Korean J. Chem. Eng., **30**(6), 1195-1200 (2013)
DOI: 10.1007/s11814-013-0037-4

An experimental study on the performance of a condensing tumbler dryer with an air-to-air heat exchanger

Yeongjin Do*, Myungjong Kim*, Taewan Kim*, Seonghae Jeong*, Sangho Park*, Sangwoo Woo*, Yeonghwan Kwon, Yoongho Jung**, Jaekeun Lee***, and Youngchull Ahn****,†**

*LG Electronics, Gaeumjeong-dong, Changwon City, Gyeongnam 641-711, Korea
**School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-dong, Geumjung-gu, Busan 609-735, Korea
***EcoEnergy Research Institute, Kangseo-gu, Busan 618-230, Korea
****Department of Architectural Engineering, Pusan National University, San 30, Jangjeon-dong, Geumjung-gu, Busan 609-735, Korea
(*Received 28 December 2012 • accepted 3 March 2013*)

Abstract−The performance of energy consumption in the closed-loop tumbler dryer with a condenser for clothes drying is evaluated as a function of the heater capacity, the drying air flow rate inside the dryer, and the cooling air flow rate. The clothes dryer in laundries used in this study consists of a tumbling drum, condenser for condensing the humid and hot air flowing out the rotating drums, and electric heater for heating the circulating drying air. Tests were performed at the heating capacity of 1.9 kW to 2.7 kW, the drying air flow rate of 60 m^3/h to 140 m^3/h, and the cooling air flow rate of 100 m^3/h to 240 m^3/h. The total energy consumption, the drying time, and the condensate water rate were also investigated. Parametric results showed that a larger heater power resulted in shorter drying time. With increasing heater power, the air temperature and the condensate rate increased due to the higher humidity ratio in the air. The drying air flow rate and the cooling air flow rate did not have a significant effect on drying performance.

Key words: Tumbler Dryer, Condenser, Heater Power, Energy Consumption, Drying Time, Cooling Air Flow, Drying Air Flow

INTRODUCTION

Laundry dryers have become an important consumer of electricity and other types of energy [1]. A residential tumbler dryer is classified into two types: air-venting dryers and closed-loop dryers with a condenser. Air-venting and open loop dryers are operated by drawing air into the dryer from the surrounding room and then heating the air with an electrically resistive heater or gas combustor. The heated air is then drawn into the rotating drum where it evaporates the liquid water of the damp clothing. The humid air is then drawn out from the drum through a lint filter by a blower, and is ultimately exhausted to the environment through duct tubing [2]. Bansal et al. [3] stated that the vent type process of drying clothes was simple, cheap, effective, reliable, and relatively fast; however, they recognized that it was relatively inefficient and had the major disadvantage of requiring a duct to exhaust the air to the environment to avoid a moisture problem. Similarly, Cochran et al. [2] also presented that in a cooler climate, a vent-type dryer was undesirable because the warm dryer air energy content was lost, and the net air loss from the house must be compensated by the household heating system.

The condensing tumbler dryer consists of a closed loop drying air side and does not need a duct to exhaust the humid air. Instead of a duct, an internal heat exchanger is used. In the condensing dryer, humid air at the outlet of the drum is cooled by the surrounding air at the heat exchanger. The humid air loses some of its humidity in the process and is recirculated through the heater into the drum. Bansal et al. [3] reported that the condensing dryer system was easier to install than the vent-type dryer. Cochran et al. [2] reported that the energy efficiency based on power consumption for a condensing dryer was lower than for the vent-type dryer.

Methods to reduce the energy consumption in clothes drying have been investigated. Deng and Han [4] researched clothes drying using rejected heat with split-type residential air conditioners. Ameen and Bari [5] evaluated the feasibility of drying clothes using waste heat with the condenser of a split-type domestic air conditioner. Lee et al. [6] investigated the effect of the flow rate of hot air and cooling water on the drying percentage and energy efficiency of the tumbler dryer. Imai and Tozaki [7] evaluated drying techniques using a heat pump to reduce energy. Braun et al. [8] studied the energy efficiency of a heat pump dryer, which was 40% higher than that of an electric dryer. Bassily and Clover [9] experimentally investigated the performance of a vent-type electric clothes dryer according to various factors such as the total weight of clothes, heater power, fan speed, and the rotating speed of the drum. They [10] also defined the mass transfer inside the drum of a clothes dryer, and correlated it to the weight of the clothes, drum speed, Reynolds number, Schmidt number, and Gukhman number based on the experimental results. In particular, many studies have been done on the improvement of performance efficiency of the vent-type dryer.

