Development of a Dryer with a Heat Exchanger to Recover Energy for Drying Agricultural Produce

Jeng-Liang Lin*

Department of Biomechatronic Engineering, National Chiayi University, Chiayi, Taiwan, ROC

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Abstract

The purpose of this study was to investigate the effect of a heat recovery by guiding the exhaust air through a heat exchanger in a hot air dryer. The temperature of inlet air could be increased by the developed heat recovery device to achieve energy saving. Experimental results indicated that the heat recovery device could increase the inlet fresh temperature 11℃, the effectiveness ratio of the heat exchanger was up to 70-80%, and heating efficiency of the heater was 50% through the analysis of inlet and outlet temperature, airflow rate as well as fuel consumption of the heater. In addition, the maximum temperature difference in the drying chamber was in the range of 0.6-1.2℃, indicating that the airflow in the drying was uniform, thus the uniform quality of agricultural produce could be obtained. In order to analyse the optimum operation conditions, the effect of fan speed on the temperature and airflow distribution was investigated in the drying system. The results showed that the optimum fan speed should be faster during start-up period and lower during a steady stage.

Keywords: drying, heat exchanger, energy, agricultural produce

1. Introduction

Drying is one of the most important processes for processing agricultural produce. There are three kinds of drying systems used in agricultural industry, they are hot air drying [1-2], dehumidification drying [3-4] and natural drying [5-6]. However, the hot air dryer is the most widely used among mechanical drying systems, especially when the weather is adverse or the automated production is used, both must rely on the mechanical drying system. In the processing of agricultural produce, in addition to the labor cost, the energy consumption of drying process is one of the major costs. Therefore, the purpose of this study was to develop a set of drying system in which the condition of hot air state could be adjusted, design a heat exchanger to recover energy and select an appropriate fan. The major demand of the drying system was to design the airflow duct to achieve the airflow distribute uniformly in the drying chamber in association with the energy recovery technology [7-8]. The energy recovery was via the heat transfer of entering the fresh air and exhaust air to increase the intake air temperature and reduce the energy consumption of drying.

2. Design and Manufacture of the Drying System

The developed dryer was a hot air drying system with capable of recirculation, the schematic diagram is shown as Fig. 1. Considering the general processing capacity and reducing the heat loss, the #430 stainless steel insulated box was used for the dryer body and its physical dimension was W2300mm × L2000mm × H2250mm. A diesel burner was used as the heater, the

* Corresponding author. E-mail address: jllin@mail.ncyu.edu.tw

Tel.: +886-5-2717656; Fax: +886-5-2717647

switch of the heater was controlled by the setting temperature. A 36” fan with airflow rate of 60 m^3/min was selected to drive hot air through the drying chamber.

