EFFECT OF CONTINUOUS AND STEPWISE CHANGE IN DRYING TEMPERATURE ON DRYING CHARACTERISTICS AND PRODUCT QUALITY

K. J. Chua, A. S. Mujumdar, M.N.A Hawlader, S. K. Chou and J. C. Ho

Department of Mechanical and Production Engineering,
National University of Singapore,
10, Kent Ridge Crescent,
Singapore 119260
E-mail : engp8774@nus.edu.sg

ABSTRACT

Samples of banana were dried in a two-stage heat pump dryer capable of producing stepwise control of the inlet drying air temperature while keeping absolute humidity constant. Two stepwise air temperature profiles were tested. The incremental temperature step change in temperature of the drying air about the mean air temperature of 30 °C was 5 °C. The total drying time for each temperature-time profile was about 300 minutes. The drying kinetics and color change of the products dried under these stepwise variation of the inlet air temperature were measured and compared with constant air temperature drying. The stepwise air temperature variation was found to yield better quality product in terms of color of the dried product. Further, it was found that by employing a step-down temperature profile, it was possible to reduce the drying time to reach the desired moisture content.

Key Words : Temperature Profile; Product Quality; Heat Pump Dryer; Banana

INTRODUCTION

The main objective of any drying process is to produce a dried product of desired quality at minimum cost and maximum throughput, and to optimize these factors consistently. Often good quality of a biological product implies that the dried product undergoes to several, physical, chemical or biological changes to yield a product of desired specifications. Drying is a notoriously energy intensive operation that easily accounts for up to 15 % of all industrial energy usage, often with relatively low thermal efficiency in the range of 25 % to 50%. Thus, in order to reduce energy consumption per unit of product moisture, it is necessary to examine different methodologies to improve the energy efficiency of the drying equipment. One possible method is to apply time-dependent drying schemes to reduce the drying time to obtain desired product moisture content.

In the present paper, we evaluate the feasibility of applying selected time-varying drying schemes to drying agricultural product to reduce drying time and improve product color.

Time-dependent drying schemes which imply time-varying supply of thermal energy for drying in the batch mode can be classified into the following categories:

1. Intermittent drying whereby heat is supplied intermittently rather than continuously. This can be done by interrupting the air flow to provide the material a "rest" period, by a continuous air flow periodically heated, or by periodic variation of air flow.
2. Dryaeration which is a drying process involving a combination of high temperature short drying period, tempering, and slow cooling concluded by final drying.
3. Air reversal drying which is reversing the direction of the airflow for a period of time and then revert it back to its original direction. This is applied to deep bed drying of particulates.
4. Cyclic drying which is a drying process whereby the air temperature, humidity or even velocity undergoes a specified cyclic pattern variation such as sinusoidal, square-wave or saw-tooth patterns.

Several experimental modeling studies have appeared in the literature on intermittent drying. For example, Giowacka and Malczewki (1986) solved Luikov's equations to predict drying of granular materials using time-varying inlet air temperature. The effect of intermittency on energy saving was studied by Jumah et al., (1996) in their study of intermittent drying of grains in a rotating jet spouted bed; they found that significant energy and quality advantages may arise from drying of heat-sensitive particles.

Ratti and Mujumdar (1993) have presented a simulation study on batch drying of shrinking hygroscopic materials in a fixed bed under time-varying flowrate. Their work has shown that the total air consumption for drying is reduced with minor or no increase in drying time. This has important economic implications in terms of reduced energy consumption for air handling which will eventually impact the overall operating cost of the dryer. Based on the above literature reviewed, intermittent and time-varying drying has been shown to offer significant advantages in terms of reducing the required energy and enhancing the product quality of heat sensitive products.

The objective of this paper is to examine the drying kinetics and product quality under conditions of step-wise increasing and decreasing drying air temperature while other drying parameters (humidity and air velocity) are kept constant. Drying kinetics and product quality dried under constant drying condition will be used as the basis for comparison.

