Korean J. Chem. Eng., **23**(4), 658-662 (2006)

Drying performance of a tumbler dryer with condenser

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(*Received 18 December 2005 • accepted 23 February 2006*)

Abstract−The effects of flow rates of hot air and cooling water on drying percentage and energy efficiency of cotton lint in a cylindrical type drum tumbler dryer (0.54 m-ID×0.34 m-high) have been determined. Drying of the lint is mainly affected by flow rate of hot air, which is a function of the diameter ratio (D_M/D_F) of motor and fan pulley and motor capacity. During the drying process in the tumbler dryer, temperatures and humidity before and after were measured to determine the drying characteristics. The volumetric flow rate of hot air increases with increasing the diameter ratio of the motor and fan pulley, whereas the volumetric flow rate of hot air decreases with an increase in the mass flow rate of the cooling water through the condenser. The energy consumed by the motor relied more on the diameter ratio of the motor and fan pulley as opposed to the mass flow rate of cooling water. Despite the increase in the drying percentage with increasing the diameter ratio of the motor and fan pulley and the mass flow rate of the cooling water, the energy efficiency decreased.

Key words: Cotton Lint, Tumbler Dryer, Drying Percentage, Energy Efficient

INTRODUCTION

Drying is an important thermal process in the fine chemical, food, metallurgical, pharmaceutical and other industries [Zahed et al., 1995]. The analysis of the drying phenomenon is more complicated than that of heat or isothermal mass transfer alone [Choi et al., 2002; Park et al., 2003]. Drying means the removal of small amounts of water or other liquid from the solid material to reduce the content of residual liquid to an acceptably low value. Drying is usually the final step in a series of operations, and the product from dryer is often ready for final packaging. A drying system is activated by hot air with temperature gradient; however, many complicated phenomena occur such as vapor expansion caused by the change in vapor pressure, specific heat of the solid in relation with moisture content, the quantity of thermal conductivity, diffusion coefficient and other related property changes, the energy loss caused by the evaporation quantity and temperature at the contact surface area with air, etc. [Chang et al., 2000].

Despite the drying process being incorporated inevitably in the product manufacturing process, a variety of unit operations that remove unnecessary water vapor and solvents are included in the final product and depend largely on the productivity and quality of the product [Chang et al., 2000]. Dying processes are used widely in the food industry, agriculture, ceramics, fine chemistry, pharmaceutical chemistry, pulp, paper manufacturing and textiles industry and in some countries that possess state-of-the-art technology; they have utilized such assets in the electronics market [Wang and Chen, 1999].

During drying of wet materials, heat and mass transfer occurs simultaneously of both the solids and in the boundary layer of the drying agent. Heat can be supplied to the material to be dried by thermal radiation, convection, and conduction or by utilizing the volumetric absorption of electromagnetic energy generated at radio or microwave frequency. This volumetric heat transfer can speed up the drying process and offers a number of benefits over conventional methods [Strumillo and Kudra, 1986]. Barker and Laird [1993] determined the effect of temperature on moisture absorption and desorption rates of cotton lint under the controlled temperature (50-90 °C) and humidity conditions. Their results indicated that both temperature and the condition (dry or humid) of air significantly affect the "diffusivity" parameter. Also, higher moisture transfer rates occur at higher temperatures and the drying rate is significantly higher than the humidification rate of the cotton lint at the same temperature. Barker [1996] obtained equilibrium moisture contents for the parts of cotton plants (leaves, sticks and burs) and all trash at the temperatures range of 5-80 °C in a moving air stream (3×10^{-4} m^3/s) and relative humidity range of 0-98%. Their results showed almost linear increase in equilibrium moisture content between the relative humidity of 20 and 70% followed by an exponential rise at the relative humidity approaching 100%.

Tumbler dryers provide a fast and convenient method for drying wet clothes, especially when space is limited for drying outdoors. It is also generally accepted that tumble-dried clothes tend to be softer and easier to iron when compared with clothes dried by other methods [Deans, 2001]. Three different systems of tumbler dryers are used nowadays. In the open-loop system, ambient air is heated to the temperature required by the particular drying operation, passes through the drum loading itself with water vapor from the textile and it is rejected, usually to outside of the laundry space. Associated with this system, additional air ducts and spread of small lint (fluff) particles at the exhaust location are needed. In the closed-loop system, humid air at the outlet of the drum is cooled down,

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losing some of its humidity in the process, and recirculated through the heater into the drum. This system has the advantage of requiring no external air ducts, but needs an internal heat exchanger and takes a long time to complete drying for a batch of laundry. Midway between these two systems is the tumbler with partial recirculation of humid air which has generally no dehumidifying heat exchanger. Recirculation is done to recover at least some of the energy from the exhaust air, but the system still requires an external air duct, so the problem with fluff is similar to the open-loop system [Conde, 1997].

