International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:4, No:2, 2010

Heat and Mass Transfer in a Solar Dryer with Biomass Backup Burner

Andrew R.H. Rigit and Patrick T.K. Low

Abstract**—**Majority of pepper farmers in Malaysia are using the open-sun method for drying the pepper berries. This method is time consuming and exposed the berries to rain and contamination. A maintenance-friendly and properly enclosed dryer is therefore desired. A dryer design with a solar collector and a chimney was studied and adapted to suit the needs of small-scale pepper farmers in Malaysia. The dryer will provide an environment with an optimum operating temperature meant for drying pepper berries. The dryer model was evaluated by using commercially available computational fluid dynamic (CFD) software in order to understand the heat and mass transfer inside the dryer. Natural convection was the only mode of heat transportation considered in this study as in accordance to the idea of having a simple and maintenance-friendly design. To accommodate the effect of low buoyancy found in natural convection driers, a biomass burner was integrated into the solar dryer design.

Keywords**—**Computational fluid dynamics, heat and mass transfer, solar dryer.

I. Introduction

PRESENTLY, there are several types of dryers being developed for drying agricultural crops. For instance, reverse flat plate absorber cabinet dryer [1], tunnel type solar dryer [2-3], mixed mode natural convection solar dryer [4-5], natural convection dryer with biomass backup [6-7], and closed-type solar dryer [8]. The researches of these dyers concluded that the size and type of crop, level of solar exposure or isolation, ambient air temperature and humidity, direction and velocity of wind, and equipment's temperature distribution architecture play a very important role in designing an efficient solar dryer. The efficiency of solar crop dryer is determined by its drying time required for specific moisture content. In fact, there is no one perfect and universal dryer that fits all agricultural crops. An inappropriate solar dryer may cause overheat or under heat thus it causes a quality deterioration of the dried crop.

A detailed mathematical modeling was presented to illustrate the feasibility of mixed mode natural convection solar dryer for common agricultural crops [5]. The modeling laid an important framework for the modeling of our proposed dryer. In fact, a mixed mode drying could back up the efficiency of the solar dryer against unpredictable weather such as rainy season when solar heat is insufficient. On the other hand, a financial feasibility analysis [9] of a solar dryer for drying agricultural crops was reportedly performed. The result showed that the unit cost of solar drying of pepper was 7% of its wholesale price. The solar dryer was able to reduce the initial moisture content of 71% to the desired 13% in two days. A technical feasibility analysis of solar drying for agricultural products of mainly coffee grains was also reportedly performed [10]. The drying time of coffee grains was reportedly reduced from 156 to 76 hours for an initial moisture content of 47%-53% to the desired moisture content of 10.3-11.7%. Solar dryer creates an increase in temperature and a reduction of mass flow's humidity. Hence, a solar dryer reduces the equilibrium of moisture content and increases the free humidity and drying air velocity.

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This work is supported by the Malaysian Pepper Board.

When In accordance to the idea of having a simple and maintenance-friendly design, a design that incorporates a natural convection dryer and a biomass burner is chosen. This dryer should ideally be able to provide an environment suitable for the drying of pepper berries and to be used by small-scale pepper farmers in Malaysia. The specific objectives of this research work are therefore:

i. to analyze the drying characteristics of pepper berries,
ii. to simulate the heat and mass transfer in a solar dryer, which works on natural convection and with biomass as the back-up energy, and
iii. to ensure that the proposed design is capable of drying the pepper berries at the optimum operating temperature.

II. Pepper Berries Drying Characteristics

Before designing the solar dryer for drying pepper berries, the pepper berries' drying curve was investigated. This investigation was conducted to determine the drying characteristics of pepper berries. The ambient air temperature was recorded prior to the experiment to indicate a controlled environment. To obtain the initial moisture content in wet base (w.b.), a sample of 200g of berries was dried at a temperature of 70^{o}C until the weight of the berries becomes constant. The berries were weighted and the different between the initial and final weight was recorded and used for the calculation of initial moisture content of the sample. In general, the weight loss and overall weight are measured form two curves in opposite magnitude as shown in Fig. 1.