EXPERIMENTAL SET-UP, MATERIALS AND METHODS

Heat pump dryer

A two-stage heat pump dryer was used to allow accurate control of both the humidity and temperature of the drying air according to the step-wise temperature profiles selected in this work. The two-stage heat pump dryer has a two-stage evaporator system with one evaporator operating at a higher pressure level relative to the other. The desired drying air conditions were generated and controlled with the use of three PID controllers. One controller was used to provide sufficient sensible heat from hot gas condenser (HGC), subcooler 1 (SC1) and subcooler 2 (SC2) to heat the drying air. The second controller was used to control the sensible heat input from an auxiliary heater to obtain higher air temperature requirements. The third controller was used to modulate the face and bypass dampers of the evaporators so as to control the dehumidification process and maintain the desired humidity of the drying air. Details of the control mechanism for the two-stage heat pump dryer can be found in Chou et al. (1998) and Hawlader et al. (1998).

Two different data-logging systems were used to record data from the entire system. An 8-bit data-logger with twenty channels was used to record data from the type 'T' thermocouples and relative humidity sensors, enabling the air conditions at various points of the system to be measured. A 12-bit data logger was used to record outputs from all the resistive temperature detectors (RTDs) and pressure transducers from the refrigerant circuit.

A reproducibility test was conducted for the sensors installed in the heat pump dryer. The air-side measurements, comprising the wet and dry bulb temperature measurements, the relative humidity and the flow velocity, displayed less than 6.5% variation. On the refrigerant-side measurements, comprising the local temperature, pressure and volumetric flow rate, less than 6.3% variation was obtained. The uncertainties due to calibration for each parameter are presented in Table 1.

Table 1. Estimated uncertainties for different measurements.

Measured property	Uncertainty	Range
Moisture content (Weighing balance)	± 0.5%	0 to 7 kg
Inlet and outlet air temperatures (type 'T' thermocouple)	± 2.4%	2.5 to 90 °C
Inlet and outlet air humidity (relative humidity sensor)	± 2.3%	22.4 to 97.3 %
Air velocity (rotating anemometer: calibrated by manufacturer)	±1.0%	0.5 to 30.0 m/s

Procedure

For each experiment, fresh bananas were purchased from the supermarket with referenced ripeness charts to ensure consistency of results. The samples were skinned peeled, sliced with an adjustable food-slicer to 3 mm thickness and cut to 30 mm x 30 mm with a twin-knife fixture. For the color tests, all samples were soaked in 2% $NaHSO_3$ solution for 5 to 6 minutes (Singh et al., 1983) to suppress enzymatic reactions, since the focus of the present work is to study the effect of drying conditions on product color due to non-enzymatic browning. The product was presented by twelve replicates and placed on plastic netted-trays positioned in the drying chamber of the heat pump dryer. The required temperature and humidity representing each type of temperature profile were entered into the respective PID controllers to regulate the refrigerant flow for temperature control and the by-pass air damper through the evaporators for humidity control. The humidity was maintained in the range of 0.0074 kg/kg to 0.0103 kg/kg dry air for all tests.

Drying tests in the two-stage heat pump were carried out with 3 different temperature-time profiles as shown in Figure 1. A constant temperature drying run at 25 °C was taken as the base case. Two step-wise, one step-up and one step-down, temperature profiles were used in this study. Taking the base-case temperature of 25 °C, two step-wise temperature settings were programmed into the PID controllers to study the effect of drying air temperature variation on the color parameters. For measurements of the color parameters of each product, the initial value of each fresh product was taken as the target value for reference. As drying proceeded, the replicates of each product were removed for weight and color measurements. Samples of each product were scanned at five different locations to obtain the averages of L, a and b values. The changes in each color parameter were then calculated with respect to the target values.

