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Mathematical Modeling of a Drying Chamber with Solar Collectors, A Combined Solar Dryer-Refrigerator with a Heat Pump

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ABSTRACT: Drying is a rational way to prevent deterioration in the quality of agricultural products and preserve them for a long time. Drying is a relatively energy-intensive process, accounting for 10-15% of global industrial energy consumption. Mathematical modeling of heat and mass transfer in drying can significantly reduce such a large amount of energy consumed. Mathematical modeling appears to be a valuable tool for controlling the process and kinetics of drying agricultural products. Therefore, mathematical modeling of the balance of heat, mass and equilibrium moisture content in dryers is relevant. (Research purpose) Mathematical modeling of solar convective dryer of agricultural products for in-depth analysis of energy exchange between air and products. (Materials and methods) Mathematical modeling was carried out on the basis of energy analysis of a solar dryer with a solar collector by the method of conservation of mass and energy. (Results and Discussion) The moisture content of apple slices in WDS was found to be 0.455 g/g and 0.598 g/g higher at the end of the first and second days of drying than in the combined solar dryer. The moisture content of the apple slices in the SOW and the combined solar dryer was 0.905 g/g and 0.307 g/g, respectively, at the end of drying. The drying rates of apple slices for the combined solar dryer and SOW were 0.262 g/(g·s) and 0.229 g/(g·s) respectively on the first day, 0.109 g/(g·s) and 0.085 g/(g·s) respectively on the second day. (Conclusions) A combined solar dryer-refrigerator with a heat pump for drying agricultural products is proposed and a mathematical model of a combined dryer with a solar collector is presented, which makes it possible to determine the air humidity and the mass of moisture removed from the dryer.

KEYWORDS: combined solar dryer, drying chamber, environment, solar radiation, drying speed, relative humidity.

I.INTRODUCTION

Currently, due to the energy crisis and problems of environmental pollution, the development of green energy is considered a priority in the world. Drying agricultural products is one of the energy-intensive processes. The energy intensity of drying mainly depends on the drying product and the energy efficiency of the drying system [1]. Reducing energy intensity by using solar energy in drying plants is an effective way to improve drying efficiency. Solar drying has the advantage that it is a renewable and free energy source, while low-temperature solar energy corresponds to a suitable drying temperature for the material [2]. However, the practical application of solar drying generally requires supplementation with other types of energy due to the influence of solar energy instability, periodic change, low heat collection efficiency, etc. [3]. Therefore, over the past decades, numerous research works have been carried out on the design and modeling of solar drying.

Many researchers have studied and proposed some designs of solar dryers for drying agricultural products. In the work of Kahn [4], the kinetics of pumpkin seed drying was studied. Gulzimen et al [5] conducted an experimental and theoretical study of the drying processes of agricultural products and proposed a mathematical model of the kinetics of drying of agricultural products. The work of Ali et al [6] investigated the factors influencing the drying process of the product and proposed the most suitable mathematical model. Rabha et al [7] proposed and studied a solar tunnel dryer through energy and energy analysis, and the average overall thermal efficiency of the solar air collector ranged from 22.95% to 23.30%.

From the above literature review, it follows that convective solar drying has not yet been widely used for drying agricultural products. In our republic, the apple is the most popular fruit for most people. It is commercially available and very rich in nutrients such as vitamin C, carbohydrates, calcium, and minerals. It is known that apples are grown seasonally, and storing apples in a ripe and dried state allows them to be constantly consumed throughout the year.

The purpose of the study is to investigate a dual-function solar refrigerator-dryer-heat pump dryer for drying apple slices and to develop the most suitable mathematical model for the drying characteristics of apple slices.

II.MATERIALS AND METHODS

Scientists from the Karshi Engineering Economics Institute (Uzbekistan) also created a combined solar dryer-refrigerator with a heat pump, which aims to use renewable energy sources for long-term storage and drying of agricultural vegetables, and fruits and food products. (Fig. 1) [8]. The proposed heat-cold supply system makes it possible to simultaneously dry and store agricultural products. In this work, a dry chamber with a flat-plate solar collector was investigated and simulated.

