EFFECT OF DISTRIBUTOR PLATE PARAMETERS ON DRYING RATE OF COARSE PARTICLES IN FLUIDIZED BEDS

H. Katalambula
Institute of Production Innovation, University of Dar es Salaam
P.O. Box 35075 Dar Es Salaam, Tanzania

ABSTRACT

Fluidized bed drying of coarse particles, with a particular emphasis on the effect of distributor plate parameters on drying rate, was investigated. A laboratory scale bubbling fluidized bed (15 cm ID) was used to fluidize wheat particles of 4.5mm average diameter. The drying air temperature was within 50 to 80 oC range. A new correlation which takes the effect of the distributor parameters into consideration was developed to predict the gas to particle heat transfer coefficient. The values of heat transfer coefficient obtained from the experiments were in the range of 0.8 to 25.2 W/m^2 oC. These values were found to be higher than ones reported for spouted beds.

INTRODUCTION

Fluidization behaviour of coarse particles is different from that for fine particles, mostly being characterized by the slow moving but quickly growing bubbles which soon fills the cross section of the bed. This results in slugs which normally remove all the technical advantages of fluidization.

The distributor plate is one of the most important components in a fluidized bed and its proper design is the key to successful and efficient operation of the equipment. Its functions include inducing fluidization as opposed to spouting and to maintain the bed in constant motion above all gas entry points during the entire operation, consequently achieving the required gas-solid contact. Among the important elements considered in the design of a distributor plate is the pressure drop across it. It is generally suggested that even gas distribution through the distributor can be ensured by using a relatively high pressure drop distributor.

Studies with a perforated distributor plate have shown that the most critical factor governing the distributor pressure drop is the open area ratio, and that the presence of fluidizing particles in the bed slightly increases the distributor pressure drop at low gas flow rates but has little effect on the pressure drop at higher gas flow rates[1].

A number of correlations have been reported by Vanecek[2] for determining the heat transfer coefficient in fluidized beds of both fine and coarse particles. Of all these, none considered the effect of distributor plate parameters on heat transfer. McGaw[3] later developed a correlation which took into account the effects of the distributor plate parameters. This shows that the effects of the distributor plate on heat transfer have been neglected in most works.

The objectives of this work therefore is:

1. To study the effect of the distributor plate parameters (i.e orifice diameter and open area ratio) on the fluidization quality of coarse, uniform size particles and to see how these parameters influence the gas to particle heat transfer and hence drying rate.

2. To develop a correlation for gas to particle heat transfer coefficient in fluidized beds of coarse particles, taking into consideration the distributor plate parameters.

EXPERIMENTAL DETAILS

Equipment

The equipment consisted of three basic zones, namely: an air heating zone, air motioning zone and the drying column as shown in figure 1. In the air heating zone, the air is heated from room temperature to the required process temperature by heaters H1 and H2.

The air motioning zone consists of a centrifugal fan (B) which can be set to deliver the required air flowrate, the fan also ensures enough static heat to fluidize the material in the column.

The drying column is cylindrically shaped, 15 cm in diameter and is made of plexiglass with the bottom closed by a distributor plate. It has a discharge port on its side for discharging the material out of the bed or for taking samples for moisture content determination. Towards the top of the column there is a baffle which can be closed to create a back pressure in the column to assist in discharging the material.