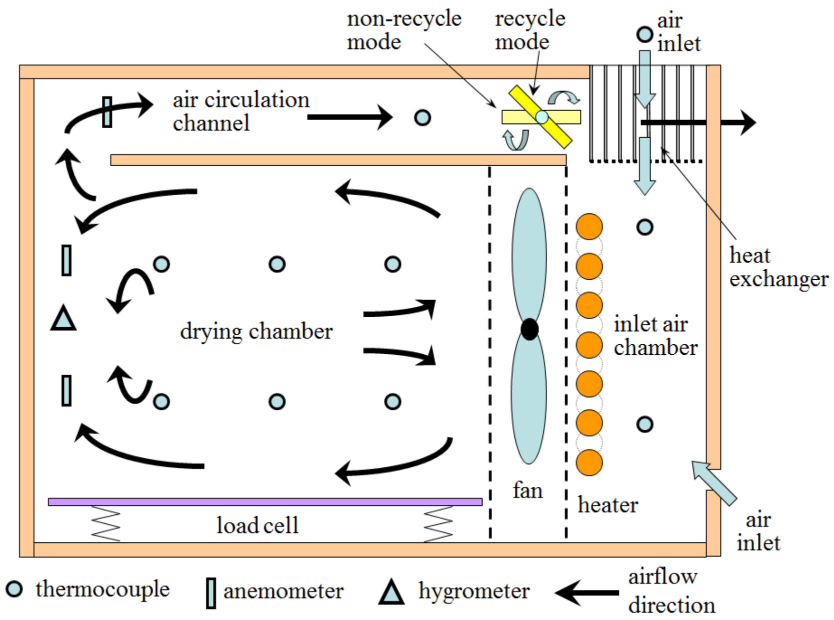

Fig. 1 Schematic diagram of the dryer with a heat exchanger

The heat recovery device with dimension of W1900mm × L400mm was a cross flow heat exchanger, its schematic diagram is shown as Fig. 2. The major component of the device was copper tubes with 440 mm in length, 20 mm in diameter and 1.5mm thickness. The tube bank of staggered tube rows consisted of odd-row and even-row in the heat exchanger having 40 and 41 tubes respectively. Totally, the heat exchange had 8 rows and 324 of tubes. Each tube with 120 of disc-type fins was used to enhance the heat recovery performance. The airflow inside the tube was the fresh air, the external airflow of the tube was the high humid hot air to be exhausted to the outside of the dryer after flowing through the agricultural produce; hence, the designed heat recovery device could achieve the purpose of pre-heating the fresh air. The airflow path in the dryer chamber was fresh air flowing through the tubes of the heat exchanger from the ambient, then roughly heating up to the set temperature by the heater, and then entering into the dryer chamber via the fan to flow through the agricultural product to absorb the moisture, and then passing through the airflow circulation duct to discharge from the drying system. There was one set of switching baffle in the airflow circulation duct which was used to control the relative humidity of drying chamber. When the relative humidity was within the operating range, the baffle was adjusted to the non-circulated position (horizontal) that could discharge the high moisture hot air directly flowing through the heat exchanger out of the dryer. When the relative humidity was too low, the baffle was adjusted to the circulated position (tilted) that could guide the high moisture hot air into the dryer chamber again to maintain the humidity of hot air in the drying chamber in order to avoid damaging the quality of agricultural produce due to the humidity being too low.

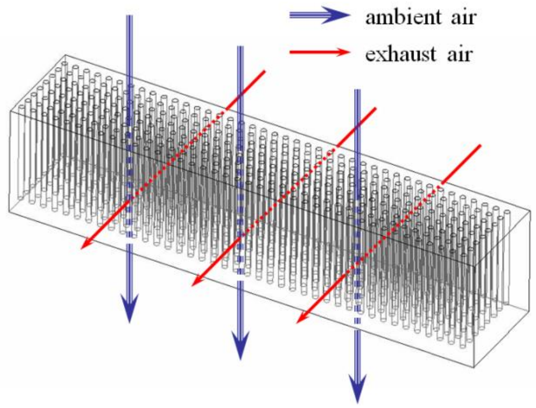

Fig. 2 Schematic diagram of the heat recovery device

The control system was mainly to control the temperature setting for start-up and shutdown of the heater, and control the humidity setting of circulation baffle. As to the fan, a frequency converter was used to control the rotating speed, the effective range of its speed control was in the range of 75-100% of maximum speed. In addition to the operating knobs on the control panel, there were some numerical displays of temperature, humidity and fan speed.

There was one set of electronic scale at the bottom of drying chamber which was able to display the total weight of drying material with the LED, and a built-in RS-232 communication interface was used to monitor and record the material weight during the drying process in real-time. The electronics scale was a welded high-strength steel plate and four weight sensors which were used to neasure the weight range of 0~2000 kg with the accuracy of 0.2 kg.

