Heat Transfer Analysis in the Chimney of the Indirect Solar Dryer under Natural Convection Mode

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An attempt is established to investigate the heat transfer from a heated chimney of an indirect solar dryer and predicted the chimney outlet temperature using energy balance equation. Tests were carried out with no-load condition under natural convection mode. Data of air velocity, temperatures, ambient relative humidity and solar radiation of the drying process are presented in order to solve the heat transfer coefficients. The result shows that temperature difference between mean air inside a chimney and ambient was 23.8 °C at maximum solar radiation of 812 W/m^2, where maximum airflow is obseved. The predicted chimney outlet temperature was found in good agreement with that of the experimental value. Temperature variation, correlation coefficient, and average absolute error are less than 10%, 0.977, and 5%, respectively. Replacing the normal chimney by heated chimney can significantly reduce the heat loss and increase the chimney efficiency.

Keywords : *chimney, natural convection, solar radiation, indirect solar dryer.*

1. INTRODUCTION

Drying food has been implemented since ancient times to reduce the amount of water content in a food product to a required level of storing for long periods. Drying using solar energy is the most cost-effective way of increasing the shelf life of the foodstuffs as the microbial activity is reduced substantially [1]. Solar food drying broadly refers to the drying technique, which uses solar radiation as input energy required for drying. Solar dryers are classified broadly as active and passive solar dryers. Their key differences are in air circulation. Active dryers have an external mechanical device (usually blower) to drive the air, whereas passive solar dryers are due buoyancy effect [2]. The operation of passive convection dryers depends solely on solar energy.

Generally, because of their low airflow circulation, the performance efficiency of passive solar dryers is considered to perform inefficiently as reported by Ekechukwu and Norton [3], which leads to excessive temperature to occur within the drying chamber. This higher temperature may lead the food to burn instead of drying. There are different ways to improve the performance of such dryers. One effective method of improving such dryers is the proper use of a heater chimney assembled with the drying chamber suggested by Bassely et al. [4]. A chimney works by increasing the buoyancy force to help airflow through the intended structure. The buoyancy force is directly proportional to the difference between the mean air temperature within the chimney and the ambient temperature and the chimney height [3]. In passive indirect solar dryers, when heated air from the collector pass through the dryer chamber, its temperature becomes decreased due to energy losses to evaporate water from the food product in turn decreases the airflow rate. Hence to enhance the airflow, the chimney has to be heated to elevate the air movement reported by Afriyie et al. [5]. A further suggestion was given by Habtay and Farkas [6] that heat transfer can enhance if the external chimney surface painted black matt having high absorptivity property. Kazansky et al. [7] studied the heat transfer from a vertical heated plate placed symmetrically in the chimney. Result showed that the air flow rate in the chimney increases with chimney height when the air in the chimney heated by the plate.

The heat transfer performance on the chimney depends on the operating parameters of the heat transfer coefficient and the flow character. There are several correlations to calculate the heat transfer from heated vertical ducts in thermal convection situations. Thermal convection heat transfer is the process by which heat transfer takes place between a solid surface and fluid surrounding it. If the motion of the fluid is due to the action of buoyancy forces, this is called natural convection else it is forced convection [8]. Generally, natural convection heat transfer coefficients are typically much smaller than those associated with forced convection. Such correlations on natural convection heat transfer used to determine convection heat transfer coefficients can be found in any basic heat transfer textbook [9].

Natural convection heat transfer is the outcome of buoyancy induced flow fields produced by temperature dependent density gradients. Newton's law of cooling equates the heat transfer flux associated with this dand the temperature difference between the surface and the surroundings. The heat transfer coefficient of the chimney duct and Rayleigh number are important in the investigation of natural convection. Several researchers

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have been studied the correlation between the Nusselt, Grashof, and Rayleigh numbers in vertical duct [10]. Churchill and Chu [11] developed a correlation of Nusselt, Grashof, and Rayleigh numbers in vertical plate applicable for uniform heating as well as uniform wall temperature. In this study, natural convection heat transfer coefficient carried out under no-load condition, in which the effect of the relative humidity of the dry air is not accounted in density calculation. However, Yan and Lin [12] and Zhang et al [13] reported that heat transfer coefficient significantly affected by the relative humidity.

