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SHORTER COMMUNICATIONS

THE EFFECT OF DIFFERENT MODES OF OPERATION ON THE DRYING PROCESSES

D. BEYER and D. C. T. PEI
University of Waterloo, Chemical Engineering, Waterloo, Ontario, Canada

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NOMENCLATURE

c_s, specific heat capacity of solid [k cal/°K kg solid];
H_s, $\frac{\dot{q}'l^2}{K_T(T_e-T_0)}$ dimensionless internal heat source;
h, heat-transfer coefficient [kcal/m²h°K];
K_c, mass-transfer coefficient [m/h];
K_l, liquid conductivity [m²/h];
K_T, thermal conductivity [k cal/°K h m];
K_v, vapour diffusivity [m²/h];
l, thickness of solid [m];
N_{Bi_h}, $\frac{h_l}{K_T}$, Biot number (heat transfer);
$N^*_{Bi_m}$, $\frac{K_c l}{\alpha}$, Biot number (mass transfer);
N_{Fo}, $\frac{\alpha t}{l^2}$, Fourier number;
N_{Ko}, $\frac{r_v(u_0-u_e)}{c_s(T_e-T_0)}$, Kossovich number;
N_{Lu_L}, $\frac{K_L}{\alpha}$, Luikov number (liquid transfer);
N_{Lu_v}, $\frac{K_v}{\alpha}$, Luikov number (vapour transfer);
p_v, partial vapour pressure [kg/m h²];
q, heat flux [kcal/m²h];
$\dot{r}_D$, rate of drying [kg/m²h];
r_v, latent heat of evaporation [kcal/kg];
$\dot{R}_D$, $\frac{\dot{r}_D}{K_c(\rho v_0-\rho v_e)}$, dimensionless rate of drying;
t, time [h];
T, temperature [°K];
u, liquid content [m³ liquid/m³ solid];
U, $\frac{u-u_e}{u_0-u_e}$, dimensionless liquid content;
α, $\frac{K_T}{p_s c_s}$, thermal diffusivity [m²/h].

INTRODUCTION

IN THE previous theoretical study [1], a mathematical model of drying was presented whereby capillary flow of liquid and vapour diffusion as well as heat transfer through solids were taken into account simultaneously. The results in the form of traditional rate of drying curve were obtained and discussed with various internal and external physical parameters on the basis that heat is supplied to the material by convection only. In industrial drying processes the heat is quite often also supplied by conduction through the belt or pan to the bottom of the material or by employing some form of internal heat source, such as microwave heating.

Moreover, the theoretical model [1] has indicated the ineffectiveness in improving the drying of a material via the intensification of the external transfer processes. It concludes that the gain with respect to drying time achieved during the stabilization and the constant rate period due to additional heat supply via external transport processes is to some extent lost as the drying process proceeds into the falling rate period which is not effected significantly. This leads to one additional possibility in improving the efficiency of a drying process, i.e. the extension of the duration of the constant rate period.

As it has been pointed out [1], the falling rate period of the drying processes starts once the moisture content at the surface reaches the maximal sorptional value U_{sm}. However, at any other location within the material, the moisture content is larger than U_{sm}. If the liquid content of the material can be equalized, or in other words, rearranged such that it is close to uniform again, then obviously the surface moisture content will again be larger than U_{sm}. Consequently, the drying will proceed again in the constant rate until the surface moisture content reaches the maximal sorption value.

In industry, such an equalization of the moisture content profile can be carried out either by making the drying process intermittently thus allowing the profile to equalize by itself, or, if the material to be dried is a bed of pellets or granulates, this equalization can be achieved by mixing or turning. A drying process utilizing this concept may be called "stage-wise" or "intermittent" drying.