The weight loss increases as time goes whereby the overall weight measured decrease indicating the moisture content being disposed through drying process. At this stage of testing, it was found that an operating temperature of 70°C is suitable for the drying of peppercorns as it retains an average of 11.5% that met the drying target of 12%±1% w.b. of moisture without destroying the volatile oil contents. It took less than seven hours to achieve the desired result compared to traditional sun-drying, which takes around five days pending the weather condition. More dryings may be carried out in order to verify the proposed temperature that dries pepper berries at the highest drying rate and meet the physical and chemical specifications for black peppers.

Fig. 1 The weight loss at a drying temperature of 70°C

III. Heat and Mass Transfer Modelling

The modeling of temperature and velocity distributions inside the dryer was performed by utilizing a commercially available computational fluid dynamics (CFD) software, STAR-CD [11]. The modeling is performed on an empty chamber without the pepper berries. Block meshing was used to model the solar dryer. For the glass and aluminum layers in the solar collector, the block meshing consists of eight corner-vertices being set up and connected. The same technique is implemented for the aluminum and clay-brick layers of the drying chamber. Fig. 2 shows the fluid and solid domain with rectangular cells and grids of the solar dryer. The fluid domain is shown in red while the solid domain of glass and aluminum is shown as blue and purple respectively.

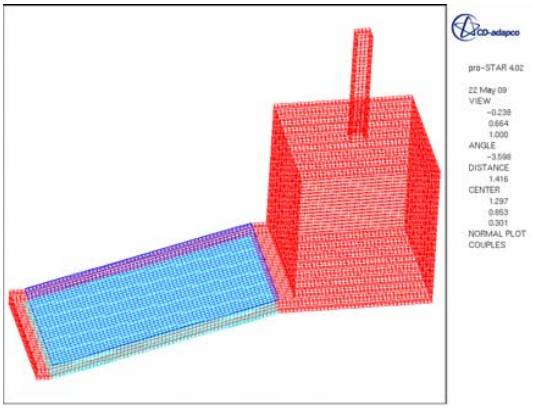

Fig. 2 Computational fluid domain of the solar dryer

The solar dryer model operates by absorbing the solar radiation as its source of heat energy. The solar intensity is 185.19 W/m^2 at solar azimuth of 0 and solar altitude of 90°. The air flow is affected by the gravitational acceleration of 9.81 m/s^2 in the negative y-direction. The molecular viscosity is 1.81 x 10^{-5} kg/ms at a specific heat of 1006 J/kg K, and conductivity of 0.02637 W/m K. The model assumes that fluid substance is ambient air and there is a turbulent air flow in the drying chamber. Hence, the initial temperature in the solar dryer is assumed to be similar to the ambient air temperature, set at 308 K. There is a heat transfer between the solid domains and fluid domain. The solid domains include aluminum, glass and clay brick as shown in TABLE .

TABLE I
MATERIAL PROPERTIES

Material	Density (kg/m^3)	Thermal Conductivity (W/m K)	Specific Heat (J/kg K)
Glass	2600	1.1	840
Aluminum	2800	180	880
Clay brick	2403	0.9	920

IV. Simulation for Natural Convection

The solar dryer is modeled for natural convection without any forces applied on the air flow at the inlet. This is to meet he targeted users, small-scale farmers, which may not have ready source of heat energy such as electricity in place for them to operate the dryer. Furthermore, the solar dryer must be simple to assemble. It must also be portable for it to be moved in order to obtain the maximum solar radiation. The profile of air flow velocity in the dryer model is shown in Fig. 3.