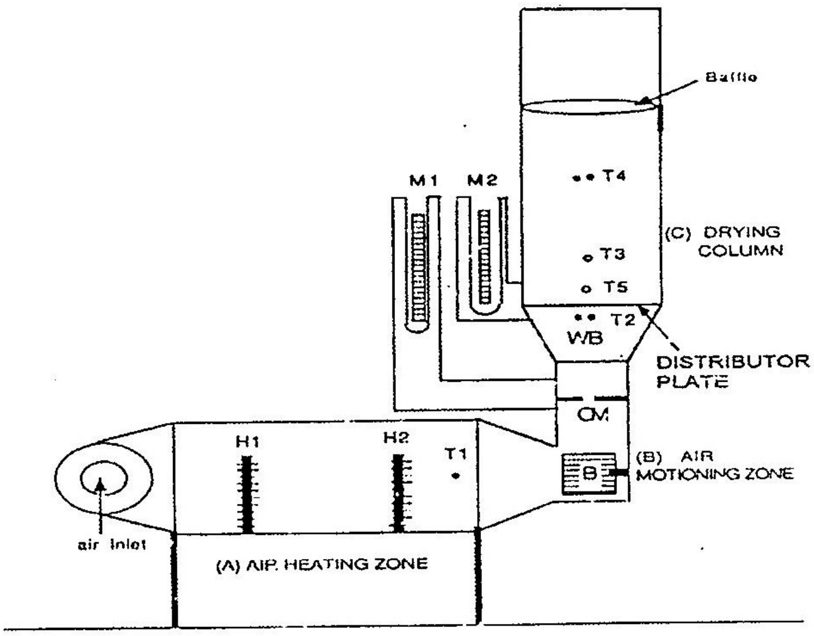

Fig. 1 Schematic diagram of the equipment used

Measurements

The inlet air temperature and relative humidity were measured using a hygrometer at the inlet to the air conditioning zone. The temperature in the air conditioning zone was monitored with thermocouple T1. In the windbox, WB, the wet and dry bulb temperatures were recorded to know the inlet condition of the gas entering the bed. The bed temperature was monitored by T3 and the outlet wet and dry bulb temperatures were measured at T4. T5 consisted of two thermocouples with shielded probes so that they essentially measured the gas temperature in the bed. The two thermocouples were placed in such a way that their probes were at different heights from the distributor. These thermocouples were used to determine if equilibrium had been attained in the bed, especially during the determination of heat transfer coefficients. The relative humidity for inlet and outlet conditions of the gas was obtained from a psychrometric chart using the wet and dry bulb temperatures.

The gas flow rate was measured using an orifice meter, OM, positioned between the air motioning zone and the drying column. Enough pipe length was provided before the orifice so as to give a fully developed flow before measurements are taken. Readings were obtained from a U-tube manometer, M1, these were then translated to velocities using a calibration curve. The pressure drop across the distributor and the bed was measured using a U-tube manometer, M2.

Fabrication of distributor plates

Distributor plates with different orifice diameters, open area ratio and pitch were designed and fabricated. The distributors were flat perforated plates with orifices arranged on a square pattern. Due to difficulty of drilling small holes on a metal plate, the distributors with small orifices (1 and 2mm) were made of plexiglass sheets, whereas those with orifices larger than 2mm were made of aluminium sheets. A total of seven distributor plates were used, with open area ratio ranging from 4.8% to 10.6% and orifice diameter from 1mm to 6mm. Table 1 gives description of distributor plates used.

Table 1 Description of distributor plates used

Distributor	Open area ratio (%)	Orifice diameter (mm)	Pitch (mm)	No of holes
D1	6.8	1.0	2.3	1,530
D2	6.8	2.0	5.8	384
D3	4.8	2.0	7.8	272
D4	10.6	2.0	5.2	598
D5	7.4	3.0	9.4	184
D6	8.4	3.0	8.9	205
D7	10.4	6.0	17.2	61

Wheat Conditioning

The material used in this study was wheat which was obtained dry. The average particle size was 4.5mm diameter and sphericity was 0.91. In order to simulate conditions of newly harvested wheat, water was added to the material to raise its moisture content. The dry wheat had a moisture content of 12-15% on a dry basis and this was raised to 27-35% on dry basis. The procedure used was that developed by Becker[4].

Four conditioning jars, of 2 litre capacity each, were charged with a measured amount of wheat, the wheat was assumed to have a moisture content of 15% d.b. The calculated amount of water was added to raise the moisture content to 30% d.b. The jars were then placed on a drum roller and wheat was mixed for a period of 10 minutes. The wheat was then stored for 48 hours at room temperature with repeated mixing at periodic intervals.

Moisture Content determination

The moisture content was determined by a standard method developed by the American Society of Agricultural Engineers, ASAE, no S352.1.

Drying runs procedure

After the conditioning period, samples were taken from the conditioning jar for determination of initial moisture content. In order to bring the bed to a steady state working condition, hot air was blown through the bed for about one hour before it was charged with the material. In the meantime, the material to be dried was weighed and recorded and the pressure drop across the distributor for the empty column and the corresponding gas velocity were recorded. After the bed had reached the required temperature, the air supply was interrupted and the material charged into the bed as quickly as possible. The bed height was read from the scale on the column and recorded. The air supply was then reinstated and the new pressure drop across the distributor and the bed and the corresponding gas velocity were recorded. Temperature readings were taken after a selected fixed time interval and material samples were withdrawn from the bed at varying intervals for moisture content determination.

A total of 15 runs in set A were made , set B was for determination of the gas to particle heat transfer coefficients. The operating conditions for each set of runs are summarized in Tables 2 and 3.

Table 2: Operating Conditions for drying runs (Set A)

Run	Distributor	U (m/s)	H (cm)	T_{gi}(°C)	W_o (kg/kg)	W_f (kg/kg)	RH (%)
A1	D1	1.40	11.0	59	36.2	16.2	52.8
A2	D2	1.40	10.0	59	30.5	16.0	50.2
A3	D2	1.00	12.0	72	32.7	11.0	43.5
A4	D4	1.00	12.0	76	31.3	12.2	41.4
A5	D4	2.10	7.0	60	28.0	12.9	30.1
A6	D1	1.00	14.0	62	28.2	10.1	37.8
A7	D2	1.00	14.5	64	26.4	15.6	33.2
A8	D7	2.18	5.5	57	27.6	17.8	29.0
A9	D4	2.30	6.5	55	31.2	21.0	27.0
A10	D1	2.10	5.0	59	28.8	15.8	10.0
A11	D1	1.40	5.0	62	26.8	15.2	10.4
A12	D2	2.1	5.0	60	33.9	18.1	10.8
A13	D2	1.4	5.0	62	33.3	18.0	10.1
A14	D4	2.1	5.0	58	29.2	16.4	10.2
A15	D7	2.1	5.0	58	32.4	18.0	10.9