Therefore, a brief study of the following three cases may prove to be useful:

1. The heat is supplied to the material by conduction through the pan or the belt as well as the convection process. This results in the modification of the heat boundary conduction at the bottom of the drying material to allow for a constant external temperature;

2. An internal heat source H_s of various intensities is included in the heat-transfer equation;

3. A multi belt drier is designed and its performance compared with an equivalent single belt drier.

RESULTS AND DISCUSSIONS

These rate curves in Figs. 1 and 2 illustrate that both the heating at the bottom of drying material and the application of internal heat source lead to a higher rate of drying during the constant rate period. This is expected since the surface temperature has to be higher as additional heat is supplied to the material. While an internal heat source shows its effect immediately after the drying process has started, the effect of heat conduction is realized only after a time lag. This is due to the fact that time is required for the heat to be transferred from the bottom to the surface of the material. Therefore, similar to the case of intensified external convective heat transfer, the application of additional heat supply will not affect significantly the falling rate period and the gains with respect to drying time achieved during the stabilization and the constant rate period due to additional heat supply will to some extent be lost as the drying process proceeds into the falling rate period at an accelerated rate.

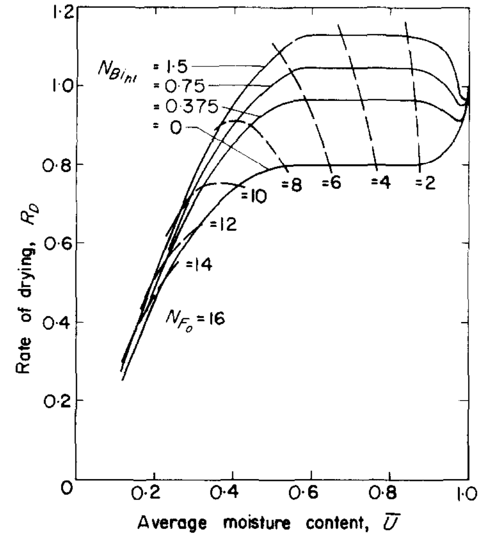

FIG. 1. Dimensionless rate of drying curves with time lines. Parameters: $N_{Lu_L} = 0{\cdot}04$, $N_{Lu_v} = 20$, $N^*_{Bi_m} = 2000$, $N_{Bi_h} = 0{\cdot}75$.

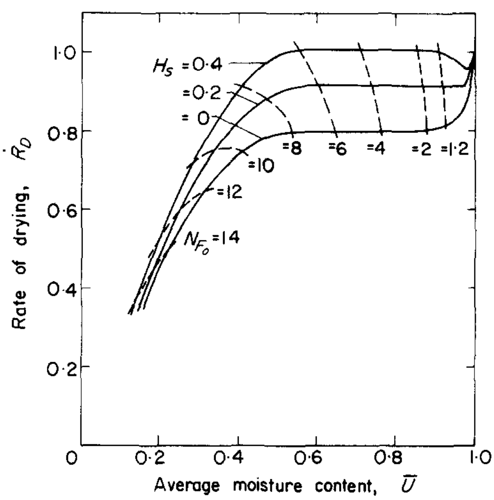

FIG. 2. Dimensionless rate of drying curves with time lines. Parameters: $N_{Lu_L} = 0{\cdot}04$, $N_{Lu_v} = 20$, $N^*_{Bi_m} = 2000$, $N_{Bi_h} = 0{\cdot}75$.

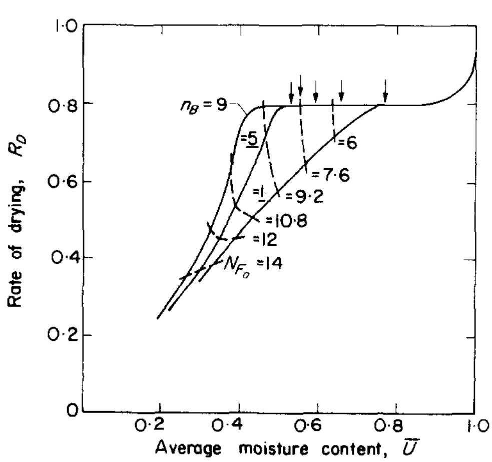

FIG. 3. Dimensionless rate of drying curves with time lines. Parameters: $N_{Lu_L} = 0{\cdot}04$, $N_{Lu_v} = 20$, $N^*_{Bi_m} = 2000$, $N\ _{i_h} = 0{\cdot}75$, $N_{Ko} = 28{\cdot}6$.