For the condensing dryer, although there have been numerical

†To whom correspondence should be addressed.
E-mail: ycahn@pusan.ac.kr

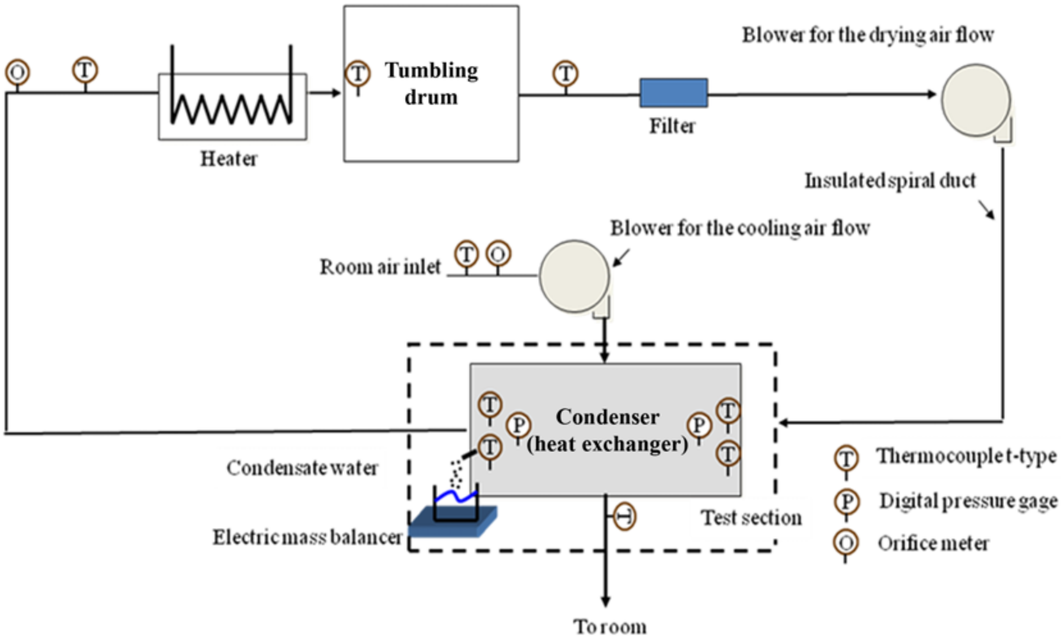

Fig. 1. Schematic diagram for evaluating the performance of the closed-loop tumbler dryer with the condenser used in this study.

studies by computer modeling, there is a lack of experimental performance analysis according to heater power and air flow rate. The condensing dryer consists of a heater, a tumbling drum, an air-to-air heat exchanger for the condenser and fans for flowing drying and cooling air. In addition, the relationship between these components is important in characterizing dryer performance. In this study, the effects of heater power, drying air flow rate inside the dryer, and the cooling air flow rate of the dryer are examined, and the performance sensitivity of parameters such as heater power and air flow rate is analyzed.

EXPERIMENTAL SETUP

Fig. 1 shows a schematic diagram for evaluating the performance of the closed-loop tumbler dryer with a condenser and it is established by the international standard [11]. It consists of a tumbling drum, a fan, an electric heater, and a heat exchanger for condensing the humid air. Each part is connected with a heavy insulated duct. To imitate tumbling motion, a residential condensing dryer with the tumbling drum (0.57 m-ID, 0.47 m-H) is used. Fans are used to generate air flow for the cooling and drying sides. The cooling fan forces the cooling air flow from the surrounding to the cooling side of the air-to-air heat exchanger, and the air conditioner maintains the temperature of the surrounding air at 23 °C. The drying fan is used to create an air stream on the drying side, which is a closed loop. Cooling flow rate is kept at 100 to 240 m^3/h throughout the drying process except in the first 20 min. Drying air flow rate is controlled from 60 to 140 m^3/h. The electric heater is used to heat the drying air in the closed loop cycle, with heater power from 1,900 to 2,700 W using an alternating current auto-transformer. The heater outlet and drum inlet temperatures are measured every 5 seconds.

