DRYING OF PARTICULATE FOODSTUFFS IN A CONFINED FLUIDIZED BED

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ABSTRACTS

A novel drying apparatus, based on the confined fluidization technique, is presented. It consists of a fixed bed of coarse particles whose interparticle voids, filled with the fine powder to be dried, constitute the fluidization environment. This system, particularly suitable for heat-sensitive products, can be considered as an alternative to fluid bed dryers with immersed heating surfaces. Drying experiments were performed on two food powders, semolina and corn flour, and the effect of different variables on the drying kinetics was investigated. The experimental results obtained show that confined fluidized bed dryers are very efficient units in which the drying time is reduced also with respect to conventional fluid bed dryers. More work is needed to extend the application of this drying technique to food powders with high initial moisture content and small particle size.

INTRODUCTION

Many raw materials as well as intermediate and finite products of agriculture and food industry are produced in form of powders. An important role in their processing is played by drying, which allows the foodstuff storage life to be extended, to enhance quality and to improve packaging, handling and transportation stages.

Indeed, due to the drying process, the residual moisture content in foods and agricultural products is lowered and, consequently, water activity decreases.

It is well known that the rate of bacteria, yeasts and moulds growth, enzymatic and non-enzymatic reactions and lipid oxidation, which cause food spoilage, are inhibited or reduced at low water activity, i.e. at low moisture content. The shelf life of dried foods is thus assured, provided that materials impermeable to external atmosphere are used for packaging.

Drying also improves some characteristics of foods like palatability and digestibility. As a side effect, the colour, flavour and the aspect of foods also change as a consequence of the process. Moreover, packaging, handling and transportation of dried products are easier and cheaper, due to the reduction of weight and volume of products with respect to wet materials, also because of the improvement in their flowability. Finally, further processing stages on dried products, like milling, take far less energy than that required to process wet products.

In recent years, the utilization of fluidized beds has been recommended for drying of granular agricultural and food products, due to the excellent heat and mass transfer rates attainable, to the reliable thermal control of the drying process consequent to the rapid mixing of solids and to the low maintenance costs of the apparatus having no mechanical moving parts(1,2).

In fluid bed dryers, rapid heat and mass transfer between particles and gas allows the overheating of products to be avoided, so that volatile and heat sensitive components are retained in the products. That increases the sensory and nutritional properties of dried foodstuffs. Moreover, fast solid particle mixing leads to nearly isothermal conditions throughout the fluidized bed, thus avoiding uneven treatments or overprocessing of foods.

However, relatively few industrial scale drying units are presently in operation, due to the poor fluidization properties exhibited by foods and agricultural products, which are generally characterized by very fine or coarse sizes and irregular shapes. Very fine solids are cohesive and tend, when fluidized, to undergo channelling and slugging if the gas velocity is kept low to prevent excessive elutriation of fines. On the other hand, coarse and odd-shaped particles require high gas velocities to be sustained and, when fluidized, give rise to irregularities in gas permeation as well as in solid circulation which dampens the aforementioned excellent transfer properties of fluidization.

Different kinds of fluid bed dryers have been devised: conventional plug-flow, vibrofluidized units, two-component fluid beds, fluid bed dryers with immersed heating surfaces.

In plug flow fluid bed units, the residence time distribution of particles is uniform, so that homogeneous processing of powders is achieved. Due to their flow characteristics, very low moisture contents can be obtained even though the thermal efficiency of the apparatus is not very high, as most of water release takes place near the gas distributor. Furthermore, the gas flow rate flowing across the bed in the form of bubbles bypasses the contact with the solids, lowering further the thermal exchange efficiency of the process.

In vibrofluidized beds, particles are maintained in the fluidized state by the combined action of air flow and vibration. These units are used to dry cohesive and sticky powders, which tend to form agglomerates that would block dryers employing unassisted fluidization. Powders with a wide particle size distribution and fragile or abrasive materials can be treated in such systems as well.

The treatment of coarse particles, as in the case of most agricultural products, can be conducted in two-component fluid bed dryers (3). Coarse particles undergoing drying are immersed in a fluidized bed of fine solids in which they can move freely. The difference of density between the granular products and the fluidized bed is such that they undergo no segregation effect. The heat and mass transfer coefficients between the dense phase of fines and the immersed particles are of the same order of magnitude as those measured between gas and particles in conventional fluidization (4).