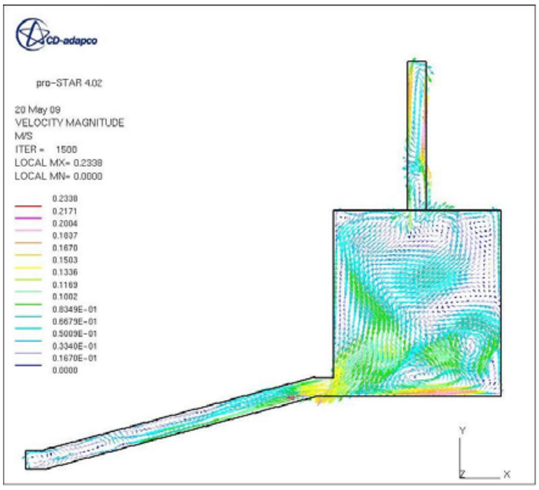

Fig. 3 Velocity distributions for natural convection

The maximum air velocity that can be achieved is 0.2338 m/s. The air flows from the inlet of solar collector to the drying chamber while some of the air flow back into the collector due to circular air flow. The highest air flow velocity is found at the area near the chimney outlet. Hence, turbulent flows under the convection heat transfer occur in the chimney as it is the high air flow region. However, air flow velocity at the center of the drying chamber is low which is below 0.1002

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:4, No:2, 2010

m/s. The high air flow velocity can contribute to shorter time in the drying of pepper berries.

Air flows through the heated aluminum surface and absorbs the thermal heat in the solar collector. The density of heated air reduces as it flows up the collector. The heated air is replaced by the cooler air flowing from the surrounding through the inlet of the solar collector. The heated air moves upward and enters the drying chamber. The convection process proceeds with the buoyancy force causing the reduction of fluid density. Hence the drying chamber obtains its heat through the heated air flowing from the solar collector. There is no sharp-edged inlet connecting the drying chamber to the chimney, so the fluid can make a smooth flow up to the chimney. As a result, no contraction region is formed. There is no turning corner in the chimney so the air flows out smoothly through it.

Fig. 4 shows the distribution of temperature in the solar dryer using contour-plot at middle section. This temperature profile is selected at the middle-section of the model. The highest temperature is 366.6K and the lowest temperature is 291.2K. The temperature of the fluid is below 340.9K in the solar collector. The fluid temperature is between 335.4K and 352.0K in the drying chamber, where the highest heat concentrates at the top of the chamber near the connection to chimney. Overall, the highest temperature region occurred in the center of the chimney with the highest temperature of 366.6K. The top and sides surfaces of the drying chamber are designated as adiabatic; hence there is no heat loss or gain through the surfaces. The highest temperature occurred in the chimney because of the turbulent flow at the chimney outlet. There is no external force to drive the heat out from the chimney. The heat only releases slowly to the surrounding by the gravitational and buoyancy forces.

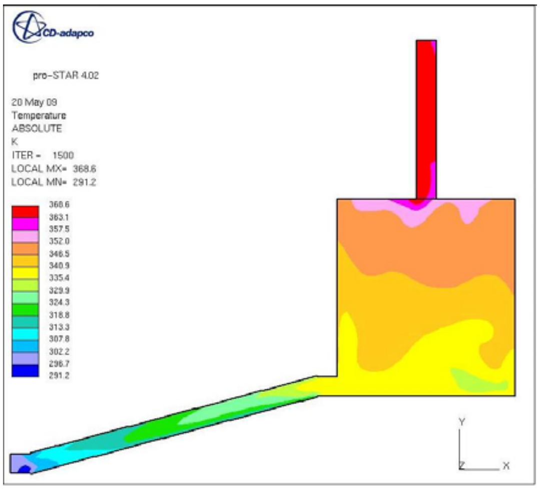

Fig. 4 Temperature distributions for natural convection

V. SIMULATION FOR FORCED CONVECTION

Forced heat convection refers to the heat transferred by the movement of fluid under the influence of an external force. CFD simulation was conducted for the solar dryer model based on the assumption that air flow is supplied into the inlet of the solar collector. Therefore, the air flow velocity at the inlet is defined as 0.1 m/s to simulate the force. The velocity of the air flow is found to be at the maximum magnitude of 1.106 m/s. The highest velocity is found at the chimney. Fig. 5 shows the air moves from the inlet of the solar collector to the drying chamber, and moves out through the chimney. The air flow velocity increases as the effective flow area reduces in the chimney.