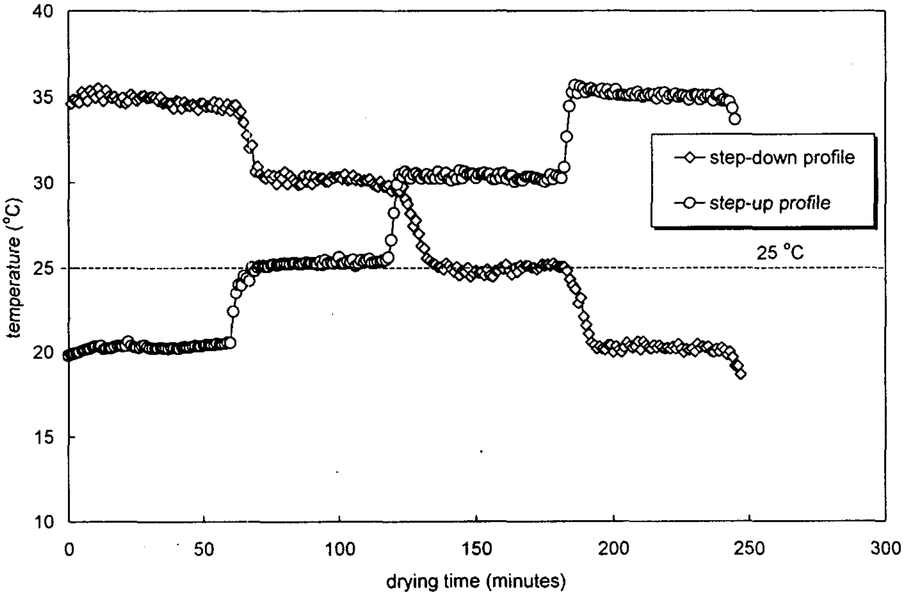

Figure 1. Step-wise temperature profiles versus drying time

Color measurements

The color values of each samples were measured using the latest Minolta CM-3500d Spectrophotometer to obtain the Tristimulus color values (Hunter L, a and b values). Hunter L represents lightness, a represents redness or greenness while b represents blueness or yellowness values. The changes in each individual color parameters were calculated as follows:

$$\Delta L = L - L_o; \qquad \Delta a = a - a_o; \qquad \Delta b = b - b_o \qquad (1)$$

The subscript 'o' refers to the target value or the initial color parameters of each product at the beginning of the drying experiments. The total color difference (ΔE) was then determined using the following equation:

$$\Delta E = \left[\Delta L^2 + \Delta a^2 + \Delta b^2\right]^{1/2} \tag{2}$$

RESULTS AND DISCUSSION

Drying kinetics

According to Karel (1988), the dynamic method for determining degradation kinetics, under conditions representative of drying, requires the acquisition of moisture, temperature, concentration and quality data during drying. The moisture-time curves are shown in Figures 2. It can be inferred from this figure that a saving time of 180 minutes or 300% can be obtained by using a simple step-down temperature variation starting for an initial drying temperature of 35 °C to finishing drying at 20 °C. Devahastin and Mujumdar (1999), in their study on batch drying of grains with step-wise change in drying air temperature, have found the reduction of drying time to be a conservative value of 30%. Of course, the degree of percentage improvement is dryer and product-dependent.

Step-up temperature drying produces a relatively linear drying curve with an inverted shape as compared to the conventional drying curves. Such a profile is not unexpected since the drying process is relatively slow at the beginning stage due to the reduced drying potential. As the product approaches the 240-minute mark, the surface is still moist and the step increase in the air temperature increases the drying rate. In terms of drying time, step-down temperature drying has significant advantage over continuous and step-up temperature drying.