Previous researchers only presented research data regarding the physical properties of cotton lint (equilibrium moisture content and effective diffusivity), energy saving of domestic tumbler dryers, etc. Therefore, in the present study, the moisture content of the cotton lint, temperature and absolute humidity of the exhaust air and other related parameters were measured with the elapsed time in a domestic tumbler dryer. Furthermore, the effects of volumetric flow rate of hot air and mass flow rate of cooling water on the drying characteristics (drying percentage and energy efficiency) were determined.

EXPERIMENTAL

The experimental setup schematic is shown in Fig. 1. A domestic cylindrical drum tumbler dryer (0.54 m-ID×0.34 m-high) was used in this experiment. The tumbler dryer rotates 45 rpm for 20 seconds and after an interval of 2 seconds, rotates in the opposite direction at 45 rpm for 20 seconds. This process was repeated until the drying process was completed. The drying experiment was conducted using 5.0 kg of the dry cotton lint as a test material while varying the flow rates of hot air and cooling water. For recording the internal temperature and humidity in the tumbler dryer, temperature (RTD, Pt-100Ω) and humidity sensors (Vaisala Inc., Model: HMT237) were connected to a computer on-line at the designated locations as shown in Fig. 1. The volumetric flow rate of hot air into the drying machine was varied by changing the diameter ratio of the motor and fan pulley and the motor capacity. The dry cotton (5 kg) was fully dipped in deionized water and dehydrated to the desired moisture content by a centrifuge. Once the dehydrated wet cotton (8.02 kg) was placed in the tumbler dryer, the power was turned on activating the blower and heater. During this process, temperature, relative humidity and the volumetric flow rate of hot air with the elapsed time were recorded and stored in a computer every 5 seconds (0.2 Hz). After 30 minutes had elapsed from the beginning of the drying process, cooling water was supplied at the desired amounts (Table 1) to reduce the absolute humidity of the humid air. To calculate the drying percentage of the cotton lint, the cotton lint was weighed before excess water was removed and the weight was measured again after the drying process was completed to compute the evaporated weight of water during the drying process. A rotating vane type anemometer (TSI's VELOCICALC Model: 8324) was installed to measure the volumetric flow rate of hot air, and the amount of energy consumed during the drying process was measured by a digital power meter (Model: WT230, Yokogawa Co.). The total mass of cooling water was measured by an integrated flowmeter.

The experimental variables and their ranges for this experiment are shown in Table 1.

Table 1. Ranges of experimental variables

Variables	Unit	Ranges
D_M/D_F	-	1.49, 1.78, 2.05, 2.40
m_{CW}	kg/s	0, 0.00333, 0.00667, 0.01083, 0.01417
Drying time, t_d	s	5400, 6600, 7800, 9000
Motor capacity	-	Small, Large

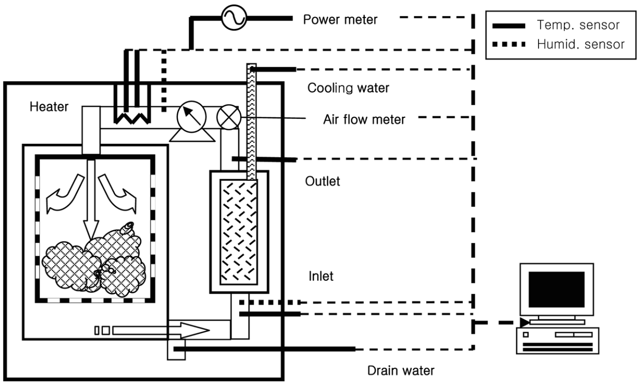

Fig. 1. Schematic diagram of a domestic tumbler dryer.