Fluidized bed dryers equipped with immersed heating surfaces are very suitable for drying heat-sensitive foodstuffs, when severe limitations in gas velocities and temperature levels in the bed have to be accepted to prevent thermal damages. In this case, if the heat needed to dry the products is supplied with just the air inlet, an excessively large distributor would be required. To overcome this difficulty, part of the heat is transferred to the powder by means of external heating surfaces immersed in the solid bed.

In addition to the several fluidization modes used in the powdered food drying operations mentioned above, this paper aims at presenting some preliminary experimental results obtained by a different technique, the confined fluidization.

THE CONFINED FLUIDIZATION TECHNIQUE

In the conventional fluidization technique, when the system is operated at gas velocities much higher than the minimum fluidization value, a large part of the gas flow rate finds its way through the bed in form of bubbles, which promotes mixing within the particulate mass; the bubble flow constitutes a way through which much of the gas bypasses the fluidized bed, thus putting a limit on the heat and mass transfer efficiency of the operation.

To rise the effectiveness of the contact between gas and particles an alternative fluidization technique has been proposed, with the objective of suppressing or at least minimizing the presence of bubbles in the particulate system whilst allowing a certain circulation of fine solids (5, 6); it consists of fluidizing a bed of relatively fine particles within the voids of a fixed bed of a coarser spherical material, which acts as a confining environment. For that reason the technique is called "confined fluidization".

The basic principles of confined fluidization are illustrated in fig. 1.

Provided that the size ratio between the two components of the system is high enough to allow free percolation, the fluidizable material forms a fixed layer at the bottom of the coarse packing as soon as it is poured into the column (A). By admitting and subsequently increasing the gas flow rate through the bed, a superficial gas velocity $U_{mf,c}$ is reached at which the fine particles attain their incipiently fluidized state (B); this can be calculated as(5):

$$U_{mf,c} = k \frac{\rho_P \, g \, \varepsilon^2_c \, d^2}{150 \, \mu_s} \quad \frac{\varepsilon^3_f (1 - \varepsilon_f)}{[\varepsilon_c(1-\varepsilon_f)+(-\varepsilon_c) \frac{d}{D}]^2} \qquad (1)$$

and for any higher velocity the confined fluidized bed undergoes a progressive expansion (C), described by a power law of the type

$$U = \alpha \, \varepsilon^n \qquad (2)$$

that can make its voidage assume values even higher than 0.9. Equation (2) is maintained also after the fluidized bed has exceeded the packing height forming a segregated bubbling layer on the top of it (D), but that is not a desirable mode of operation.

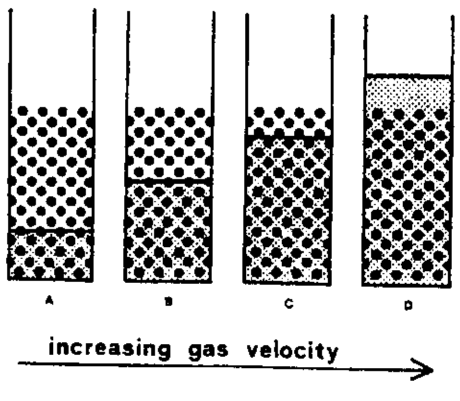

Fig. 1 - Behaviour of a fine particle bed of particles undergoing confined fluidization.

Altogether, the distinctive feature of a confined fluidized bed is that it reacts to any gas flow rate increase past minimum fluidization with its expansion, rather than with bubble formation. Compared with the conventional fluidization technique, where the interstitial velocity within the dense phase is practically unchanged by a velocity increase, the prevention of bubbling is accompanied by an unusual increase of the gas-particle slip velocity. This can easily grow, at constant total pressure drop, up to levels that can greatly accelerate any process whose kinetic is determined by the velocity of mass transfer phenomena occurring between particle surface and gas phase. This is the case of drying processes that operate on particulate solids for which the fluidization technique is advisable, especially when the drying mechanism is controlled by the superficial heat transfer and the rate of moisture removal is constant. In such a situation, a secondary benefit provided by the confining sphere packing is that of acting as a thermal flywheel for the fluidized particulate mass.