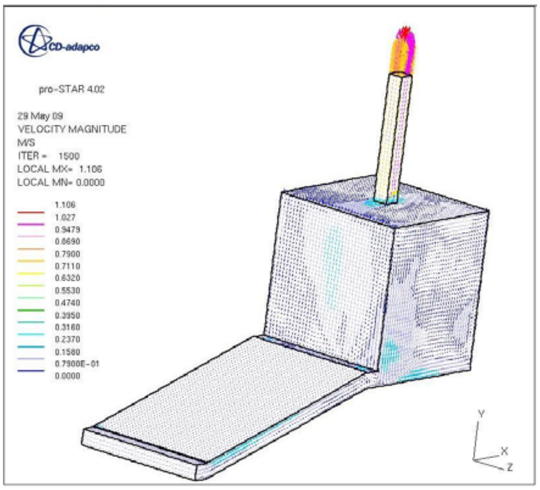

Fig. 5 Velocity distributions for forced convection

The temperature distribution modeled at the middle-section is shown in Fig. 6. The highest temperature obtained is 311.5 K and the minimum temperature is 298.3 K. Most of the heat accumulates at the top corner of the drying chamber where the air velocity is low hence the temperature is 311.5 K.

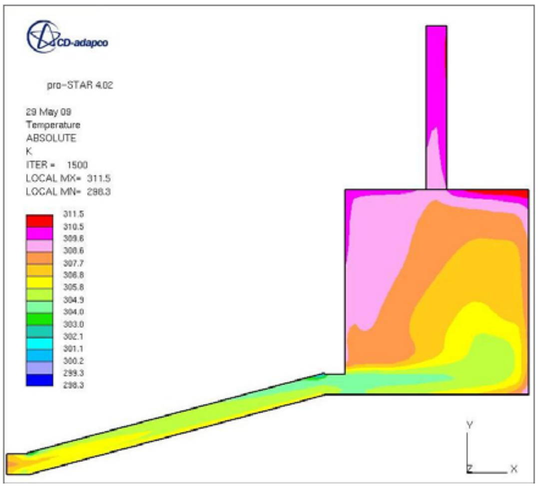

Fig. 6 Temperature distribution for forced convection

In the chimney, the heat temperature is within the range of 308.6 K to 310.5 K. Forced convection modeled at 0.1 m/s forces the air heated by solar radiation through the solar collector into the drying chamber. The fluid also flows under the force supplied at the solar collector's inlet. Heat accumulates in the drying chamber with temperature ranges from 303K to 311.5K. Despite a small volume of high thermal heat accumulated at the top corner of the drying chamber, most of the heat was released through the chimney.

The temperature profile of natural convection model as shown in Fig. 4 has a uniform layered thermal heat distribution in the drying chamber from lower to upper parts. The fluid domain has three temperature regions in the drying chamber where the fluid temperature is between 335.4 K and 352.0 K. In comparison, the heat distribution profile of forced convection model is inconsistent as shown in Figure 6. Inconsistent heat distribution in the drying chamber is not suitable for drying pepper berries. This is because the pepper berries are to be placed evenly on trays that are fixed horizontally in the drying chamber.

VI. Conclusions

From the two temperature profiles simulated, it is deduced that heat and mass transfer by natural convection is more suitable for drying pepper berries with solar radiation. In the natural convection model, the thermal heat distribution in the drying chamber was uniformly distributed, suitable for drying the pepper berries. The uniform heat distribution at the center of the drying chamber with a range from 335.4K to 352.0K is sufficient for drying the pepper berries at a wet base of 12%. When the biomass heater was operated for forced convection process, the temperature distribution in the drying chamber consisted of several regions with different temperatures. The heat distribution in the drying chamber was more homogeneous in the natural convection model.

Acknowledgment

The research work was carried out at the Faculty of Engineering, Universiti Malaysia Sarawak.

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