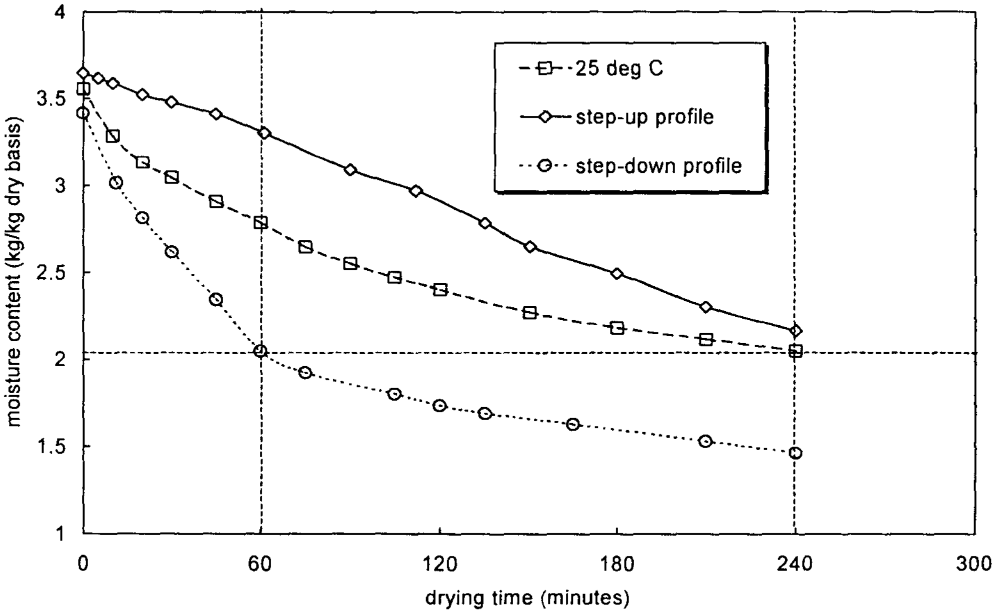

Figure 2. Moisture content of banana samples versus drying time

The drying rate curves for each of the temperature profiles are shown in Figures 3. It can be observed from these figures that step-wise air temperature drying produces very unexpected drying rates. For the step-down temperature profile, two conventional first and second falling drying rate curves exist in tandem. Such findings can be attributed to the lower temperature tempering effect on the product causing a lower falling rate. After the second temperature drops, the drying rate curve flattens due to its low moisture content in the last stage of drying.

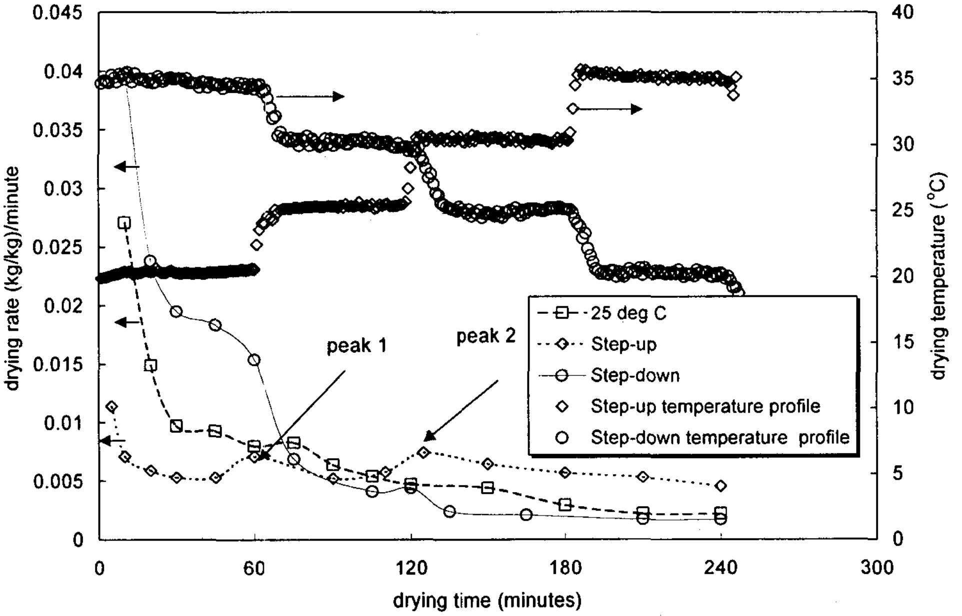

Figure 3. Drying rate of banana samples versus drying time

Two drying rate peaks can be detected for the step-up temperature profile. Due to the slow initial drying, the product still has a high moisture content and thus is still able to experience increase in drying rate when the air temperature is increased by a step temperature of 5 °C. Devahastin and Mujumdar (1999) have shown through the simulation of their validated model for grain drying that the drying rate is higher for step-down temperature above those for constant temperature drying. Such finding is consistent with our results.

Product Color

From Figure 4a, step-down and constant temperature profiles of 25 °C were able to maintain the lightness of the banana samples. Comparing both step-wise temperature profiles, it appears that the step-down temperature reduction scheme is able to better conserve the lightness of the product. During the initial stage of drying, the banana samples are able to withstand a higher temperature gradient as compared to the final stage of drying. Thus, it would appear that step-down temperature drying would speed up drying without producing significant 'darkening' on the external surface of the banana samples.

In terms of the reduction in redness of the banana samples, it is shown in Figure 4b that both step-wise temperature profiles do not have favorable effect when compared to continuous temperature drying. However comparing Figures 4a and 4b, it can be observed that the magnitude of change in redness is relatively small as compared to Δ L.