3. Material and Method

The uniformity of temperature distribution in the drying chamber and the performance of heat recovery were the two indexes for assessing the developed heat recovery dryer. In terms of temperature distribution, the drying chamber was divided into 12 equal segments, since both the heater and fan were installed at the central location of the dryer, consequently, it was expected that the temperature of drying chamber should be bilateral symmetrically. Therefore, analyzing the temperature of right-half space in the chamber would be able to describe the temperature distribution of overall dryer chamber. Six k-type thermocouples were installed on the upper and lower positions of front, middle as well as rear sections at the right side portion of dryer chamber. Each thermocouple was encased by a stainless steel tube, and then inserted into approximately 575 mm from the side of the dryer to measure the temperature at the upper and lower positions of the front, middle as well as rear sections in the right-half space of dryer chamber. Hence, there were temperatures at 6 locations used to analyze the uniformity of temperature distribution. As to analyze the performance of heat recovery device, there were 3 k-type thermocouples installed to measure the temperature before and after the fresh air flowing through heat exchanger, and the temperature of high-temperature humid air before flowing through the heat exchanger. In addition, a k-type thermocouple was installed to measure the intake air temperature at the bottom air intake. As to the measurement of airflow speed in the drying chamber, there were 3 hot wire anemometers installed on the upper and lower positions of drying chamber front section as well as the front-end of airflow circulation duct. A portable relative humidity meter in association with the output signal cable, which was placed at the inside of drying chamber door, was used to measure the relative humidity in the drying chamber. The installation locations of sensors are shown as Fig. 1. The thermocouples, humidity meter, and anemometers were all connected to an automatic data acquisition system (Advantech Adam 5000), and then the Genie graphic control software was used to record the variation of temperature, humidity and airflow speed during tests.

The experiments for temperature distribution, relative humidity change, and airflow distribution were performed without drying material in the dryer chamber with setting temperature of 50℃. The experiments of the optimum speed for fan were to set the frequency converter at 45, 50, 55 and 60 Hz, and 4 replications were performed for each speed, the duration of each test was approximately 40 minutes.

4. Results and Discussion

4.1. Analysis of the airflow and heat recovery device

During the tests of fan at the maximum speed, when the temperature of drying chamber reached the setting temperature after the system was a start-up, the heater stopped and the temperature of intake air gradually decreased until the temperature in the drying chamber was lower than the start-up temperature of the heater. Then the heater started again to increase the temperature of intake air. This kind of cycle was able to achieve the purpose of temperature control (Fig. 3). The experimental results showed that the time required by the drying system from the start-up to the stable state was approximately 400 seconds, afterward, the heater was in the mode of stopping for 120 seconds and starting for 80 seconds to maintain the variation of air temperature in the drying chamber within 5℃ approximately. Therefore, even this drying system used the simplest on-off control technique, it could still control the hot air temperature effectively. It could also be shown from the temperature values at 6 locations that the temperature inside the drying chamber was very uniform. At the stage of the transient heating process after start-up, the temperature difference inside the drying chamber was larger, about 1.2℃. After the system was stable, the temperature difference between the highest temperature and lowest temperature was around 0.6-0.8℃. The experimental results all showed that the highest temperature value appeared at the upper position of the rear section of the drying chamber, while the lowest temperature value appeared at the upper position of the middle section. Theoretically, this result was reasonable since there should have the highest temperature value after just passing through the heater; however, due to the heat transfer of partition board above the middle section, the temperature could be lower than the front section. As to the relationship between the inlet and outlet temperature as well as temperature difference of heat exchanger, it is shown in Fig. 4. The experimental results showed that the heat exchanger was able to increase the air temperature up to 11℃. It indicated that the performance of the developed heat recovery device was good.

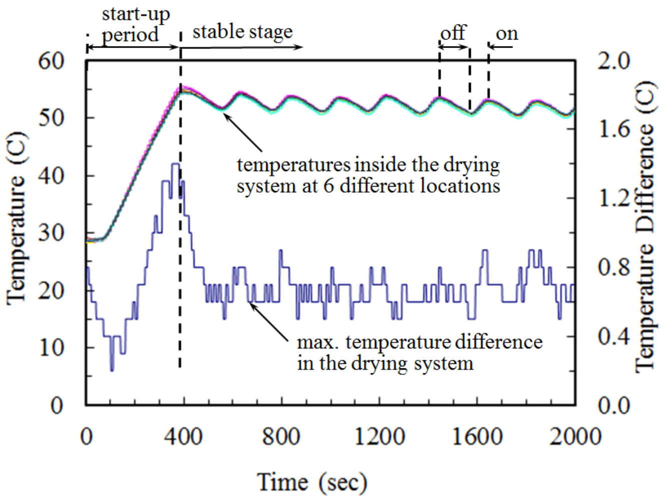

Fig. 3 Variation of temperatures at 6 different locations and maximum temperature difference in the dryer