EXPERIMENTAL SET UP AND PROCEDURE

The experiments reported in this paper were performed in different types of dryers: a natural convection oven, a forced convection oven with temperature and humidity control, a conventional fluidized bed and a confined fluidized bed. Food powders subjected to the drying treatment were semolina and corn flour, whose physical properties are reported in table 1. The drying temperature was maintained between 40 and 60 C to avoid starch gelatinization.

The fluidized bed drier consists of a perspex column 70 mm ID and 600 mm high. A porous plate at the base of the column, made of sintered brass, provides a uniform distribution of the gas flow throughout the bed cross section.

Table 1 - Properties of food powders.

Material	d_p (μm)	r_p (kg/m^3)	U_{mf} (cm/s)	X_0 (kg H_2O/kg d.m.)
Semolina	344	1,450	5.50	0.103
Corn flour	393	1,540	4.60	0.134

The fluidizing gas is air, preheated to the test temperature by an electrical heat exchanger, which in turn is regulated by a PID controller. The air flow rate is measured by a set of rotameters and the column is insulated with glass wool. The temperature of the inlet gas and of the bed is measured with thermocouples, one of which drives the temperature controller. A water manometer, fitted to a pressure tap at the base of the column just above the gas distributor, is used to measure the pressure drop across the bed.

The same apparatus is used in the confined fluidization drying experiments. The confining packing is made of stainless steel spheres 10 mm in diameter. An external rule aside the column allows the height of the confined bed of fines to be read.

Fluidization experiments are preliminarly made to determine the minimum fluidization velocities of the two powders in both the unconfined and the confined condition.

Subsequently, fluid bed drying experiments are carried out batchwise as follows: a predetermined weight of powder, of known initial moisture content, is introduced into the fluidized bed at ambient temperature. Every ten minutes, powder samples are taken from the fluid bed drier and introduced in an oven, operating at a temperature of 105 °C, to determine, by differential weighing, the residual moisture content. The same experimental procedure is used to determine the drying kinetics in the confined fluidized bed drier.

For the sake of comparison, drying experiments are also performed in a natural convection oven and in a temperature and humidity controlled oven, which simulate the drying conditions in conventional dryers. The test temperature is set at the same value as in the fluid bed experiments and the relative humidity in the climatic chamber is always kept at 3%.

RESULTS AND DISCUSSION

The effects of some of the principal variables influencing the drying process were investigated by carrying out a set of experiments on the two solids in the drying systems previously described.

Fig. 2 shows typical drying curves for semolina at 45 °C in different apparatus. It can be observed that in the confined fluidized bed drier, the drying kinetics in the first drying period, i. e. the constant rate period, are very fast compared with those measured in the natural convection oven and in the fluid bed drier. In the second drying period, the falling rate period, drying rates become very slow and the process is controlled by the rate of moisture diffusion inside the particles. This means that the reduction of the external resistance to heat and mass transfer, which is one of the important characteristics of the fluidization operation, does not play any role in this case. The drying kinetics measured in the confined fluid bed drier and in the fluid bed drier in the falling rate period are similar and even faster than those measured in the natural convection oven.

The performance comparison between conventional and confined fluidized bed dryers is made both at equal superficial and interstitial gas velocity. In the first condition, i.e. at equal gas throughput and total energy expense, the confined system appears to be much more efficient, owing to the higher gas-particle slip velocity, which is expected to be the key variable when the external resistance is the one controlling the heat and water transfer rates. This circumstance is confirmed when the two systems are operated at the