Table 3. Operating conditions for determination of gas to particle heat transfer coefficient (set B)

Run	Distributor	U (m/s)	H (cm)	T_{gi} (°C)	Time (min)	RH (%)
B1	D2	2.00	2.5	55	6.0	23.2
B2	D1	1.82	6.5	56	6.0	22.2
B3	D1	2.08	3.0	55	6.0	21.1
B4	D3	0.81	6.5	56	6.0	21.8
B5	D5	1.68	5.0	59	6.0	20.2
B6	D5	2.00	2.0	61	4.0	20.0
B7	D7	1.58	2.5	59	4.0	19.7
B8	D7	2.21	4.0	60	5.0	20.0
B9	D6	1.10	6.0	60	5.0	19.4

Effect of distributor parameters on drying rate

In order to test the effect of the distributor plate parameters, runs with similar condition but different distributors were compared. The parameter tested were open area ratio and orifice diameter. To test the effect of orifice diameter, distributors with the same open area ratio but different orifice diameters were used. To test the effect of open area ratio, distributors with same orifice diameter but different open area ratio were used. For this purpose therefore, distributors D1, D2, D4 and D7 were used.

Determination of gas to particle heat transfer coefficient

The procedure used was that given by Vanecek[2] and Botterill[5] involving the heating of a fluidized charge whose temperature changes with respect to time. It was assumed that the gas temperature was uniform throughout the bed.

The weighed amount of material was placed in the already preheated bed and the bed height was recorded. The inlet and outlet gas temperature were recorded at time t = 0 and then every minute thereafter up to 5 minutes. The corresponding pressure drop and gas velocities were also recorded.

This was repeated using different distributor plates and different amounts of material in the bed. Heat transfer coefficients were calculated from the equation below:

$$\ln\frac{(T_{gi}-T_{go})_t}{(T_{gi}-T_{go})_{t=0}}=\frac{h_{gp}aUh\rho_g C_g t}{M_p C_p (h_{gp}ah+U\rho_g C_g)} \tag{1}$$

Wen[6] showed that the particle surface area per unit volume of bed is obtained by:

$$a=6\frac{(1-\varepsilon)}{d_p} \tag{2}$$

RESULTS

To facilitate comparison of the drying runs undertaken with different initial moisture contents, the normalized moisture content was used. The normalized moisture content is the ratio of moisture remaining in the material to the initial moisture content:

Normalized moisture content = W/Wo (3)

Effect of Distributor Parameters on Drying Rate

To test the effect of orifice diameter, distributor plates with the same open area ratio (ϕ = 6.8%) were used. Runs with similar conditions (A1 and

A2) were compared, the orifice diameters were 1mm and 2mm. Figure 2 shows the comparison of the drying curves for the two runs. The distributor with orifice diameter of 1mm was found to be better than the one with orifice diameter of 2mm, thus suggesting that the finer the distributor, the better will be the performance of the bed and hence the higher will be the drying rates. Figure 3 shows the comparison of the drying curves for runs of same orifice diameter but different open area ratio. The comparison of their mean normalized moisture content shows that the distributor with open area ratio of 10.6% is better than that with an open area ratio of 6.8%.

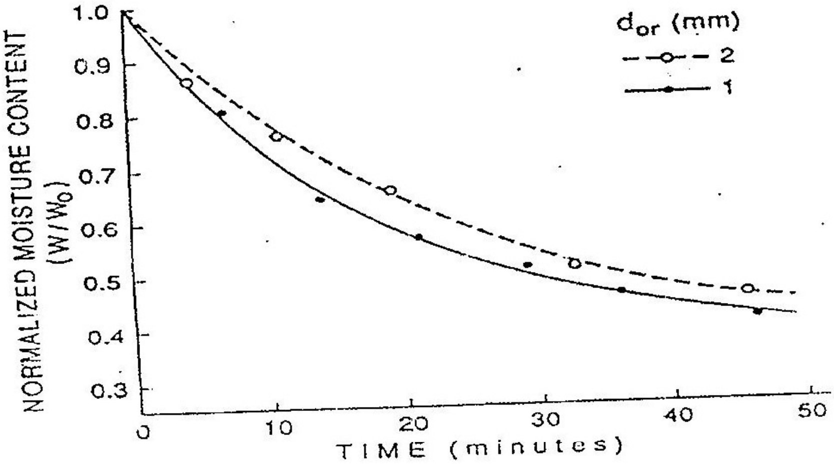

Fig 2 Effect of orifice diameter on drying rate (runs A1 and A2)