Fig. 1. Combined solar dryer-refrigerator with heat pump

To achieve the goal, mathematical modeling was carried out based on energy analysis. The energy analysis of the solar dryer with solar collector was carried out using the mass and energy conservation method. In the process of drying apple slices, the energy inflows of the solar dryer include solar energy and the electricity used by the fan, and the energy outflows of the solar dryer include the heat losses of various places (solar collector, connecting channel, dry chamber, etc.) and the drying air exiting the dry chamber.

The general equation for the conservation of mass of the drying agent (air) can be expressed as follows:

$$\sum m_{a.in} = \sum m_{a.out} \tag{1}$$

Here, $m_{a.in}$ and $m_{a.out}$ – mass air flows at the inlet and outlet of the dryer, $m^3/hours$.

The general equation for the conservation of moisture mass can be calculated as follows:

$$\sum (m_{a.in} w_{in} + m_{h.m.}) = \sum m_{a.out} w_{out} \tag{2}$$

here w_{in} and w_{out} – mass velocity at entry and exit, m/sek; $m_{h.m.}$ – mass flow of wet material, $m^3/hours$.

The general energy conservation equation can be expressed as follows:

$$Q - W = \sum m_{a.out}\left(h_{out} + \frac{V_{out}^2}{2}\right) - \sum m_{a.in}\left(h_{in} + \frac{V_{in}^2}{2}\right) \tag{3}$$

here Q – amount of heat transferred to the drying agent, Dj; W – amount of heat consumed to evaporate moisture, Dj; h_{in} and h_{out} – Enthalpy of drying agent at inlet and outlet, Dj/kg; V_{in} and V_{out} – speed of body movement during entry and exit, м/с.

The following assumptions can be made:

The airflow for drying was assumed to be stationary [9].

The kinetic energy of the solar dryer can be neglected [7].

Therefore, the energy saving of the apple slice drying process can be determined as follows based on the above assumptions and equations:

$$Q - W = m_a(h_{exit} - h_{in}) \quad (4)$$

The relative humidity of the air for drying can be calculated as follows:

$$\varphi = \frac{wP}{(0{,}622 + w)P_s} \quad (5)$$

here$w$ – wet air speed, m/s;P – partial pressure of humid air, Pa;P_s – saturation pressure, Pa.

The collector efficiency was calculated using the formula:

$$\eta = \frac{Q_{usef}}{\alpha\tau I A_k} \quad (6)$$

hereQ_{usef} – useful heat, Dj; α - absorption capacity; τ– transmittance; I – solar radiation intensity, W/m^2; A_k – heat transfer surface area, m^2.

The enthalpy of the drying agent (air) can be expressed:

$$h = C_{pa}T_a + wh_s \quad (7)$$

The useful heat received by the collector can be calculated using the formula:

$$Q_{usef} = m_a C_{pa}(T_{a.exit} - T_{a.in}) \quad (8)$$

The specific energy consumption (SEC) of the system can be determined as follows:

$$SEC = \frac{Q_{usef} + E_{ven}}{m_{water}} \quad (9)$$

hereE_{ven} – fan energy consumption, W; m_{water} – mass of water removed, kg.

The mass of water removed can be determined by the formula:

$$m_{water} = \frac{m_p(m_{\text{н}} - m_{\text{к}})}{100 - m_{\text{к}}} \quad (10)$$

herem_p – amount of product moisture, kg; $m_i$andm_f – initial and final mass of moisture of the drying agent.

III.RESULTS AND DISCUSSION

A set of experimental data to study the characteristics of drying apple slices was carried out on 2022 year 7-8 June. The change in solar radiation intensity is shown in Fig. 2.