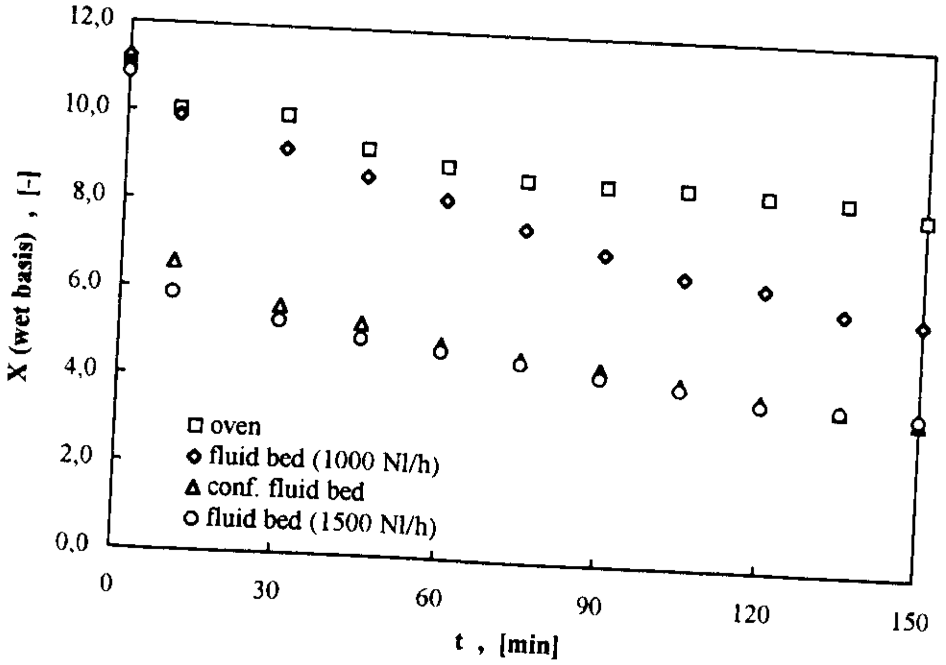

Fig. 2 - Curves of moisture content of semolina (wet basis) vs. time in different dryers.

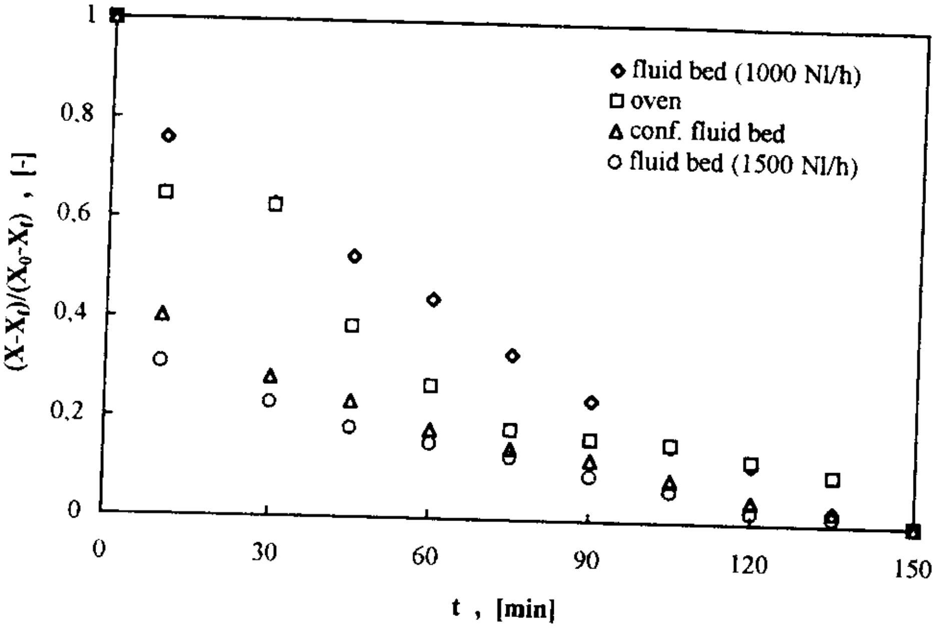

Fig. 3 - Dimensionless moisture reduction vs. time for semolina in different dryers.

same interstitial gas velocity: in this case the drying kinetics in the two dryers are nearly coincident.

When reported in terms of the ratio of residual over initial free moisture content, as in fig. 3 for semolina, the influence of process equipment and operating conditions on drying kinetics can more easily be evaluated.

The advantage of fluidization and the role of operative velocity on drying kinetics in the two fluidized bed dryers can again be observed, and a specific feature of the confined technique of fluidization, affecting the first minutes of the constant rate period of drying is highlighted: due to thermal flywheel action of the coarse packing constituting the confining environment, the fresh material entering the fluidized bed unit undergoes a heating action which is much faster than in conventional fluidization, where the fluidizing medium is the only heat source available for the solid.