The air-to-air heat exchanger, which is shown in Fig. 2, for condensing humid air flowing out the tumbling drum is enclosed by an insulated acryl case, with drying air flows on one side and cooling air flows on the other side. It is a plate type heat exchanger that has fins to enhance heat transfer. Temperature, relative humidity, and pressure at the inlet and the outlet of both streams in the heat exchanger are recorded during the entire drying process. Simultaneously, the quantity of condensed water from the drying air by heat transfer at the heat exchanger is checked by using a mass balance. All components are connected with a heavy insulated spiral duct to reduce heat loss to the ambient. The energy consumption and the drying time are evaluated for the heating capacity of 1.9 kW to 2.7 kW, the drying air flow rate of 60 m^3/h to 140 m^3/h, and the cooling air flow rate of 100 m^3/h to 240 m^3/h.

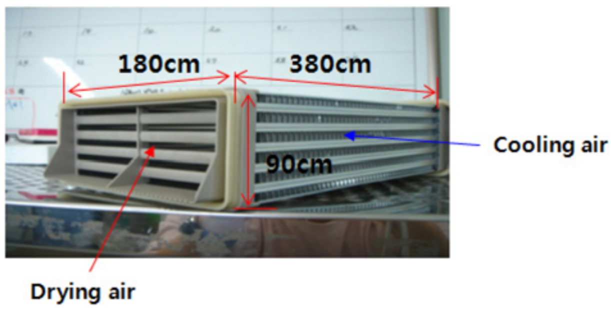

Fig. 2. A photograph of the heat exchanger.

RESULTS AND DISCUSSION

1. Effect of the Heater Power

Fig. 3 shows the test results of air temperature at the inlet and the outlet of the condensing heat exchanger (HEX) during the drying process. Based on the profiles of drying temperature, the drying process can be divided into three stages: rising temperature stage, stable temperature stage, and cooling stage. The rising temperature stage lasts approximately 60 minutes in this experiment. In this stage,

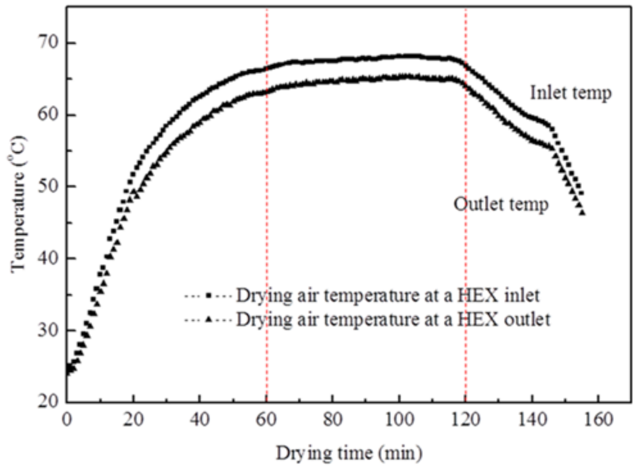

Fig. 3. Variation of air temperature at the inlet and the outlet of the condensing heat exchanger (HEX) during the drying process.

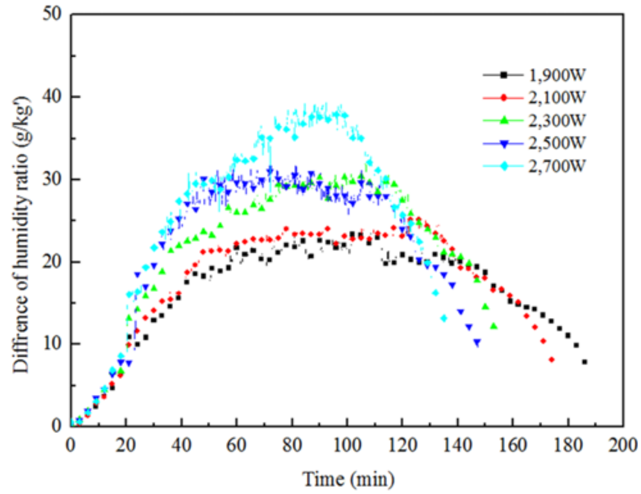

Fig. 5. Differences of humidity ratio between the inlet and the outlet of heat exchanger.