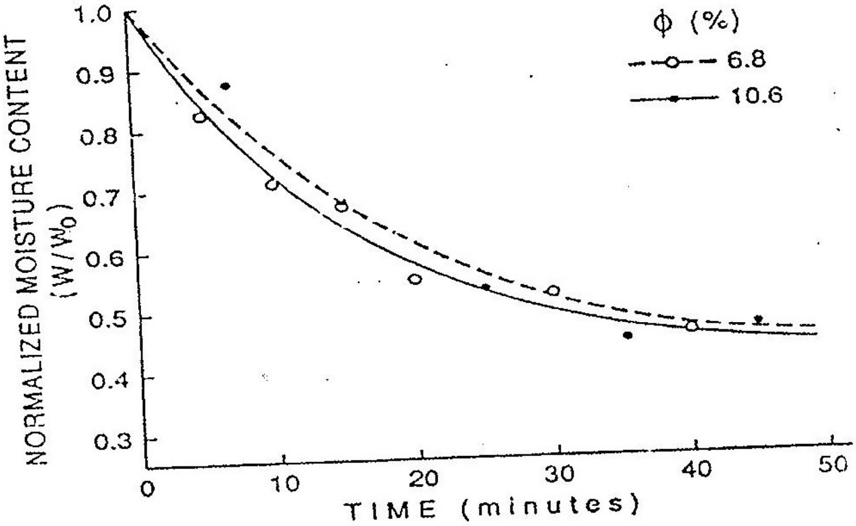

Fig.3 Effect of open area ratio on drying rate (runs A3 and A4)

Development of the heat transfer correlation

The gas to particle heat transfer coefficient was determined and results are given in Table 4.

Table 4 Gas to particle heat transfer coefficients

Run	Distributor	U (m/s)	Re	h_{gp}(W/m^{2}°C)	Nu
B1	D2	2.00	453.1	14.35	2.05
B2	D1	1.82	431.7	6.92	0.99
B3	D1	2.08	487.2	8.92	1.28
B4	D3	0.81	198.1	0.72	0.10
B5	D5	1.68	368.3	3.98	0.57
B6	D5	2.00	436.7	12.26	1.75
B7	D7	1.58	357.9	06.91	0.99
B8	D7	2.21	500.6	23.32	3.34
B9	D6	1.10	260.9	02.65	0.38

The experimental data for heat transfer were correlated in terms of Nusselt number as function of dimensionless quantities in which variables affecting the gas to particle heat transfer coefficient are grouped. The dimensionless variables included in this study are:

- Reynolds number (based on particle diameter) Re = $\rho_g U d_p / \mu_g$
- Ratio of particle diameter to bed height = d_p/H_n
- Ratio of Particle diameter to orifice diameter = d_p/d_{or}
- Open area ratio, ϕ
- Ratio of Column diameter to orifice diameter = D_c/d_{or}
- Ratio of particle diameter to pitch = d_p/P
- Ratio of superficial gas velocity to minimum fluidization velocity = U/U_{mf}
- Nusselt number, Nu = $h_{gp} d_p / \lambda_g$

Nusselt number was then presented as a function of the dimensionless quantities:

$$Nu = \{\mathrm{Re}, (\frac{d_p}{H_n}), (\frac{d_p}{d_{or}}), \phi, (\frac{D_c}{d_{or}}), (\frac{d_p}{p}), (\frac{U}{U_{mf}})\} \qquad (4)$$

The correlation was developed using the statistical package SAS on the VAX780 main frame computer. The analysis showed that the last two parameters in equation 4 were insignificant and the parameter D_c/d_{or} was included in the open area ratio. The lumped parameter $(d_p/d_{or})\,\phi$ was then developed to account for the effect of the interaction between particles and distributor properties.

Based on the extensive number of experiments, the following correlation was obtained:
For 150 < Re < 600

$$Nu = \exp(-20.1)\mathrm{Re}^{3.3}\left(\frac{d_p}{H_n}\right)^{0.2}\left(\frac{d_p}{d_{or}}\phi\right)^{-0.4} \qquad (5)$$

However, due to the high exponent and very small coefficient on the Reynolds number, it was deemed necessary to break the correlation into two parts. To establish the breaking point, a plot of the observed Nusselt number Vs Reynolds number was made (Fig. 4). The figure suggests almost an exponential relationship (solid line). Fitting straight lines on the two parts of the curve, the intersection came very close to Re = 430 (dashed lines). This was then taken as a partitioning point. Thus, two correlations were developed in the range of Reynolds number = 150 to 430 and 430 to 600.