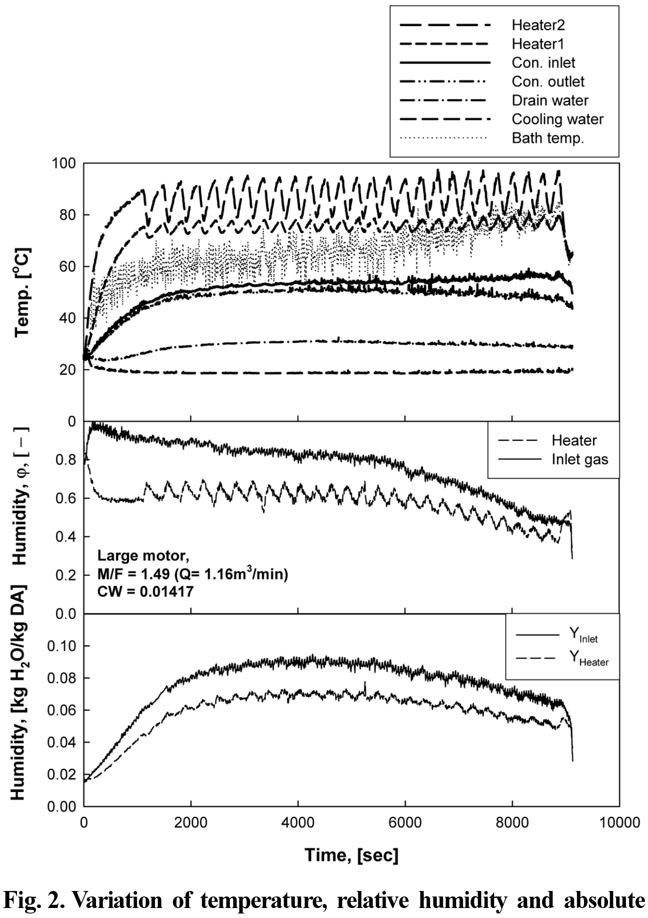

Fig. 2. Variation of temperature, relative humidity and absolute humidity with the elapsed time in the domestic tumbler dryer.

RESULTS AND DISCUSSION

Variation of temperature in the tumbler dryer, the relative humidity and temperature in the inlet and outlet of the condenser with the elapsed time are shown in Fig. 2. Cooling water refers to water introduced into the condenser; drain water refers the sum of the condensed water discharged from the bath due to evaporation, and the water refuse from the condenser was created by the injected cooling water. The inlet and outlet gases were differentiated into the inlet and outlet of the condenser as a standard. The heater temperatures were measured at two points before entering the bath of the domestic tumbler dryer. As can be seen in Fig. 2, the temperature discrepancy recorded at the two points in the heater can be attributed to their locations: one being closer to the center and the other, closer to the wall. Also, fluctuation in the heater temperature during the drying process can be explained by the on-off control of the tumbler dryer. The bath temperature was measured by inserting a temperature sensor in the bath that measured the temperature of the wet cotton during the drying process. This temperature sensor records temperature at the point of contact between the cotton lint and the hot air which causes temperature fluctuation as shown in Fig. 2(1).

Fig. 2(2) shows the relative humidity and the measured temperature in the inlet chamber and the heater which can be used to calculate the absolute humidity.

The computed absolute humidity from the relative humidity data is shown in Fig. 2(3). Absolute humidity of the gas passing through the heater is lower than that passing through the condenser owing to condensation of humid air. The quantity of condensed water during the drying process can be calculated by integrating the difference in absolute humidity ($Y_{Inlet}-Y_{Heater}$) with the elapsed time. The quantity of condensed vapor is 2.95 kg according to the data shown in Fig. 2(3). The actual weight of water in the cotton lint before and after the drying process was recorded as 2.96 kg. Therefore, the experiment data obtained by the hygrometer well represents the drying characteristics of cotton lint with the elapsed time.

The volumetric flow rate of recirculation air was controlled by the diameter ratio of the motor pulley to the fan pulley at a given cycle speed of the motor. At a given motor cycle speed, if the diameter ratio of the motor and fan pulley increases, the power conveyed to the motor will increase and consequently increase volumetric flow rate of recirculation air. Volumetric flow rates of recirculation air with variation of D_M/D_F for both large (N_{motor}=2,670 rpm) and small motors (N_{motor}=1,585 rpm) are shown in Fig. 3. As can be seen, the volumetric flow rate of recirculation air is a function of D_M/D_F in a situation without the drying run. The volumetric flow rate of recirculation air increases with increasing the ratio of D_M/D_F, but the increasing rate decreases due to the increase of power inflicted on the motor. For example, the motor cycle speeds are 1,769 and 1,285 rpm at D_M/D_F of 1.49 and 2.40, respectively. At the given D_M/D_F and the mass flow rate of cooling water, variation of the volumetric flow rate of recirculation air with changing D_M/D_F in a large motor is larger than that in a small motor.