In our previous work (Chua et al., 2000) it was observed that other time-temperature varying profiles such as square-wave and sinusoidal temperature profiles were not able to reduce the change in yellowness. Both step-wise temperature profiles were found to be effective in reducing the change in yellowness of the banana samples as shown in Figure 4c. This led us to infer that both the surface temperature of the product and the rates of moisture removal have significant influence on the change of the color components. Different temperature profiles would naturally generate different product surface temperature profiles. The variable surface heat flux due would then be conducted towards the product internal sections. Depending on the magnitude of this heat flux, internal moisture migrates to the surface at different rate. The rate of migration is function of the internal moisture gradient. The formation of the surface moisture due to the surface may act as a protective layer to minimize color degradation. As a result, it is important to examine the continuous change in surface temperature resulting from continuous or discrete temperature change. It is equally important to examine the time-temperature history of the product resulting from any step-change in drying temperature.

Figure 4d clearly shows that there is a significant difference in the overall color change of the banana samples dried under step-wise temperature variation compared to samples under constant temperature drying. Reduction in the net change in color can be as high as 23.1% and 40.8% for step-down and step-up profiles, respectively. More interesting is the comparison between step-wise temperature profiles. The step-up temperature profile appears to better improve color change in banana samples. This finding is consistent with our previous work (Chua et al., 2000) which found that low initial drying rate allows sufficient time for the internal moisture to diffuse to the surface ensuring a constant film of moisture at the surface until the critical moisture content. Thus, banana, a product with high sugar content, would be continuously coated with a layer of moisture during the initial stage of drying. This layer reduces the effect of surface heat-up, resulting in a reduced non-enzymatic reaction. The layer of surface moisture, during the initial drying stage, probably prevents dehydration of the surface sugar molecules and hence reduces the rate of the Maillard reaction, thus lowering the overall color change ((Eichner et al., 1985).