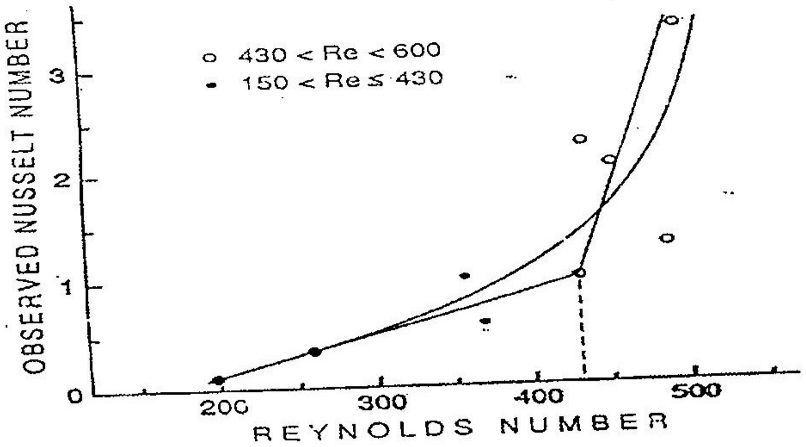

Fig. 4 **Dependence of Nusselt number on Reynolds number and the partitioning point**

For 150 < Re ≤ 430

$$Nu = (5.5)10^{-5}\,\mathrm{Re}^{2.2}\left(\frac{d_p}{H_n}\right)\left(\frac{d_p}{d_{or}}\phi\right)^{0.5} \qquad (6)$$

For 430 < Re < 600

$$Nu = (4.2)10^{-5}\,\mathrm{Re}^{1.5}\left(\frac{d_p}{H_n}\right)^{0.1}\left(\frac{d_p}{d_{or}}\phi\right)^{-0.7} \qquad (7)$$

Fig. 5 shows the plot of observed Vs predicted Nusselt numbers for full range correlation and figure 6 shows the same relationship for the partitioned correlations. Comparison of the two shows that the partitioned correlation gave a better fit than the full range correlation.

The group $(d_p/d_{or})\,\phi$, in equation 6 suggests that if other dimensionless groups are held constant, then for a given open area ratio, a decrease in orifice diameter leads to an increase in the Nusselt number and hence an increase in gas to particle heat transfer coefficient. This is the same as shown in Fig. 2. Also Fig. 7 shows the same trend for runs made at Re = 230.

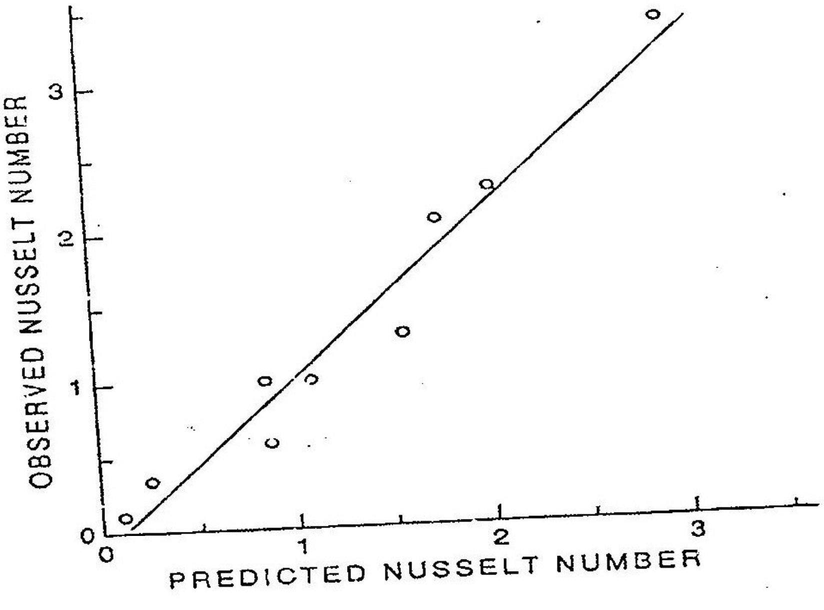

Fig. 5 Observed vs predicted Nusselt number for full range correlation

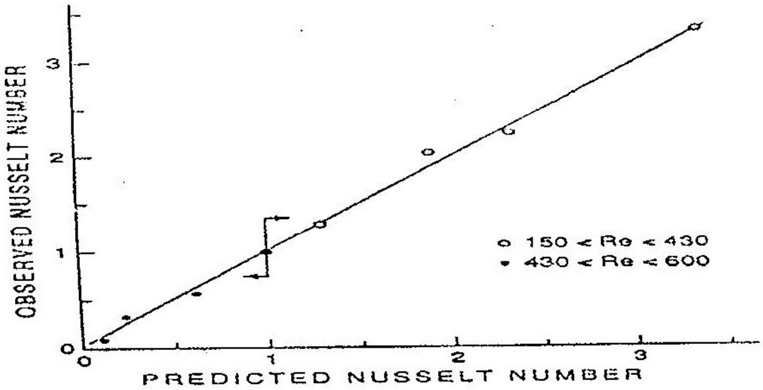

Fig. 6 **Observed vs predicted Nusselt number for partitioned correlation**

Equation 7 suggests that for a given open area ratio and if other groups are held constant, an increase in orifice diameter leads to an increase in Nusselt number and hence the gas to particle heat transfer coefficient. This is opposite to equation 6 but comparison of drying curves A8 and A9 developed at Re > 430 agrees with equation 7. (Fig. 8).