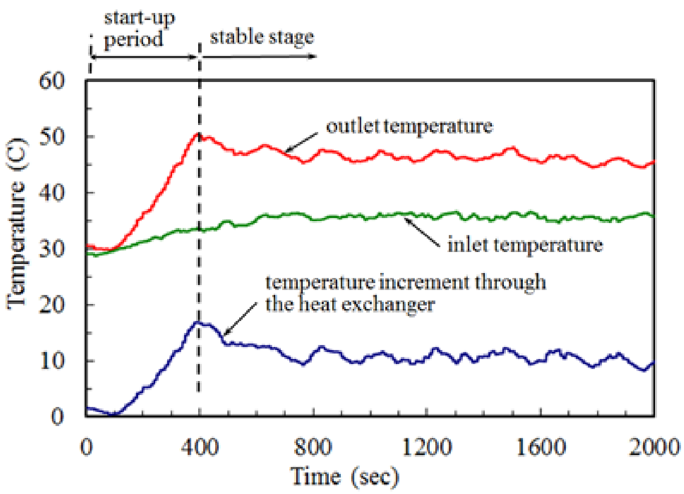

Fig. 4 Variation of inlet and outlet temperatures of the heat exchanger as well as its temperature increment in the dryer

The results of relative humidity change in the drying chamber showed that the relative humidity gradually decreased from 63% to a relatively stable value of 18% after around 20 minutes (Fig. 5). From the psychrometric chart, it was able to obtain that relative humidity of air was approximately 20% for air with the temperature of 30℃ and relative humidity of 60% at the initial state after the heating process of temperature up to 50℃. From this evidence, it was able to verify that the results of this study were reasonable and the developed drying system had a good airtight chamber. Consequently, it was able to reduce the energy consumption due to the heat loss. As obtained from the psychrometric chart, the enthalpy values of air before and after the heating were 71 and 92 kJ/kg respectively. In association with the airflow rate 60 m^3/min and the dry air specific volume 0.9 m^3/kg approximately, it was able to obtain the heat effectively added to the intake air was 84 MJ/hr. From the fuel amount measured before and after the tests, the average fuel consumption of diesel was 4.5 liter/hr. In addition, based on the specific gravity and heat value of diesel used by the heater were 0.85 and 45 MJ/kg respectively [9], combustion heat of diesel would be 172 MJ/hr. Therefore, the heating efficiency of heater for this drying system was about 50%.

