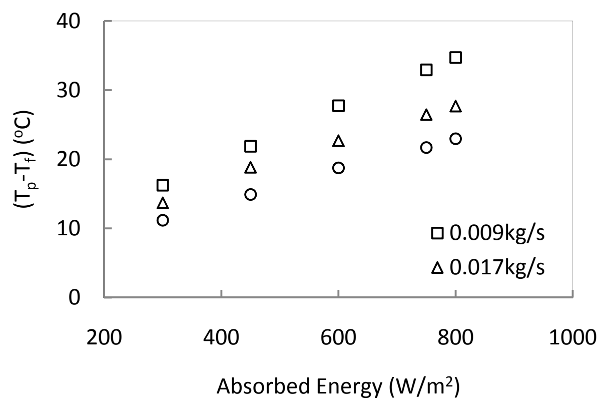

Figure 3 Variation of ($\overline{T_p}$ - $\overline{T_f}$) with absorbed thermal energy for different mass flow rates

It is noteworthy to examine the influence of air mass flow on hot air temperature since each of these parameters influences convective heat transfer. Fig. 4 depicts the variation of average hot air temperature with air mass flow rate for a given absorbed energy level of 750W/m^2.

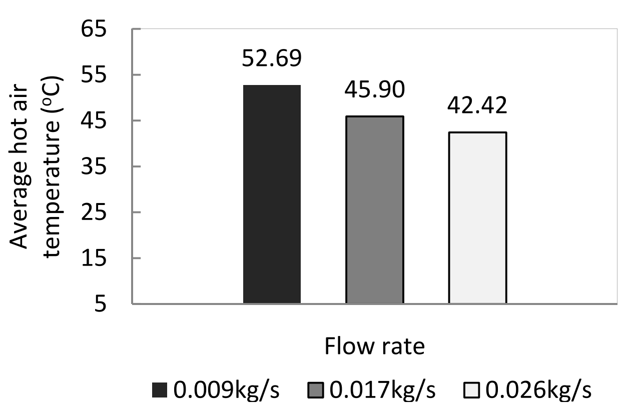

Figure 4 Influence of air mass flow rate on average hot air temperature for absorbed thermal energy of 750 W/m^2

It can be seen that hot air temperature drops significantly as the flow rate is increased from 0.009 to 0.026 kg/s. For instance, it decreases from 52.69 to 42.42^{o}C amounting to about 19.4% for the entire range of air mass flow investigated. The expected decrease in hot air temperature with mass air flow rate reduces its drying capability to remove the moisture from food product causing longer drying process. Researchers have recommended the hot air temperature range of 45-55^{o}C for drying temperature sensitive food products like fruits and vegetables [11]. Therefore, the importance of selecting a suitable value for the air flow circulation rate arises, so that optimum values of h_{cpf} and hot air temperature are achieved for satisfactory operation of dryer system. Further, it is not economically desirable to substantially increase air flow rate beyond a certain limit.

The present study demonstrates that the absorbed thermal energy and air flow circulation have an increasing influence on h_{cpf}. However, the increased absorbed energy causes the rise in hot air temperature while the opposite is true for higher air mass flow rate. It therefore becomes important to investigate the extent of sensitivity of these parameters on hot air temperature. The sensitivity curves for hot air temperature have been obtained for variations of air flow rate and absorbed energy with respect to base values of air flow rate of 0.017 kg/s and absorbed thermal energy of 600W/m^2. Results of sensitivity analysis are depicted in Fig. 5. It can be seen that air mass flow rate in contrast to absorbed thermal energy has relatively more influence on hot air temperature rise.

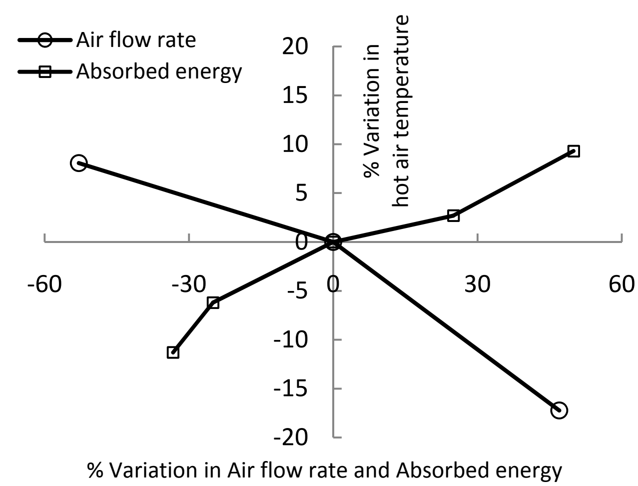

Figure 5 Sensitivity curves for hot air temperature

CONCLUSION

In the present work, the laboratory model of mixed-mode solar dryer has been designed and constructed to study the influence of absorbed energy and airflow circulation rate. Based on the present experimental investigation, it can be concluded that absorbed energy and air mass flow rate have increasing influence on convective heat transfer rate. It has been shown that, for a given mass flow rate, the increased absorbed energy results in higher drying air temperature which in turn increases the h_{cpf}. On the other hand, despite increasing influence of air mass flow on heat transfer, it has decreasing effect on hot air temperature. Thus, it is important to select a proper air mass flow rate keeping in view of drying capability of hot air with an objective of obtaining shorter drying period. It is noteworthy to mention that the proposed test results of a dryer with no load can satisfactorily be utilized for accurate thermal modelling and computer simulation of solar dryer with load for a given plate-fluid temperature.

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