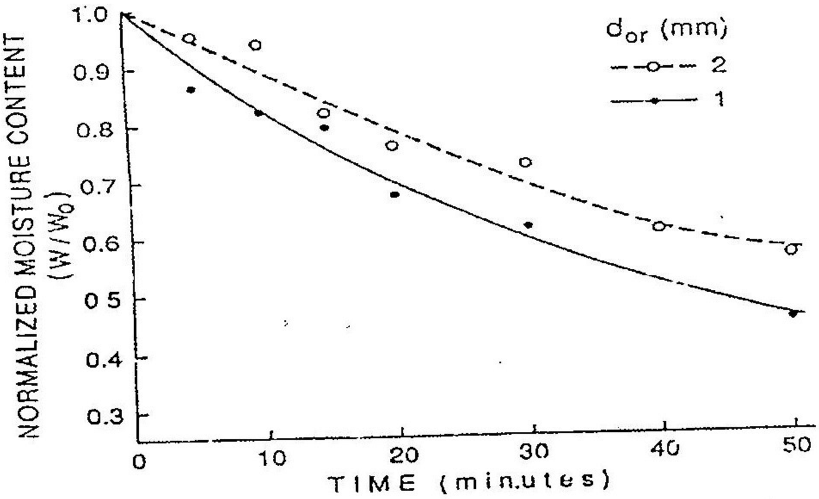

Fig. 7 **Effect of orifice diameter on drying rate at low Reynolds number (runs A6 and A7)**

Figs. 9 and 10 shows the effect of orifice diameter in case of high Reynolds number, the trend is opposite to what was observed in Fig. 2. Figure 11 shows the effect of open area ratio. This also is opposite to what was observed in Fig. 3.

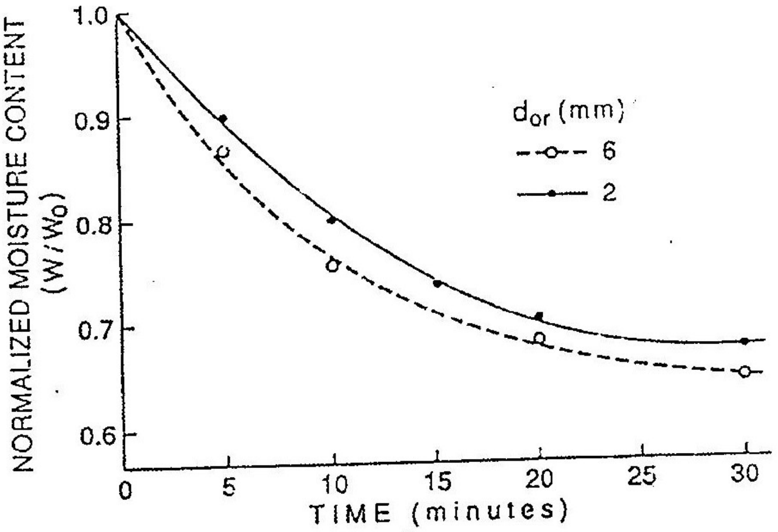

Fig. 8 Effect of orifice diameter on drying rate at high Reynolds number (runs A8 and A9)

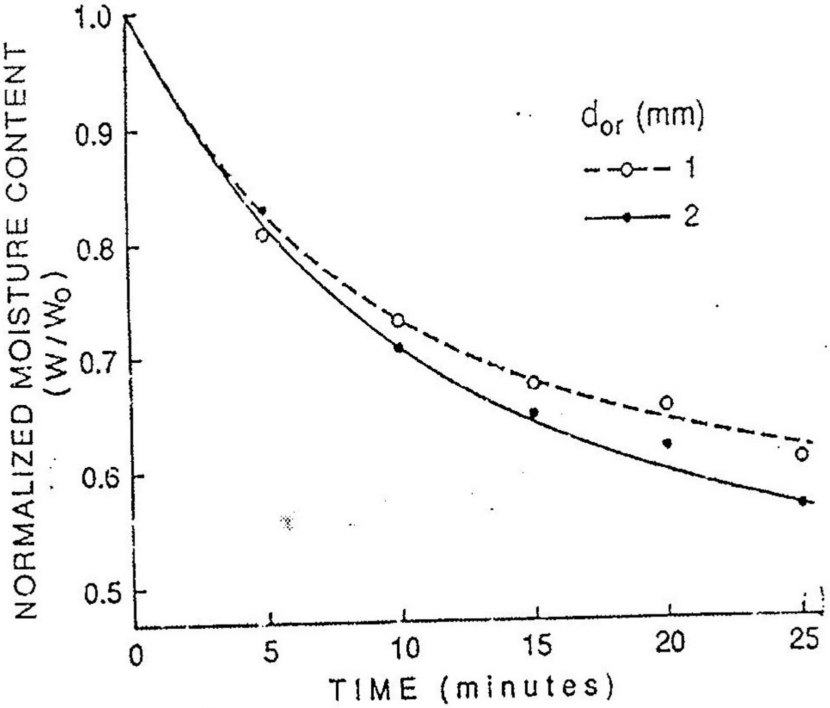

Fig.9 Effect of orifice diameter on drying rate at high Reynolds number (runs A10 and A11)