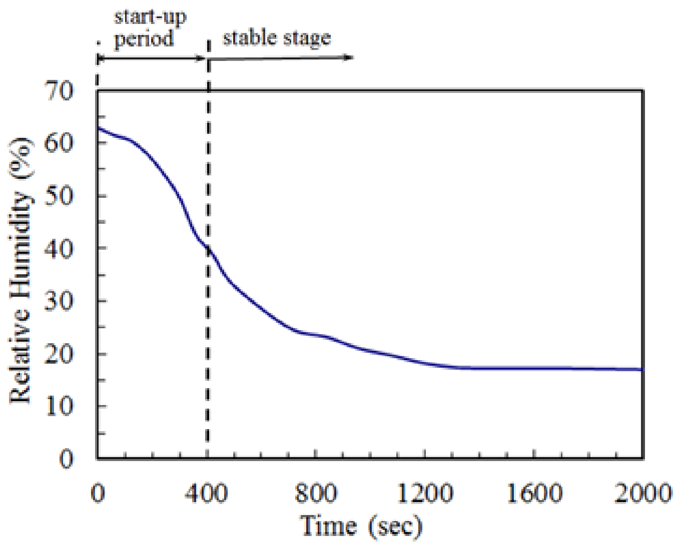

Fig. 5 Variation of relative humidity in the dryer

The experimental results showed that the heat recovery device was able to increase the intake air temperature from the atmospheric temperature of 35℃ to 46℃. When the performance of heat exchanger was analyzed, heat exchange effectiveness ratio could be used [10]. The ratio describes the effectiveness of the heat exchanger for heating the cold fluid to the entering temperature of the hot fluid. The definition of the ratio is temperature difference for airflow flowing through the heat exchanger with lower heat capacity and the maximum temperature difference in the heat exchanger. The maximum temperature difference flowing through the heat exchanger was the difference value between the temperature of airflow circulation duct and the atmospheric temperature. Since there was partial air intake entering the drying chamber through the bottom of the heater used to avoid overheating the heater, the fresh air in the heat exchanger had lower heat capacity. Applying the above stated approach to assess the effectiveness ratio of heat recovery system required to measure the temperature of airflow circulation duct, which was the temperature of hot and humid air before flowing through the heat exchanger. Generally, its value was about the same as the average temperature in the drying chamber. If the hot and humid air temperature was 50℃ for performing the analysis, the theoretical temperature increase limit was 15℃. Therefore, the effective ratio of the heat recovery device could achieve over 73%.

4.2. Optimum operation of the fan speed

After the drying system was start-up, the temperature of drying chamber increased rapidly to reach the set temperature, and then the on-off control was used to achieve the purpose of temperature control. The temperature increase rate after the drying system start-up is shown in Fig. 6. The experimental result showed that the faster the fan speed, the faster the transient response. When the fan speed increased from 45 to 60 Hz, the temperature increase rate could be increased from 7 to 8℃/min, especially, in the range from 50 to 55 Hz. Fig. 7 shows the average and standard deviation values of maximum temperature difference for the total 6 locations of upper and lower positions in the front, middle as well as rear sections of drying chamber during the stable period, which might be the maximum temperature difference in the drying chamber. The experimental results showed that the temperature in the drying chamber became less uniform at the fan speed of 55 Hz, however, its value was only around 1℃. Therefore, if the fan was controlled within the speed range, the drying chamber could have a fairly uniform temperature and airflow. Hence, it was able to achieve the prerequisite of uniform quality for the agricultural produce.

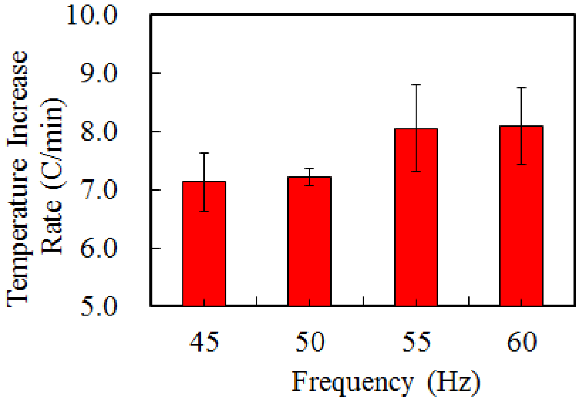

Fig. 6 Variation of temperature increase rate with fan speed after start-up

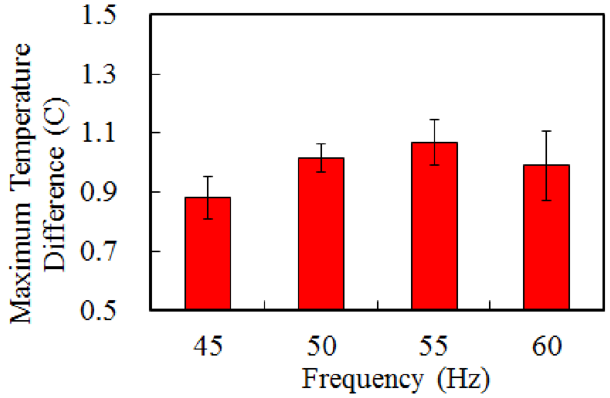

Fig. 7 Variation of the maximum temperature difference among six locations in the dryer with fan speed