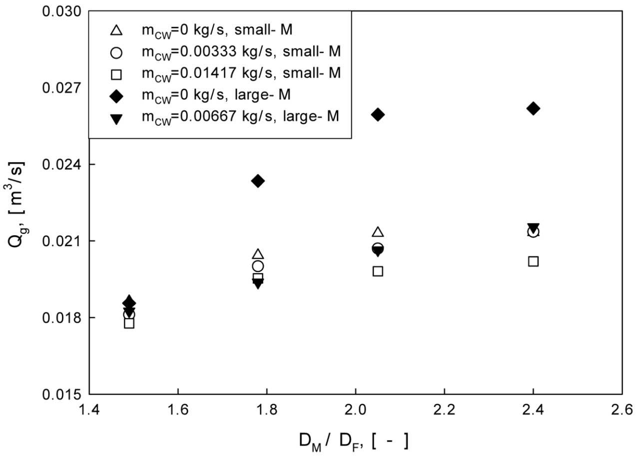

Fig. 3. Variation of volumetric flow rate of the recirculation air with the diameter ratio (D_M/D_F).

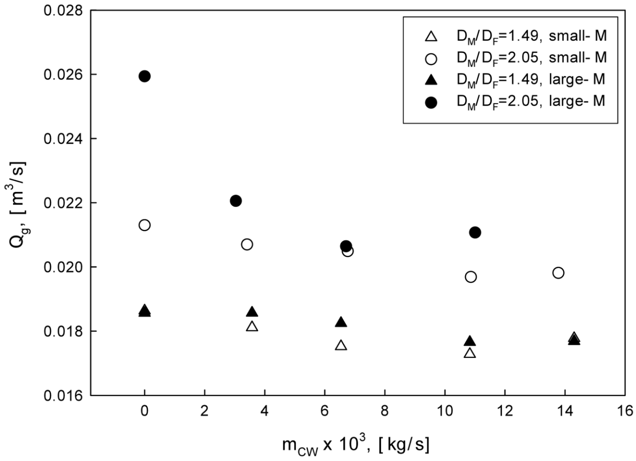

Fig. 4. Effect of the mass flow rate of cooling water on the volumetric flow rate of the recirculation air with the diameter ratio (D_M/D_F).

Variation of volumetric flow rate of recirculation air at different mass flow rate of cooling water supplied to the condenser is shown in Fig. 4. As can be seen, the mass flow rate of cooling water is inversely proportional to the volumetric flow rate of recirculation air. The recirculation air and cooling water passing through a constant volume of condenser in a countercurrent mode may led to a gradual increase in the mass flow rate of cooling water and an increase in the volume of the cooling water passing through a condenser, thereby ultimately reducing the recirculation air volume that could be passed through. Therefore, with an identical motor and diameter ratio of the motor pulley to the fan pulley, the pressure drop in a condenser increases with increasing cooling water flow rate, which may lead to a decrease in the volumetric flow rate of recirculation air passing through the condenser in the tumbler dryer. As can be seen in Fig. 4, volumetric flow rate of the recirculation air is suppressed with a slight increase in the mass flow rate of cooling water. This can be explained by the entrainment of the cooling water from the condenser to the rotating vane type anemometer, which may be a possibility of deterioration in drying capabilities due to entrainment of the cooling water from the condenser to the heater in the tumbler dryer.

The effect of mass flow rate of cooling water on the motor power as a function of the diameter ratio of the motor pulley to the fan pulley is shown in Fig. 5. As can be seen, the power does not change significantly with variation of mass flow rate of the cooling at a given

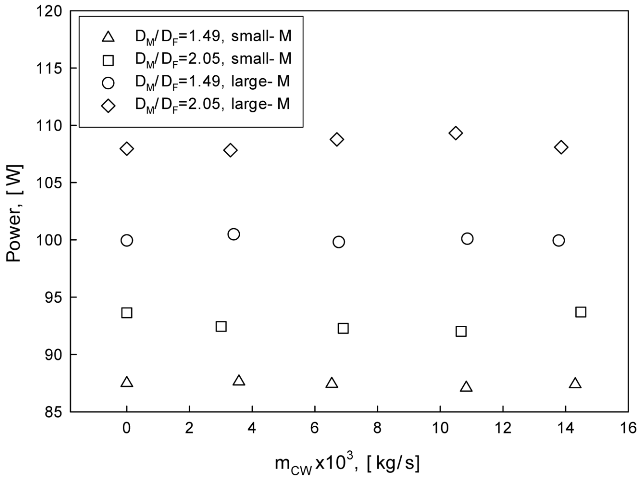

Fig. 5. Effect of mass flow rate of cooling water on motor power.