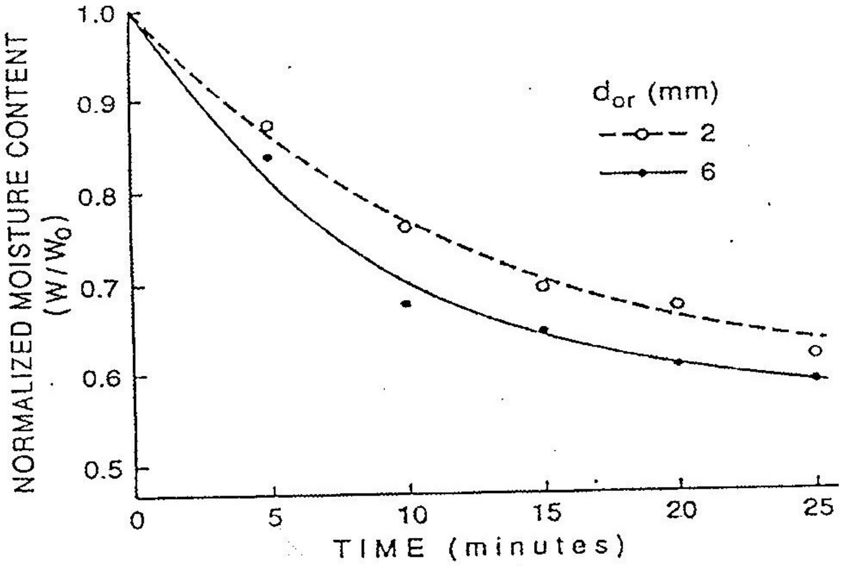

Fig. 10 Effect of orifice diameter on drying rate at high Reynolds number and large open area ratio (runs A14 and A15)

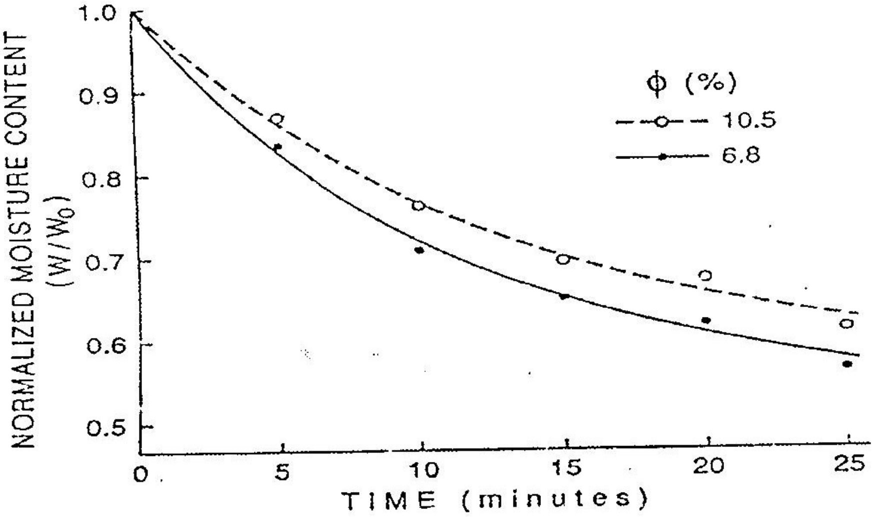

Fig. 11 Effect of oriice diameter on drying rate at high Reynolds number (runs A12 and A14)

DISCUSSION

From above, it is clear that the effect of distributor parameters have been observed to change with Reynolds number. In the low Reynolds number region, the finer distributor gave higher drying rates than the coarse one.

This agrees with the suggestion of Clift[7] that fluidization quality increases with decrease in orifice size. However, it was found that in the high Reynolds number region, the opposite was the case, i.e the larger the orifice size, the higher were the drying rates. This agrees with McGaw's observation[3] that the heat transfer coefficient increases by increasing the hole diameter or decreasing the hole pitch. It therefore shows that the effect of orifice diameter changes with a change in Reynolds number.

The open area ratio also exhibits a changing behaviour with a change in Reynolds number. The open area ratio governs the plate pressure drop, and a change in the superficial gas velocity affects both the distributor plate pressure drop and the Reynolds number. A high distributor pressure drop has been observed to give more stable fluidization, this suggests that the distributor pressure drop influences the nature of gas discharge into the bed.