Though not reported here, experiments confirmed the well known result that temperature affects the drying rate. As the temperature of the bed increases, the drying rate in the fluid bed drier increases. The same trend is also observed in the confined fluid bed drier as well as in the natural convection and in the forced convection oven. Analogous results obtained with corn flour are illustrated in fig. 4. The higher efficiency of the confined fluidization technique is more evident here, even when the conventional fluid bed is operated at the same interstitial gas velocity. Drying is much faster in the first period, whereas the efficiency of the process decreases in the subsequent period of velocity fall.

CONCLUSIONS

Experimental results obtained thus far allow the following conclusions to be drawn:

a) confined fluidization is a promising technique which can be used to dry particulate foodstuffs. In particular, it appears to provide a decrease in the drying time compared with that measured in conventional fluidization, at least in the period of constant drying velocity;

b) the practical absence of bubbles, through which the excess gas flow rate tends to bypass the fluidized bed, seems to be the reason for its enhanced thermal efficiency, as the gas/particle contact is improved;

c) the presence of the confining spheres reduces the bed section available for the gas flow. Thus, at the same gas flow rate, a higher interstitial velocity is reached compared with a conventional fluidized bed unit of the same

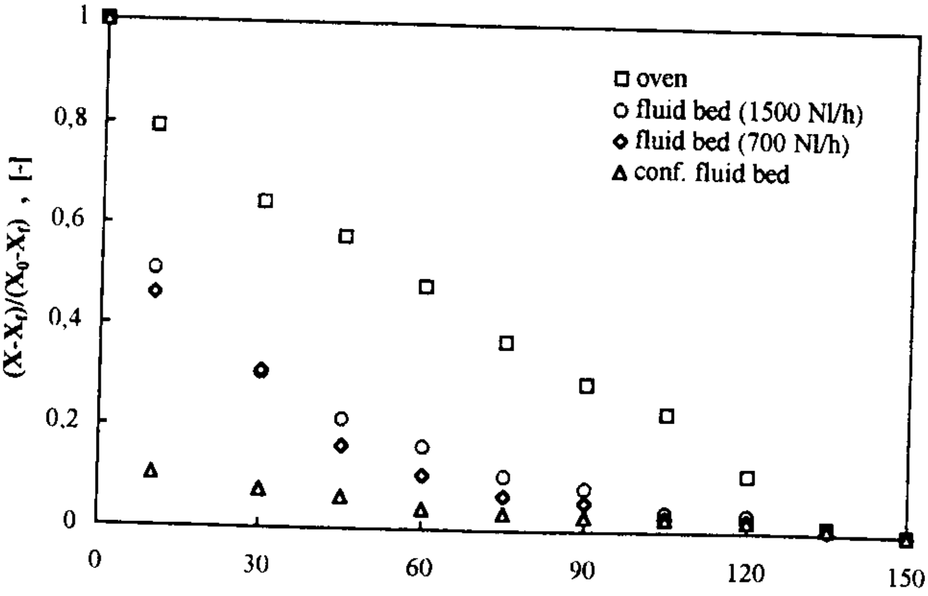

Fig. 4 - Dimensionless moisture reduction vs. time for corn flour in different dryers.

cross section. A faster particle circulation and a better contact between gas and solid, which are promoted by the increase of gas velocity, determine a parallel increase of drying rates.

More work is needed to clarify other fundamental aspects of dynamics and of heat and mass transfer in confined fluidized beds, together with the drying characteristics of various types of food and agricultural products, in order to predict drying kinetics of foodstuffs in these fluidized systems.

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SYMBOLS

d fine component diameter
D coarse component diameter
d_p mean particle diameter
g gravity acceleration
k parameter in Eq.(l)
n expansion index
t time
U superficial gas velocity
U_{mf} minimum fluidization velocity
$U_{mf,c}$ minimum fluidization velocity in the confined state
X moisture content of the solid
X_o initial moisture content
X_f final moisture content
a parameter in Eq.(2)
e fluidized bed voidage
e_f, e_c voidage of fine, coarse particles
e_{mf} minimum fluidization voidage
μ_g gas viscosity
r_p particle density

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WHEAT

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