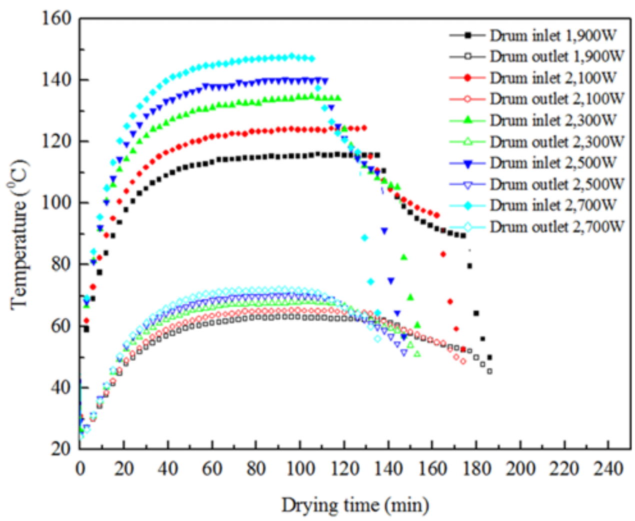

Fig. 4. Variation of the air temperature at the drum inlet and the outlet as a function of heater power.

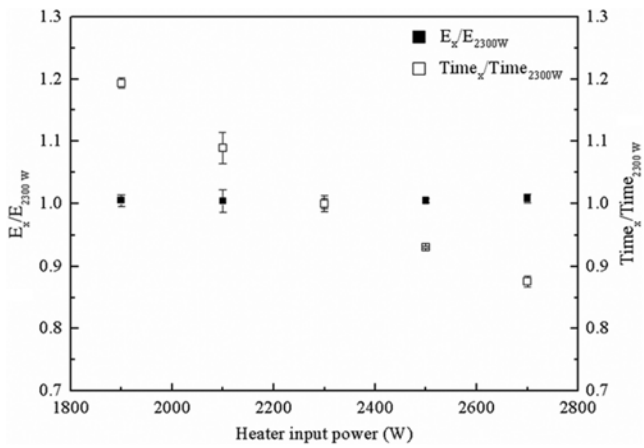

Fig. 6. Effect of heater power on the total energy consumption and the drying time normalized by the specific heater power of 2,300 W at the drying air flow rate of 100 m^3/h, and the cooling air flow rate of 172 m^3/h.

the laundry in the drum absorbs adequate thermal energy to evaporate its water content. The stable temperature stage lasts approximately 120 minutes and the water condensation rate is the highest. Finally, the drying process proceeds to the cooling stage.

Fig. 4 shows the variation in the air temperature at the inlet and the outlet of the tumbling drum as a function of the heater power. The drying air flow rate and the cooling air flow rate are 100 m^3/h and 172 m^3/h, respectively. The drying air temperature and the relative humidity at various locations of the dryer cycle are measured to analyze the effect of the heater power on the performance of the dryer. The air temperature at the drum inlet increased with increasing heater power and the air temperature at the drum inlet ranged from 115 °C to 150 °C as the heater power increased from 1,900 W to 2,700 W, respectively. The relative humidity of air increases with the increase of air temperature. The increased heater power causes high temperature and high moisture content. Fig. 5 shows the differences of humidity ratio between the inlet and the outlet of the heat exchanger as a function of heater power and drying time. At the highest heater power condition, the difference of humidity ratio shows maximum value and and the drying time is shortest. Consequently, the evaporation of water in the tumbler dryer is enhanced as the heater power is increased.

Fig. 6 shows the effect of the heater power on the total energy consumption and the drying time normalized by the specific heater power of 2,300 W, the drying air flow rate of 100 m^3/h, and the cooling air flow rate of 172 m^3/h. The performance of the tumbler dryer used in this study was analyzed with respect to energy consumption and drying time. The total energy consumption rate has almost no relationship to the heater power. In addition, the larger the heater power, the shorter the drying time. Total energy consumption is due to the fan and the heater power. This result means that the increase in the rate of energy use by the heater is compensated by the decrease of the fan power due to the shorter drying time.