The objective of this paper is to predict the outlet temperature of the indirect solar dryer chimney using the fundamental energy equation and compare the result with the experimental ones. Solar radiation, chimney surface and ambient temperatures, airflow rates at inlet, and air temperature within the chimney are measured to provide a further understanding of the flow due to heat transfer by natural convection in the chimney.

2. MATERIAL AND METHOD

2.1 System description

The geometrical model of the indirect solar dryer consists of a vertical cylindrical chimney having an inside diameter of 100 mm and firmly fixed onto the drying chamber as shown in Figure 1. A sufficient duct length was considered to ensure the thermal fully developed conditions at the chimney outlet. The external surface of the chimney was coated with black matt to elevate the ability to absorb more solar radiation.

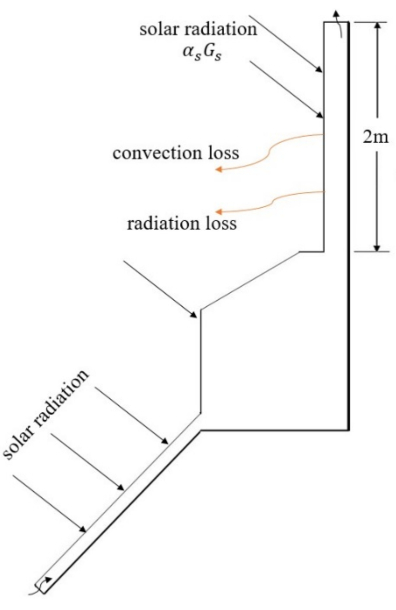

Figure 1. Schematic view of chimney geometry

When solar radiation hits a surface of the opaque materials, do not transmit radiation. If the material is dark and dull, very few reflections can occur. As such, the majority of incidents on dark opaque surfaces will be absorbed. As a result of absorption, the surface temperature increases significantly. In the current configuration, five small holes were drilled along with the chimney height in order to accommodate the temperature sensors. Other thermocouples also fixed at the outer chimney surface and various locations in the dryer.

Mathematical formulations have been applied with the assumption that steady operation condition exists, uniform inlet velocity and physical properties of air were to be varying linearly with temperature. Average hourly solar radiation and average air temperature inside the chimney were noted.

2.2 Experimental set-up

Experimental studies under no-load conditions were carried out in the laboratory of Szent István University Godollo (47.4°N and 19.3°E) Hungary, on different days of September. The experimental data of global solar radiation, ambient temperature, surface temperature, air flow rate, and inlet and outlet air temperature of the chimney were measured every 10-minute intervals and plotted continuously against time for five hours of a day. If the fluctuation of solar radiation did not exceed by more than 50 W/m^2 over a five-minute duration, then 'Quasi-steady' conditions can be assumed [14]. The temperatures were collected using an 8-channel temperature data logger from the various locations of the dryer system as shown in Figure 2. To determine the daily solar radiation data Kipp and Zonen pyranometer model CM 11 (± 0.1 W.m^{-2}) was used. The analogue sensors voltage signal sensors were converted into digital signals through the Advantech ADAM-4017 analogue input module in a data acquisition system. The air velocity was measured using a handheld anemometer (Eurochron EC-MR 330, ±0.3%) located at the entrance of the solar collector.

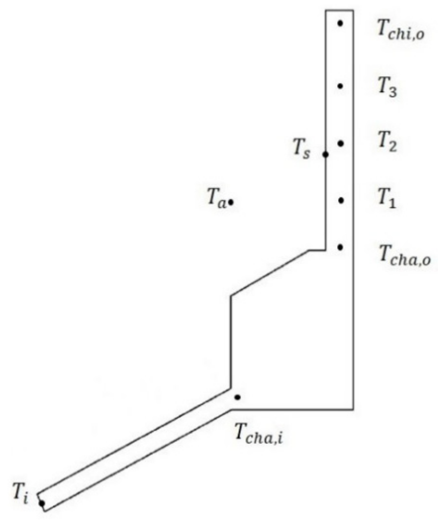

Figure 2. Placement of thermocouples in drying system

2.3 Mathematical formulations

Mathematical equations governing natural convection flow and the heat transfer in a vertical cylindrical chimney are the Navier-stokes equation and energy equation. Choosing the boundary at the outlet of the drying chamber and the *y*-axis is directed vertically upward along the chimney length. The temperature, airflow velocity, and density for inlet boundary con-