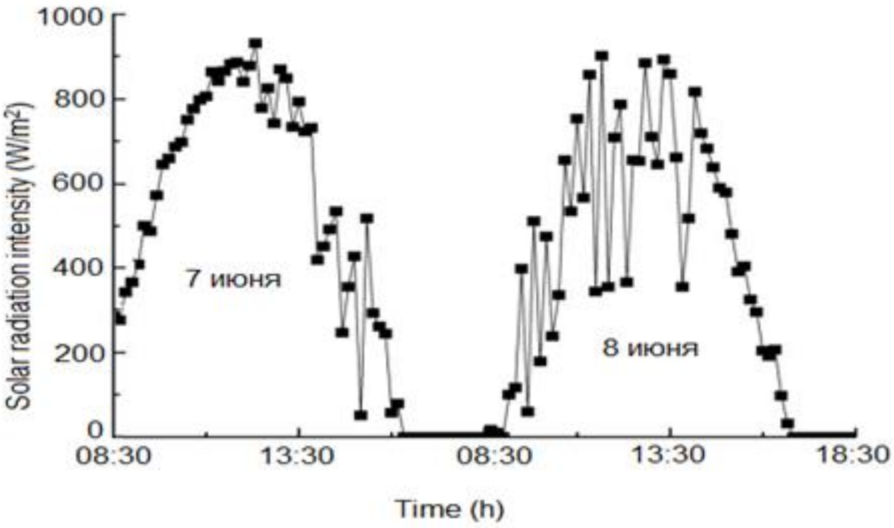

Fig. 2. The change of solar radiation intensity.

The maximum values of solar radiation intensity for two days were 970 W/m^2 and 975 W/m^2, respectively. The maximum values of solar radiation intensity for two days occur at 12:50 and 12:55, respectively. The solar radiation intensity gradually increased to a maximum value and then decreased during the drying experiment period. Changes in air temperature and relative humidity are shown in Fig. 3.

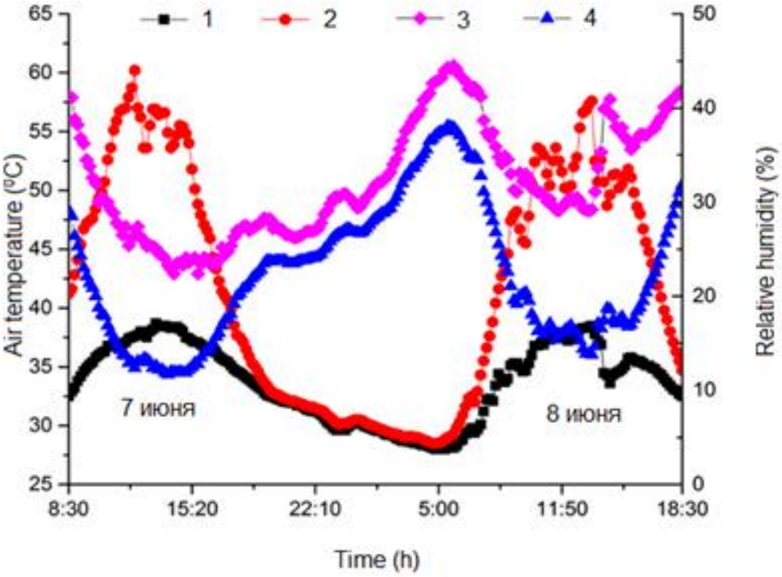

Fig. 3. The change of air temperature and relative humidity: 1-ambient temperature; 2-temperature inside drying chamber; 3-ambient environment relative humidity; 4-relative humidity inside drying chamber

The ambient temperature range was 28…38.5℃. In this case, the temperature range inside the drying chamber was 28.5…60.2℃. The average temperature inside the drying chamber was about 44℃. The range of relative ambient humidity was 22.4...44.5%. In this case, the range of relative humidity inside the drying chamber was 11.7...38.1%. These results indicate that the operating parameters can meet the design requirements in terms of drying temperature control in the drying chamber.

The change in moisture content in apple slices is shown in Fig. 4. The moisture content of apple slices in the open-air dryer (OAD) was 0.455 g/g higher than that of the combination dryer at the end of the first day, and the moisture content of the OAD slices was 0.598 g/g higher than that of the combined solar dryer at the end of the second day of drying. The moisture contents of apple slices in OAD and combined solar dryer were 0.905 g/g and 0.307 g/g, respectively, at the end of drying. These results show that the performance of the combined solar dryer is higher than that of the OAD under the same conditions. In addition, according to Fig. 3, the drying temperature has an important influence on the various sun-drying curves of apple slices.