2. Effect of Drying Air Flow Rate

Fig. 7 shows the test results of air temperature at the inlet and

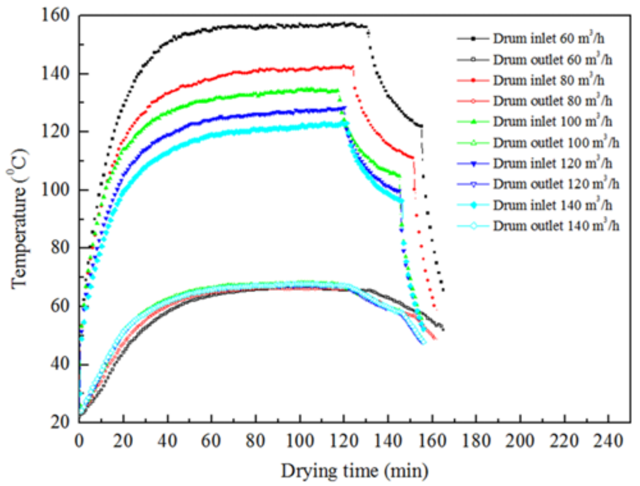

Fig. 7. Test results of air temperature at the drum inlet and the outlet as a function of drying air flow rate at the heater power of 2,300 W and the cooling air flow rate of 172 m³/h.

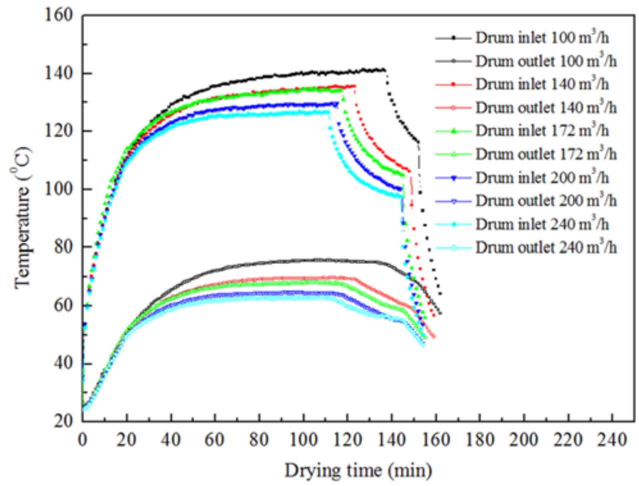

Fig. 9. Test results of the air temperature at the drum inlet and the outlet as a function of cooling air flow rate at the heater input power of 2,300 W and the drying air flow rate of 100 m³/h.

the outlet of the tumbler dryer as a function of the drying air flow rate at the heater power of 2,300 W and the cooling air flow rate of 172 m³/h. The air temperature at the drum inlet decreases with increasing drying air flow rate. The air temperature at the drum inlet ranges from approximately 122 °C to 157 °C as the drying air flow rate decreases from 140 m³/h to 60 m³/h. The drying time increases with the decrease in drying air flow rate under the 100 m³/h range, and the difference in drying time is insignificant in the upper range of 100 m³/h. These results show that the advantage of high temperature with decreasing air flow rate has a small effect on drying time. In this experiment, a drying air flow rate between 100 to 120 m³/h is the optimal condition with respect to energy consumption and the temperature difference between the drum inlet and the outlet is changed from 47 °C to 81 °C. Also, the temperature difference between the condenser inlet and the outlet is increased as the drying air flow rate is increased and changes from 2 to 4.4 °C. The drying time increases slightly with the decrease in drying air flow rate.

Fig. 8 shows the effect of the drying air flow rate on total energy consumption and the drying time normalized by the specific drying air flow of 100 m³/h. The energy consumption and the drying time are increased at the low drying air flow rate. The total energy consumption based on the drying air flow rate inside the dryer is optimized at a flow rate between 100 m³/h to 120 m³/h. It is concluded that total energy consumption is expected to rise significantly for an air flow rate greater than 140 m³/h.