dition were taken from the measured data at the outlet position of the drying chamber. The governing equations under the assumptions as followed:
Continuity equation:

$$\frac{\partial u}{\partial y}+\frac{1}{r}\frac{\partial\left(rv'\right)}{\partial r}=0 \tag{1}$$

Momentum y-direction equation:

$$\rho\left[u\frac{\partial u}{\partial y}+v'\frac{\partial u}{\partial r}\right]=-\frac{\partial P}{\partial y}+\mu f_1+\rho g\beta\Delta T \tag{2}$$

where, $f_1=\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)+\frac{\partial^2}{\partial y^2}\right]$

Energy equation:

$$u\frac{\partial T}{\partial y}+v'\frac{\partial T}{\partial r}=\frac{\lambda}{\rho C_p}f_2 \tag{3}$$

where: $f_2=\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial y^2}$

An energy balance equation is applied to describe the performance of a chimney. The net rate of solar energy absorbed by the external chimney surface was calculated as the difference of the total incident solar radiation radiated to the surface and the overall heat loss from that surface, both due to radiative and convective heat transfer processes.

$$q_{net}=\alpha_s I-U_0\left(T_s-T_a\right) \tag{4}$$

This net solar radiation is used to heat up the air within the chimney and equal to the rate of heat transfer to the fluid. Steady state and negligible effect of heat transfer due to conductivity can be assumed.

$$q_{net}=\frac{\dot{m}C_p}{A_{ch}}\Delta T \tag{5}$$

The net rate of energy absorbed by the surface of the chimney is then:

$$\frac{\dot{m}C_p}{A_{ch}}\Delta T=\alpha_s I-U_0\left(T_s-T_a\right) \tag{6}$$

The heat transfer processes taking place on the external chimney surface are rather more complex than is in the case for the inside surface heat coefficient as radiation and convection heat transfer due to wind speed involvement. Depend on the wind speed around the chimney surface, the dominant mechanism, natural or forced convection, will be selected to compute the convective heat transfer coefficient.

For forced convection heat transfer due to wind is given by McAdams [15]:

$$h_{wind}=5.7+0.38V \tag{7}$$

Cengel [9] suggested that the natural heat transfer coefficient is negligible when the result of $Gr/Re^2 < 0.1$, forced convection is negligible when $Gr/Re^2 > 10$ and neither is negligible when $0.1 < Gr/Re^2 < 10$.

The radiative heat transfer coefficient from the external surface to the sky with referring to ambient temperature with a simplified linear equation is computed according to Duffie and Beckman [16]:

$$h_r=\sigma\varepsilon_s\left(T_s+T_{sky}\right)\left(T_s^2+T_{sky}^2\right) \tag{8}$$

The sky temperature calculated by [17]:

$$T_{sky}=0.0552T_a^{1.5} \tag{9}$$

The external overall heat loss coefficient from the surface to the ambient is then defined in terms of the convective and radiative components thus:

$$U_0=h_{wind}+h_r \tag{10}$$

When heat is added to the air by solar radiation, the air density varies with temperature, a flow can be induced due to gravity force acting on the density variations. Such buoyancy-driven flows are called natural-convection flows. In natural convection, the buoyancy induced flow is determined by the Rayleigh number as given based on chimney height, L [18]:

$$Ra_L=\frac{g\beta\Delta TL^2}{v_f^2}\cdot \mathrm{Pr} \tag{11}$$

The local Rayleigh number more specifically as the Grashof number, Gr_L is usually used in heat transfer for the definition of the flow regime to be laminar or turbulent which has the same role with Reynolds number in forced convection flows. An important characteristic of the flow is the rate of heat transfer through the chimney surface. The average Nusselt number for natural convection from chimney wall given by Cengel [9] where for laminar flow ($Ra<10^9$):

$$Nu=0.68+\left(0.67Ra^{1/4}\right)/\left[f_3\right]h^{4/9} \tag{12}$$

and for turbulent flow ($Ra<10^{12}$):

$$Nu=\left\{0.825+\left(0.387Ra^{1/6}\right)/\left[f_3\right]^8 h^{8/27}\right\}^2 \tag{13}$$

where: $f_3=1+\left(0.492/\mathrm{Pr}\right)^{9/16}$.