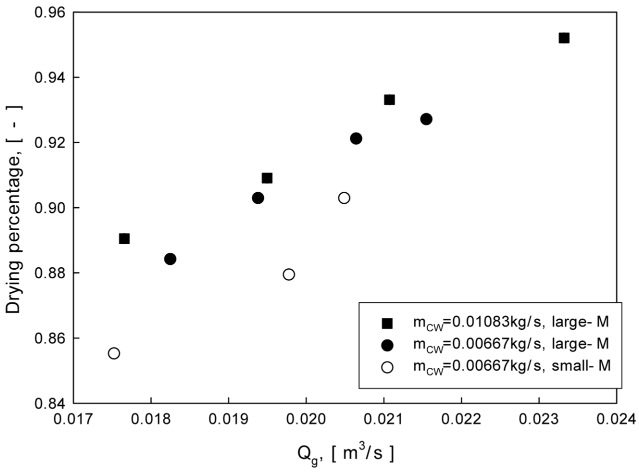

Fig. 6. Effect of the diameter ratio (D_M/D_F) on percentage of drying.

D_M/D_F. The motor power increases with increasing the diameter ratio of the motor pulley to the fan pulley.

The effect of recirculation air rate on the drying percentage is shown in Fig. 6 where the drying percentage increases with increasing the recirculation air rate in the tumbler dryer, leading to increase the drying medium to evaporate water from the cotton lint. The quantity of gas circulating in the tumbler dryer increases concurrently with the increase in the motor cycle rate, and this ultimately causes an increase in the drying percentage.

The effect of circulation air flow rate on the energy efficiency in the drying process is shown in Fig. 7 where the energy efficiency is defined by the following equation [Stromillo and Kudra, 1986]:

$$\eta = \frac{\text{energy required for moisture evaporation}}{\text{total energy supplied to dryer}} \tag{1}$$

As can be seen, the drying efficiency decreases with increasing recirculation gas flow rate as in the case of the mass flow rate of cooling water increases. To increase the volumetric flow rate of recirculation air, the mechanical operation power may increase accordingly with a larger diameter ratio of the motor and fan pulley. The cause of decreasing drying efficiency can be attributed to the increase of drying load that needs to be dried by the heater with increasing volumetric flow rate of the recirculation air. A critical factor is believed to be the heat loss in the falling-drying rate.

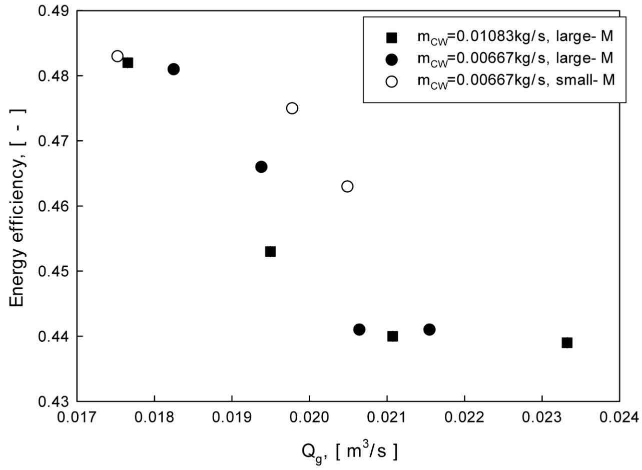

Fig. 7. Variation of the energy efficiency with the diameter ratio (D_M/D_F).

Table 2. Drying percentage and energy efficiency with drying time

Drying time, [s]	Weight after centrifuge, [kg]	Energy efficiency, [%]	Drying percentage, [%]
9,000	8.02	43.9	95.2
7,800	8.02	46.7	88.4
6,600	8.02	49.0	78.9
5,400	8.02	49.8	66.6

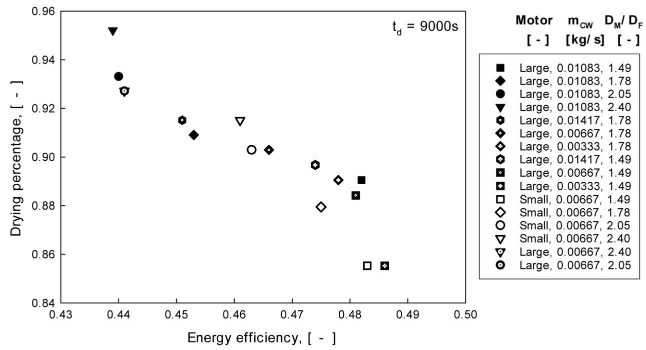

Fig. 8. Percentage of drying versus energy efficiency in the domestic tumbler dryer.