Fig. 8 shows the average and standard deviation values of effectiveness ratio of the heat exchanger with fan speed during the stable period. The experimental results indicated that the effectiveness ratio was in the range of 70-80% and the lowest effectiveness ratio was at the fan speed of 55 Hz, which was consistent with the fact that temperature to be less uniform at the fan speed of 55 Hz. Although higher fan speed should have higher heat transfer resulting in higher effectiveness ratio, there was not a clear relationship between effectiveness ratio and fan speed. The reason might be that airflow was interrupted by the switching baffle in the airflow circulation duct before passing through the heat transfer and fan speed in the operation range was not a critical factor for heat transfer.

Applying the large spiral fan in a small space, its airflow direction was not likely to be uniform. For the three selected measuring locations, the measured results of airflow speed in the drying chamber are shown in Fig. 9. The location of the maximum average airflow speed was in the front end of airflow circulation duct which was reasonable since its cross area was the smallest, and airflow velocity increased with the increase of fan speed; however, the airflow speed of that location did not increase significantly as the frequency over 50 Hz. The results also indicated that increase of fan speed did not increase the airflow rate of the other two locations.

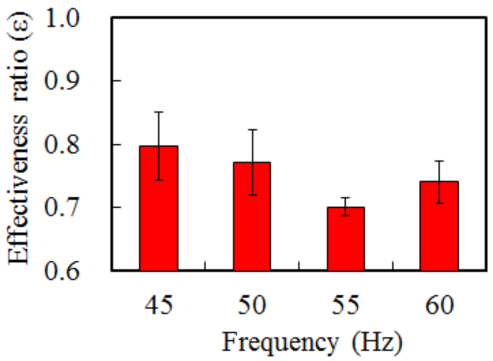

Fig. 8 Variation of the effectiveness ratio of the heat exchanger with fan speed

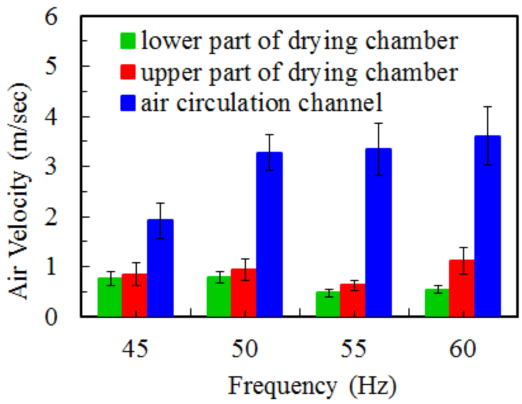

Fig. 9 Variation of airflow velocity at three locations in the dryer with fan speed

As summarized from the experimental results of fan speed, the analysis of temperature data showed that faster fan speed after the start-up shortened the time of reaching the setting temperature and lower fan speed was better for the temperature uniformity in the drying chamber. Therefore, the optimum operation mode of fan speed should be faster during the start-up period and lower after reaching the stable stage for improving the performance of dryer.

5. Conclusions

The developed drying system of this study was able to achieve the heat recovery and reduce the energy requirement for drying agricultural produce. The experimental results showed that the developed drying system had a good airtight chamber and the effectiveness ratio of the designed heat recovery device could reach 70-80%. Through the analysis of inlet and outlet temperature, airflow rate, as well as fuel consumption of heater, the heating efficiency of heater was up to 50%. In addition, the maximum temperature difference in the drying chamber was in the range of 0.6-1.2℃, which indicated that the temperature distribution of drying system was fairly uniform. Therefore, it was able to achieve the purpose of uniform quality for the drying agricultural produce. In addition, from the experiments of the effect of fan speed on drying system, the optimum operation for fan speed should be faster at the heating start-up stage and lower after reaching the stable stage.

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