The physical properties of air assumed to vary linearly with temperature (°C) because of the low temperature range encountered [19]. The following empirical relationships are assumed as:

$$\mu=\left[1.983+0.00184\left(T_f-27\right)\right]10^{-5} \tag{14}$$

$$\rho=\left[1.1774-0.00359\left(T_f-27\right)\right] \tag{15}$$

$$\lambda=\left[0.02624+0.0000758\left(T_f-27\right)\right] \tag{16}$$

$$C_p=\left[1.0057+0.000066\left(T_f-27\right)\right]10^3. \tag{17}$$

$$\beta=1/T_f \tag{18}$$

To validate the predictions of the heat transfer model, two statistical parameters are compared, i.e.

correlation coefficient and average absolute error. Correlation coefficient (R) is a statistical tool provides information on linear relationship between the predicted and experimental values. Average absolute error (Δ) is also defined as a quantity used to measure how close the predicted values are to the experimental ones.

$$R = \frac{\sum_{i=1}^{i=N}\left(y_{\exp}^{i} - \bar{y}_p\right)\left(y_p^{i} - \bar{y}_p\right)}{\sqrt{\sum_{i=1}^{i=N}\left(y_{\exp}^{i} - \bar{y}_p\right)^2 \sum_{i=1}^{i=N}\left(y_p^{i} - \bar{y}_p\right)^2}} \quad (19)$$

$$\Delta_{avg} = \frac{1}{N}\sum_{i=1}^{i=N}\left|\frac{y_{\exp}^{i} - y_p^{i}}{y_{\exp}^{i}}\right| * 100 \quad (20)$$

3. RESULTS AND DISCUSSION

3.1 Airflow rate and temperature

The performance of the chimney effect strongly depends on the temperature between the mean air temperature of the chimney and the temperature of the surrounding ambient air and also the intensity of the solar radiation. Figure 3 presents the variation of solar radiation, ambient air temperature, chimney surface temperature and the mean air temperature of the chimney between 10:00 to 15:00. It seems that mean air temperature increases with increasing solar radiation with a higher value was observed at around 1:00 pm.

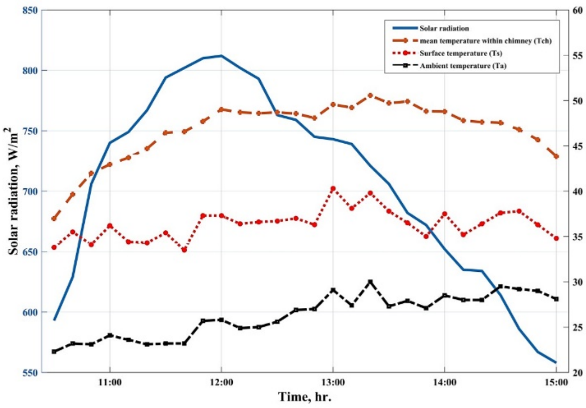

Figure 3. Variation of solar intensity, mean air temperature, surface and ambient temperature with time of the day

The solar radiation and mean air temperature varied from 558 to 812 W/m^2 and 37 to 51 °C, respectively. while, surface and ambient temperatures varied from 34 to 40 and 22 to 30 °C, respectively. It is clearly seen that the maximum global solar radiation is observed with 812 W/m^2 at 12:00 hr., whereas ambient air, surface and mean temperatures were observed maximum with 30 °C, 42 °C and 52 °C at around 1:00 pm respectively. It is also seen that the maximum temperature difference between mean air temperature and the ambient temperature was 23.8 °C at maximum solar radiation. This temperature difference assured for buoyancy force to happen.