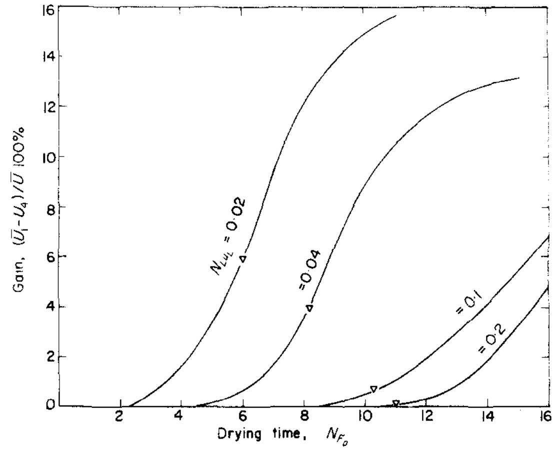

FIG. 4. Gains achieved by "intermittent" drying processes. Parameters: $N_{Lu_v} = 20$, $N^*_{Bi_m} = 2000$, $N_{Bi_h} = 0{\cdot}75$, $N_{Ko} = 28{\cdot}6$ ("V" indicate the beginning of the falling rate period).

The above observations on the overall effects of the external drying paraments and additional heat supplies have been, to some extent, established by many experimental investigations [2–5]. While experimental investigations, however, do not allow to clearly establish the significance of each individual parameter, the theoretical model permits such a parameter study.

Based on the results of the previous discussion, the extension of the duration of the constant rate period provides another possibility in improving the efficiency of a drying process. To explore the feasibility of such a drying process, a multi-belt drier design will be used as the basis for discussion.

For illustration purposes, it is assumed that all belts are running at the same speed and at the end of each belt the surface moisture content of the material will reach the maximal sorptional value U_{sm}. The material then dropped from one belt to the next and the newly formed layer of granulates has redistributed itself and assumed to have achieved a new uniform moisture and temperature distribution. The values of these new "initial" conditions of each belt are assumed to be respectively equal to the average remaining moisture content of the granulates at the end of the preceding belt.

In Fig. 3, the rate of drying, R_D, is plotted as a function of the average remaining moisture content $\bar{U}$ with the number n_B of belts as parameter. Clearly, if the $n_B = 1$, the drying process is continuous in the sense that the material is dried from its initial moisture content to the final value with one constant rate period followed immediately by the falling rate period. As expected, with increasing number of belts, the duration of the total constant rate periods increases. Moreover, Fig. 3 indicates that the required residence time on the belt that follows is progressively shorter than on the proceeding one. In other words, it is evident that at the surface of the material the maximal sorptional moisture content is reached earlier on the third belt than on the second one. (The arrows indicate the end of each individual belt.)

The advantage of such an "intermittent" process can further be illustrated by these dotted time lines drawn in Fig. 3. These time lines show that drying time is not only gained as the constant rate period is prolonged, but more important, an additional gain is made during the first interval of the falling rate period.

In establishing some points of reference about the feasibility of such an "intermittent" drying process, two sets of drying rate curves are calculated with the Luikov number N_{Lu_L} as parameter. The number of belts is equal to one and four respectively and comparison is made between the corresponding drying rate curves. The average moisture content $\bar{U}_1$ and $\bar{U}_4$ respectively are obtained as a function of the dimensionless drying time N_{Fo} and the percentage differences $[(\bar{U}_1 - \bar{U}_4)/\bar{U}_1]$ 100 per cent are plotted as a function of N_{Fo} with N_{Lu_L} as parameter where "V" indicates the beginning of the falling rate period.