The drying percentage and the energy efficiency with drying time at the diameter ratio of 2.40, the mass flow rate of cooling water of 0.01083 kg/s, and the drying time from 9,000 to 5,400 s are shown in Table 2. The reduction of drying time may led to increase in the energy efficiency and decrease in the drying percentage.

The relationship between the drying percentage and the energy efficiency of the tumbler dryer is shown in Fig. 8. The drying percentage decreases with increasing the energy efficiency. The drying percentage increases with increasing volumetric flow rate of the recirculation air. It is reasonable to conclude that in terms of energy efficiency, the required gas volume for heating increases, which may lead to a decrease in energy efficiency. Also, the drying percentage increases due to the larger cooling effect at the condenser from an increase in cooling water, but decreasing gas temperature leads to a larger power consumption that may cause low energy efficiency.

CONCLUSION

1. At the constant diameter ratio of the motor and fan pulley, the volumetric flow rate of recirculation air decreases with increasing mass flow rate of the cooling water.

2. The motor power consumption depends more on the diameter ratio of the motor and fan pulley than mass flow rate of cooling water.

3. The drying percentage increases linearly with increasing the diameter ratio of the motor and fan pulley or volumetric flow rate of the recirculation air.

4. The energy efficiency decreases with increasing the diameter ratio of the motor and fan pulley and mass flow rate of the cooling water.

5. The drying percentage decreases with increasing the energy efficiency. Further work is required to investigate the optimum operating condition between the drying percentage and the energy efficiency for the tumbler dryer with condenser.

NOMENCLATURE

D_M : pulley diameter of motor [m]
D_F : pulley diameter of fan [m]
m_{CW} : mass flow rate of cooling water [kg/s]
N_{motor} : motor speed [1/min]
Q_g : volumetric flow rate [m^3/s]
T : temperature [°C]
t_d : drying time [s]
Y_{heater} : absolute humidity of heater [kg H_2O/kg dry air]
Y_{inlet} : absolute humidity of condenser inlet [kg H_2O/kg dry air]
η : energy efficiency for drying [-]

REFERENCES

Barker, G. L. and Laird, J. W., "Drying and humidification rates for cotton lint," *Transactions of the ASAE*, **36**(6), 1555 (1993).

Barker, G. L., "Equilibrium moisture content of cotton plant compounds," *J. Agric. Engng Res.*, **63**, 353 (1996).

Chang, Y. S., Lee, S. W., Kim, S. Y. and Chung, P. S., "Experimental study on performance characteristics of drum type dryer (*Korean language*)," Spring Conference Proceeding of The Korean Society of Mechanical Engineers, 187 (2000).

Choi, K. B., Park, S. I., Park, Y. S., Sung, S. W. and Lee, D. H., "Drying characteristics of millet in a continuous multistage fluidized bed," *Korean J. Chem. Eng.*, **19**, 1112 (2002).

Conde, M. R., "Energy conservation with tumbler drying in laundries," *Applied Thermal Engineering*, **17**, 1163 (1997).

Deans, J., "The modeling of a domestic tumbler dryer," *Applied Thermal Engineering*, **21**, 977 (2001).

Park, Y.-S., Shin, H. N., Lee, D. H., Kim, D. J., Kim, J.-H., Lee, Y. K., Sim, S. J. and Choi, K.-B., "Drying characteristics of particles using thermogravimetric analyzer," *Korean J. Chem. Eng.*, **20**, 1170 (2003).

Strumillo, C. and Kudra, T., *Drying: principles, applications and design*, GORDON AND BREACH, Poland (1986).

Wang, Z. H. and Chen, G., "Heat and mass transfer in fixed-bed drying," *Chem. Eng. Sci.*, **54**, 4233 (1999).

Zahed, A. H., Zhu, J. X. and Grace, J. R., "Modeling and simulation of batch and continuous fluidized bed dryers," *Drying Technol.*, **13**, 1 (1995).