Because of low surface temperature, more heat loss happened from the chimney surface to the surrounding. The effect of this loss can be explained from Figure 5, where the temperature variation between the outlet and inlet of the chimney remains constant.

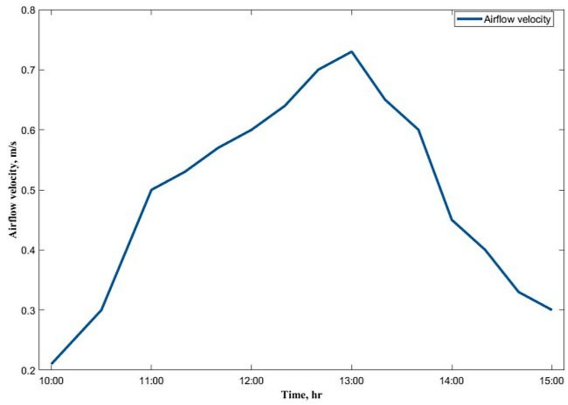

Figure 4. Variation of inlet airflow rate

Figure 4 shows the variation of inlet airflow velocity with the time of the day. The airflow velocity is strongly dependent on the solar radiation effect and the temperature difference between mean air temperature within chimney and that of the surrounding ambient air temperature. It can be seen that the velocity value is observed with 0.72 m/s at 13:00 hour, where maximum temperature occurred.

3.2 Temperature distributions along chimney height

The effect of stack height on the air temperature within the chimney is significant. The larger the chimney height, the higher the chimney outlet air temperature. As expected from Figure 5, air temperature increases as chimney height increases. However, even if the air temperature inside the chimney increases by 45% at higher solar radiation, the external surface temperature of the chimney remains below the chimney air temperature. The kinks in the results shown for chimney height less than 0.6 m are due to the transition from laminar to turbulent flow of the natural convection heat transfer coefficient.

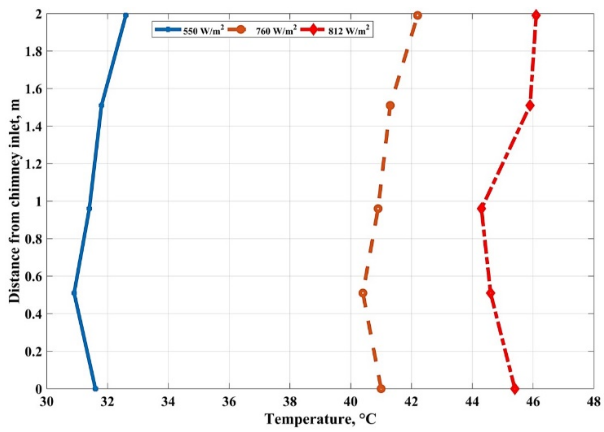

Figure 5. Temperature distribution along chimney height

The variation of the outlet and inlet air temperature within the chimney height for a given solar radiation input almost constant regardless of the chimney height due to the lack of temperature stratification within the drying chamber.

It can be observed clearly that the air temperature within the chimney height increases as the solar radiation increases, which results in a higher temperature difference with the surrounding ambient temperature.

3.3 Prediction of chimney outlet temperature

The external chimney surface is exposed to both radiative and convective heat losses. The radiative heat transfer coefficient was estimated from Equation (8) on different values surface and sky temperatures. For estimating the convective heat transfer coefficient, first evaluate the values of Grashof and Reynolds numbers and found the Grashof number was dominant than Reynolds number. Besides, the flow type was found laminar flow. Then Equation (12) was applied to estimate the convective heat transfer coefficient. The chimney outlet temperature was predicted by evaluating Equation (6) on different solar radiation, mass flow rate, and ambient and surface temperatures inputs. The predicted outlet temperature was compared with the experimental result as shown in Figure 6.

The variation temperature difference between predicted and experimental was found to be less than 10%. This variation can be accepted using correlation coefficient which turned out 0.977 with average absolute error of 5%. This variation can be accepted using correlation coefficient which turned out 0.977 with average absolute error of 5%.