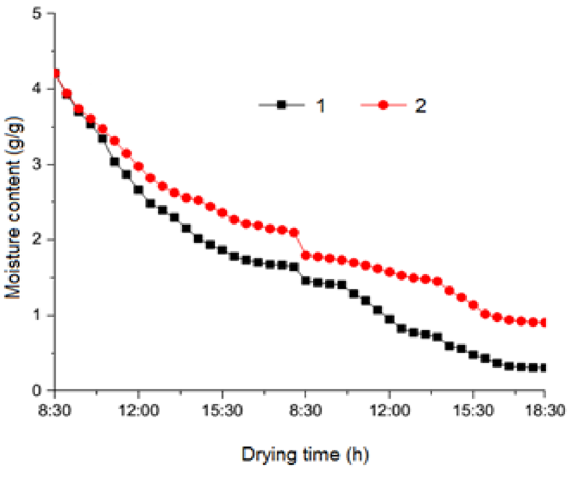

Fig. 4. The change of lemon slices moisture content: 1-combined solar dryer; 2-open sun drying

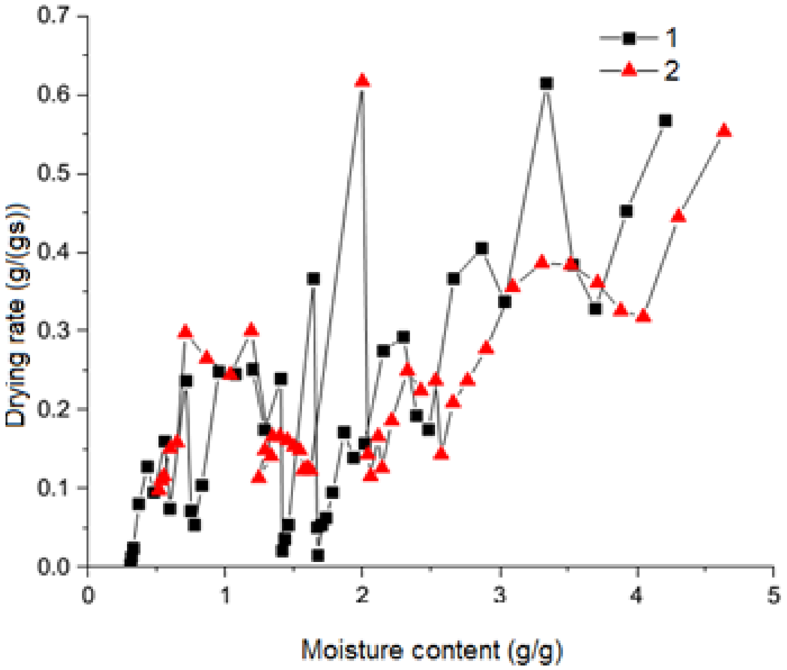

Fig. 5. The change of drying rate for lemon slices' drying: 1-combined solar dryer; 2-open sun drying

In Fig. Figure 5 shows the variation in drying rate of apple slices in typical experiments. The drying rate of apple slices on the first day was higher than on the second day. The average drying rate of apple slices for the combined solar dryer and OAD was 0.262 g/(g·s) and 0.229 g/(g·s), respectively, on the first day. The average drying rate of apple slices for the combined solar dryer and OAD was 0.109 g/(g·s) and 0.085 g/(g·s), respectively, on the second day. The average drying speed of apple slices for the combined solar dryer was higher than for the OAD due to the high temperature of the drying air. Combined with the results presented in Fig. 3, these results show that the drying speed of apple slices is significantly affected by the drying air temperature. The performance of the combined solar dryer was higher than that of the OAD.

IV.CONCLUSION

A combined solar dryer-refrigerator with a heat pump for drying agricultural products for the climatic conditions of the Republic of Uzbekistan is proposed and a mathematical model of a combined drying installation with a solar collector is given based on an energy analysis of the drying installation.

Experimental studies were carried out to study the characteristics of drying apple slices. In experimental studies, the maximum values of solar radiation intensity were 970...975 W/m^2, the ambient temperature range was 28...38.5°C, and the ambient relative humidity range was 22.4...44.5%.

During the experiment, it was determined that the moisture content of apple slices in OAD was 0.455 g/g higher at the end of the first day, 0.598 g/g higher at the end of the second day of drying, than that of the combined solar dryer. The moisture contents of apple slices in OAD and combined solar dryer were 0.905 g/g and 0.307 g/g, respectively, at the end of drying.

The drying rate of apple slices in typical experiments was determined, which for a combined solar dryer and OAD was 0.262 g/(g·s) and 0.229 g/(g·s) respectively on the first day, 0.109 g/(g·s) and 0.085 g /(g·s) respectively on the second day.

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