3. Effect of Cooling Air Flow Rate

Fig. 9 shows the test results of air temperature at the drum inlet and the outlet as a function of the cooling air flow rate with the heater power of 2,300 W and the drying air flow rate of 100 m³/h. The air temperature of the drum inlet increases with the decrease in cooling air flow rate. The temperature of the drum inlet ranges from approximately 122 °C to 157 °C. The temperature difference between the drum inlet and the outlet increases with the decrease in cooling air flow rate and is changed from 54 °C to 58 °C. Similarly, the temperature difference between the condenser inlet and the outlet is in-

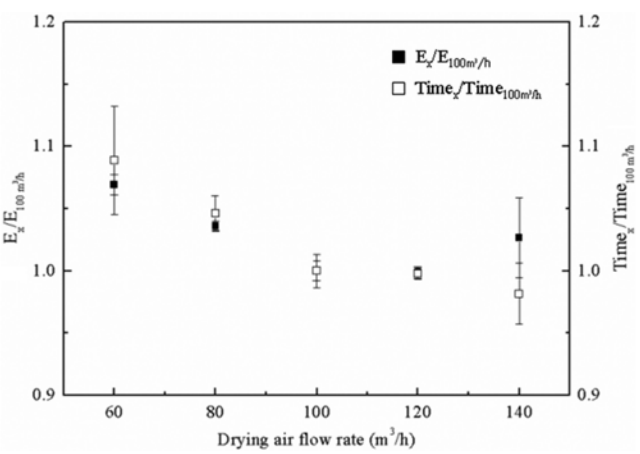

Fig. 8. Effects of the drying air flow rate on total energy consumption and the drying time normalized by the specific drying air flow rate of 100 m³/h.

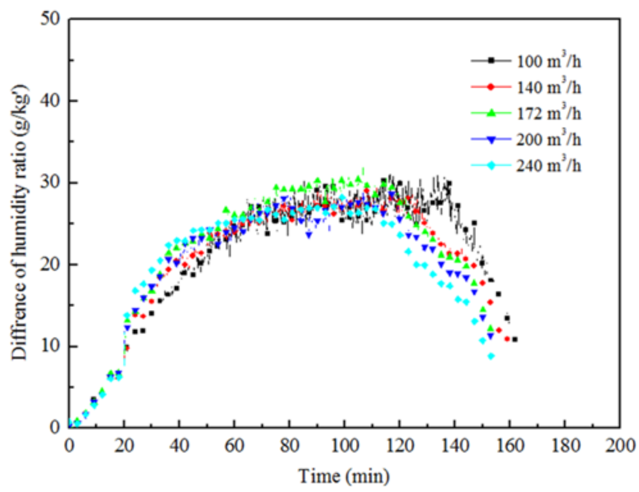

Fig. 10. Difference of humidity ratio between the inlet and the outlet of heat exchanger as a function of the cooling air flow rate.

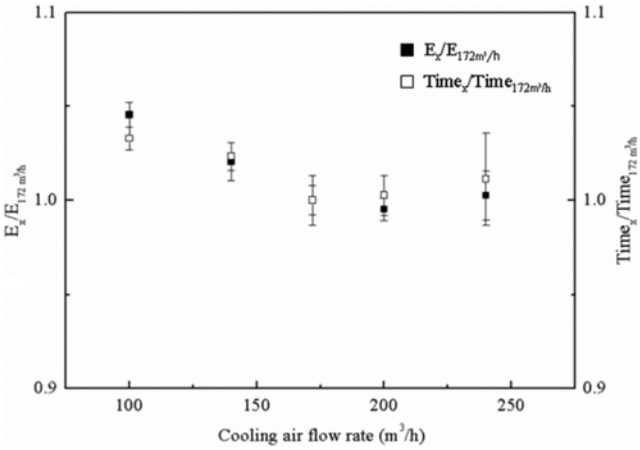

Fig. 11. Effect of cooling air flow rate on the total energy consumption and the drying time normalized by the specific cooling air flow rate of 172 m^3/h.

creased with the decrease in cooling air flow rate and is ranged from 2 to 4.3 °C, and the drying time is increased with the decrease in cooling air flow rate.

Fig. 10 shows differences of humidity ratio between the inlet and the outlet of heat exchanger as functions of cooling air flow rate and time. At the beginning of the drying period, such as 20-60 minutes, the condensation is slightly proportional to the cooling air flow rate because of the vigorous mixing effects of large air volume. During 60 to 120 minutes that kind of tendency does not appear and the case of 172 m^3/h shows highest condensation. And at the final period, the high cooling air flow rate shows short drying time.