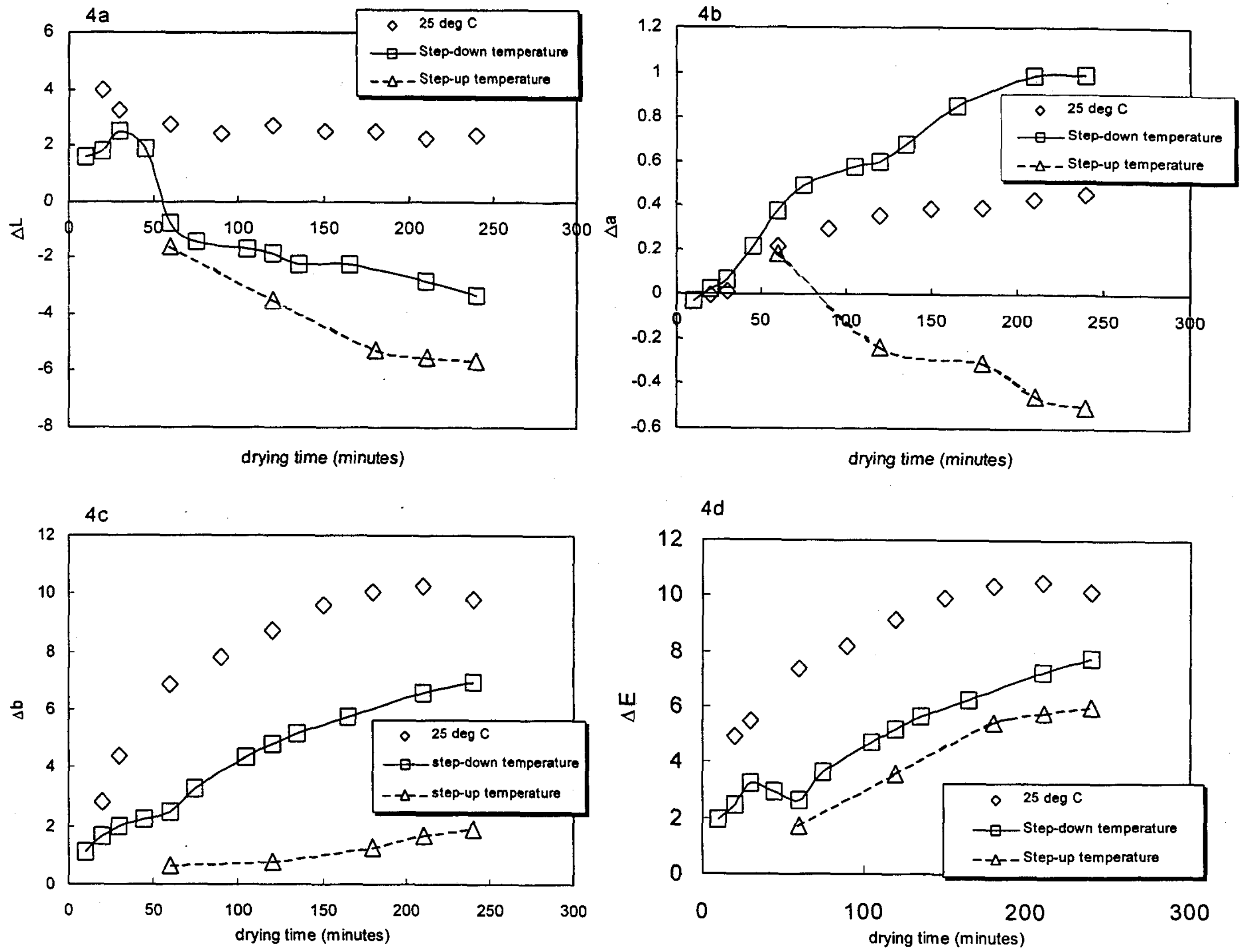

Figure 4. Various color component of banana samples versus drying time

CONCLUSIONS

Time-varying drying air temperature in batch drying of banana slices is shown to have favorable impact on drying kinetics as well as the color of the dried products. Tests carried out in a two-stage heat pump dryer showed that stepping the air temperature down from an initial value of 35℃ to finish drying at 20℃ gives reduced color degradation in the order of 40%. Saving in drying time up to 180 minutes was observed the air temperature was stepped up from an initial value of 20℃ to finish drying at 30℃.

NOTATIONS

a	Hunter redness value	–
b	Hunter yellowness value	–
E	Hunter color difference	–
L	Hunter lightness value	–

Greek symbols

△	change in color parameters	–

REFERENCES

1. Chou, S. K., Hawlader, M. N. A., Ho, J. C. and Chua, K. J. 1998. An improved design of a heat pump tunnel dryer, Asean Journal on Science & Technology for Development, Indonesia, pp. 10-18.

2. Chua, K. J., Mujumdar, A. S., Chou, S. K., Hawlader, M. N. A., and Ho, J. C. 2000. Heat pump drying of banana, guava and potato pieces. : Effect of cyclical variations of air temperature on convective drying kinetics and colour change, Drying Technology, 18, No.(4&5), pp. 907-936.

3. Chua, K. J., Chou, S. K., Hawlader, M. N. A. and Ho, J. C. 1998b. A two-stage heat pump dryer for better heat recovery and product quality, Journal of The Institute of Engineers, Singapore, Volume 38, No. 6, pp. 8-14.

4. Eichner, K., Laible, R. and Wolf, W. 1985. The influence of water content and temperature on the formation of Maillard reaction intermediates during of plant products. In Properties of Water in Foods, Editor Simatos, D. and Multon, J.

L., Matinus Nijhoff Publishers, Dordrecht, pp. 191-210.

5. Giowacka, M. and Malczewski, J. 1986. Oscillating temperature drying, Drying of Solids, edited by Mujumdar, A. S., pp. 77-83.

6. Hawlader, M. N. A., S. K. Chou, J. C. Ho and K. J. Chua. 1988. On the development of a heat pump dryer to maximise heat recovery. In Drying '98 : Proceedings of the 11th International Drying Symposium, Thessaloniki, Greece, pp. 616-623.

7. Jumah, R. Y., Mujumdar, A. S. and Raghavan, G. S. V. 1996. A mathematical model for constant and intermittent batch drying of grains in a novel rotating jet spouted bed, In Mathematical Modelling of Drying Processes, editors Turner, I. W. and A. S. Mujumdar, Marcel Dekker, pp. 339-380.

8. Ratti, C. and Mujumdar, A. S. 1993. Fixed-bed batch drying of shrinking particles with time varying drying air conditions, Drying Technology, 11, pp. 1311-1355.