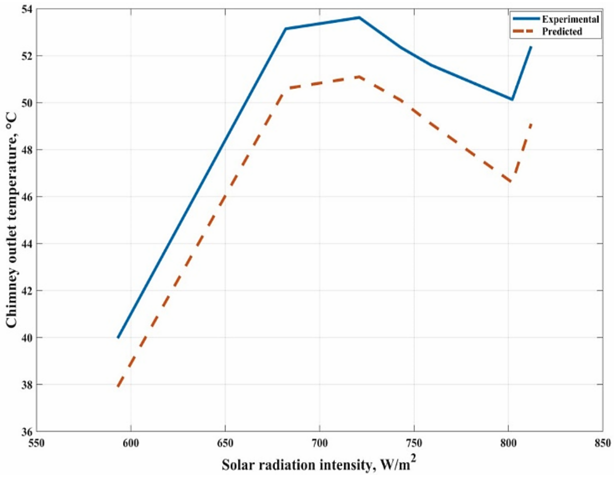

Figure 6. Experimental and predicted temperature variation with solar radiation

4. CONCLUSIONS

A simple mathematical formulation was applied to evaluate the heat transfer along with the cylindrical chimney of the indirect passive solar dryer. Besides, Nusselt and Rayleigh's numbers were used in this study to evaluate the heat transfer across the chimney. Metrological data (solar insolation, ambient temperature, chimney surface temperature and temperature inside the chimney), as well as airflow velocity, were measured experimentally to minimize the number of iterations required to evaluate the heat transfer coefficient and to assess the performance of the chimney. It is observed that higher values of mean air temperature and airflow velocity were obtained to higher values of solar radiation.

Result of the experiment showed that maximum temperature difference of 23.8 °C was obtained for buoyancy effect to occur in the chimney. However, due to the lower temperature of the external surface temperature as compared with the mean air temperature within the chimney, results in increasing the heat loss to the surrounding. Moreover, the mathematical approach for predicting the outlet temperature of the chimney is in good agreement with the experimental results with a correlation coefficient of 0.977. It can be suggested from the result that replacing the normal chimney by such solar chimney can significantly reduce the heat losses as well as increase the thermal efficiency.

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NOMENCLATURE

A_{ch}	chimney inlet area
q_{net}	net heat absorbed by the surface
$\dot{m}$	mass flow rate
U_0	overall heat transfer coefficient
h	heat transfer coefficient
I	solar radiation
T	temperature
C_p	specific heat of air at constant pressure
y_{exp}	experimental value
y_p	predicted value
Nu	Nusselt number
Ra	Rayleigh number
Re	Reynolds number
Pr	Prandtl number

Greek symbols

ρ	air density
ν	kinematics viscosity of air
μ	dynamic viscosity of air
λ	thermal conductivity of air
β	coefficient of expansion of air
σ	Stephan-Boltzmann constant
ε_s	emissivity of the black matt
α_s	absorptivity of the black matt

Superscripts

r	radiative
wind	wind convection
a	ambient
s	chimney surface
sky	sky
f	mean air temperature

АНАЛИЗА ПРЕНОСА ТОПЛОТЕ КОД ДИМЊАКА ИНДИРЕКТНЕ СОЛАРНЕ СУШАРЕ У РЕЖИМУ ПРИРОДНЕ КОНВЕКЦИЈЕ

Хабтај Ј., Бузаш Ј., Фаркаш И.

Истражује се пренос топлоте код загреваног димњака индиректне соларне сушаре и предвиђене излазне температуре коришћењем једначине енергетског биланса. Испитивања су вршена у условима без оптерећења у режиму природне конвекције. Подаци о брзини протока ваздуха, температури, релативној амбијенталној влажности и сунчевом зрачењу су коришћени за добијање коефицијената преноса топлоте. Резултати показују да је разлика између средње вредности температуре у унутрашњости димњака и амбијента 23,8 C^0 при максималном сунчевом зрачењу од 812 W/m^2 када је проток ваздуха максималан. Утврђено је добро слагање између предвиђене излазне температуре из димњака и експерименталне вредности. Варирање температуре, коефицијент корелације и просечна апсолутна грешка износили су мање од 10% односно 0, 977 односно 5%. Заменом класичног димњака загреваним димњаком може се знатно смањити губитак топлоте и повећати степен искоришћености димњака.