Fig. 11 shows the effect of the cooling air flow rate on total energy consumption and the drying time normalized by the specific cooling air flow rate of 172 m^3/h. Over the cooling air flow rate of 172 m^3/h, the total energy consumption does not change in the range of less than 1% compared with 2,300 W of the heater power, 100 m^3/h of the drying air flow rate, and 172 m^3/h of the cooling air flow rate. When the cooling air flow rate is lower than 172 m^3/h, the energy consumption and the drying time are increased according to the decrease of cooling air flow rate. The total energy consumption based on the cooling air flow rate inside the dryer is optimized at a flow rate of 172 m^3/h. It is concluded that the total energy consumption is expected to rise significantly for an air flow rate greater than 172 m^3/h. This result means that the change of fan power for cooling air flow is compensated with the drying time, and the optimal control point is 172 m^3/h.

Fig. 12 shows the sensitivity analysis for energy consumption and drying time in the closed-loop tumbler dryer with the condenser. The fraction of set variable of X-axis means the ratio of the parameter normalized by each standard of parameters such as the heater power of 2,300 W, the drying air flow rate of 100 m^3/h, and the cooling air flow rate of 172 m^3/h. As previously mentioned, the heater power has no effect on total energy consumption, while the drying and the cooling air flow rates show the effect in the range of less than 0.9 the fraction of the set variable. With the exception of the cooling flow rate, the other two parameters of the heater power and the drying flow rate reduce the drying time of the closed-loop tumbler dryer with the condenser. In particular, the heater power shows a more significant effect than the drying air flow rate in the drying time.

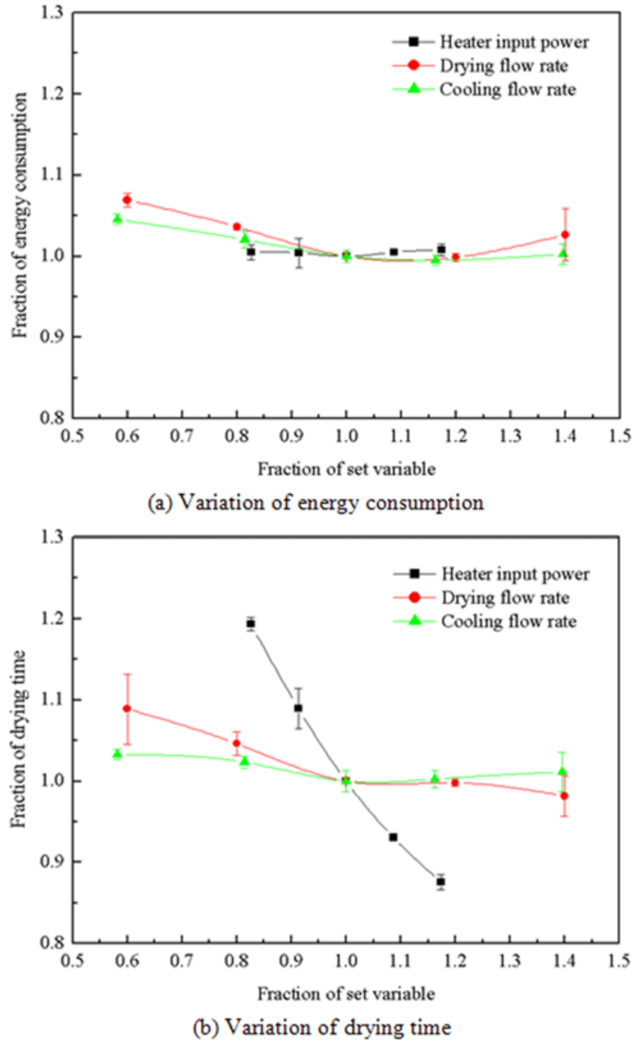

Fig. 12. Sensitivity analysis for energy consumption and drying time in the closed-loop tumbler dryer with the condenser as a function of heater power, drying air flow and cooling air flow.

CONCLUSIONS

The performance of a closed-loop tumbler dryer with a condenser was investigated experimentally from the view of the energy consumption, the drying air flow rate inside the dryer, and the cooling air flow rate. The total energy consumption, the drying time, and the condensate water rate were also measured. Parametric test results show that a larger heater power results in shorter drying time: as the heater power increases, the air temperature increases and the condensate rate increases due to the higher humidity ratio in the air. Several industry standards express the limit of the maximum operating temperature to protect damage to laundry and burning of the equipment. However, the drying air flow rate and the cooling air flow rate do not have significant effects on the drying performance. Among the other parameters, the heater power has the greatest effect on drying time.

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