It is evident in Fig. 4 that the "intermittent" procedure improves the efficiency even during the first interval of the falling rate period. This is particularly true for materials exhibiting small values of N_{Lu_L}, i.e. for porous solids which are difficult to dry. It has been shown previously [1] that the moisture content profiles corresponding to small N_{Lu_L} has a much steeper profile towards the surface. Therefore, at the end of each constant rate period, the remaining average moisture content, $\bar{U}$, is larger for small values of N_{Lu_L}. Consequently, the amount that can be removed during additional constant rate period is also larger. However, it should also point out that such a steep moisture content profile toward the surface may also be resulted by intensified external transfer processes or by additional means of heat supply. Therefore, one may conclude that such an "intermittent" process will be especially feasible for any drying processes whereby the duration of the constant rate period is severely shortened either by intensifying the external transfer processes or by additional heat supply to the drying material. Furthermore, the general agreement between the results of experimental observation reported in literature and the prediction of the parameter study presented here, may be looked upon as a partial verification of the theoretical model for the drying process.

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HEAT-TRANSFER REGIMES IN VERTICAL, PLANE-WALLED, AIR-FILLED CAVITIES

M. Dixon and S. D. Probert
School of Mechanical Engineering, Cranfield Institute of Technology, Cranfield, Bedford MK43 0AL

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NOMENCLATURE

- Cp, specific heat of air at atmospheric pressure;
- d, thickness of the air layer;
- g, local acceleration due to gravity;
- Gr, Grashof number based on d ($\equiv g/\beta \Delta T d^3 \rho^2/\mu^2$);
- h, height of the fluid layer;
- hd, aspect ratio;
- k, thermal conductivity of air;
- Pr, Prandtl number $\left(\equiv \dfrac{\mu Cp}{k}\right)$;
- Ra, Rayleigh number ($\equiv Gr.Pr$).

Greek symbols

- β, coefficient of thermal expansion of the air;
- ρ, density of the air at atmospheric pressure;
- μ, dynamic viscosity of the air;
- ΔT, temperature difference across the air layer of thickness d.

INTRODUCTION

Free convective flow phenomena in plane, enclosed, vertical air layers at atmospheric pressure are of a complex nature. Three regimes of heat transfer can be distinguished within vertical cavities for the laminar flow region of Grashof number and these have been termed the conduction, the transition and the boundary-layer regimes respectively.

In the conduction regime heat is transferred predominantly by gaseous conduction and the temperature gradients are linear except near the top and bottom of the cavities. In the transition regime convective flow becomes significant and the temperature profiles across the air layer are no longer linear. However, the boundary layers on the hot and cold walls merge with one another and gaseous conduction remains the dominant heat-transfer mechanism. The boundary layer regime is characterized by separate thermal boundary layers on the hot and relatively cold walls and the temperature profiles exhibit steep gradients at the walls with a zero or inverted slope within the core region. Consequently convection rather than gaseous conduction is the predominant mechanism of heat transfer.

LIMITS OF THE REGIMES

Eckert and Carlson [1] proposed that the delineation of the three regimes could be obtained from relationships of the form:

$$Gr = f(h/d). \qquad (1)$$

A limit for the conduction regime has been derived theoretically by Batchelor [2] to be:

$$Gr = 695(h/d). \qquad (2)$$

It is debatable, however, whether the limits of the flow regimes are dependent upon the aspect ratio (h/d), and no conclusive evidence has yet been offered to support this contention. For fluids of various Prandtl numbers (> 1), MacGregor and Emery [3] found that the flow regimes were characterised by the Rayleigh number. Moreover, it has been stated by de Graaf and Van der Held [4] that the aspect ratio has only a minor effect in controlling the flow conditions. Hence Brooks and Probert [5, 6] conducted an interferometric investigation on air layer widths of 0·635, 1·27