Massimilla[8] has reported that the mode of gas discharge into a bed of coarse particles is predominantly of jet type as opposed to a chain of bubbles which is the characteristic of fine particles. However, the formation of jets depends on a number of factors including the particle diameter, orifice diameter, bed height and gas velocity at the orifice. Massimilla[8] also reported a correlation developed to relate the ratio of penetration length to orifice diameter as a function of pressure and inlet gas velocity for a given orifice size and gas and bed solids properties.

The correlation is:

$$\frac{L}{d_{or}} + \frac{1}{2}\cot an\theta = 13\left(\frac{\rho_g U_{or}}{\rho_g \sqrt{g d_p}}\right) \tag{8}$$

The above equation suggests that for a low gas velocity at the orifice and very small orifice diameter, the penetration length can be very small, almost negligible since at low gas velocities, the jet half angle θ is small and therefore the value of cotan θ is large. This means that no jets are being formed in the bed. Patrose and Caram[9] reported that for the same bed material, the jet half angle increases with an increase in orifice inlet gas velocity. Thus, for a given gas velocity at the orifice and particle diameter, the jet half angle will be constant. Therefore, increasing the orifice diameter will increase the penetration length and hence increase the possibility of jet formation. In the case where the jet penetration length is negligible, the gas discharge mode into the bed should be that of a chain of bubbles and no jets.

This can be explained by the fact that in the case of a fine distributor, the holes are small and very close to each other and one large particle lying on the distributor can cover two or more orifices. When gas discharges from these orifices, it cannot form a jet through a particle. Instead the gas will be diverted horizontally and may break up into a chain of bubbles (see Fig.12). The only sure way of having jets in the bed is to use a distributor with an orifice diameter greater than the particle diameter (see Fig. 13).

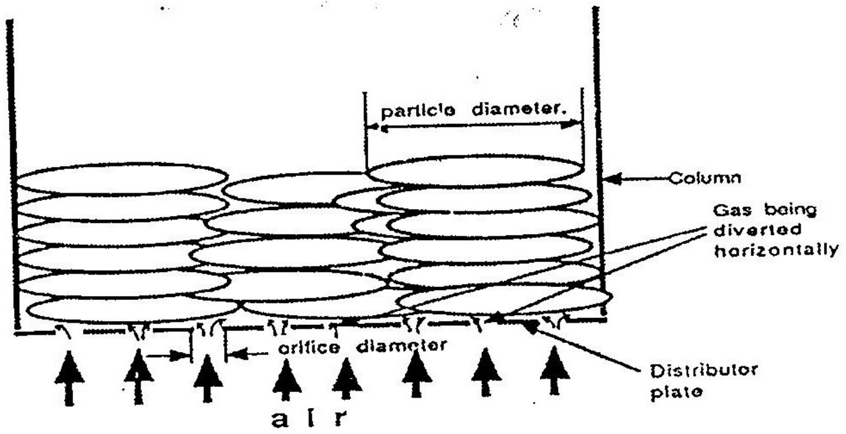

Fig. 12 Bed with particle size greater than orifice diameter

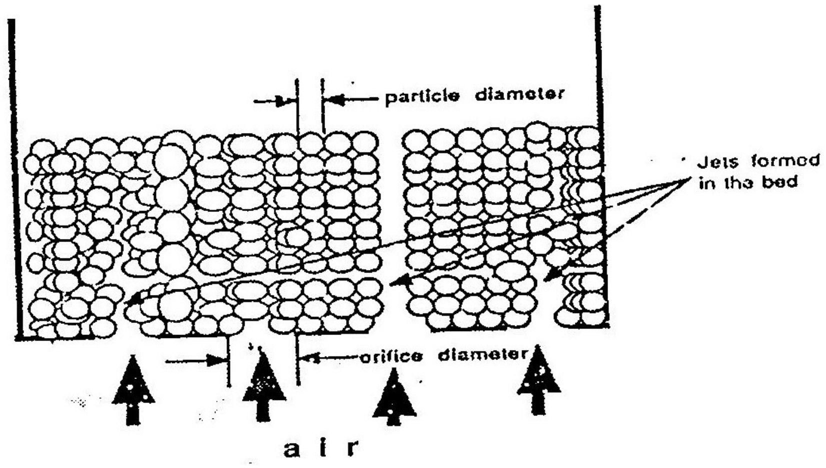

Fig. 13 Bed with particle size smaller than orifice diameter

Since most of the work reported by Massimilla[8] used orifice diameter greater than 10 times the particle diameter, his generalization that an increase in particle diameter changes the gas discharge mode from a chain of bubbles to jets should be supplemented by some information on the orifice diameter involved.

Massimilla[8] also reported on a number of transport models, one of which is called "the solid-free tubular jet model" and it relates the temperatures, jet to bed heat transfer coefficient, orifice gas velocity and orifice diameter by the equation:

$$\ln\left(\frac{T - T_B}{T_{gi} - T_B}\right) = \frac{-4h_{jb}(h - h_o)}{\rho_g U_{or} d_{or} C_p} \tag{9}$$

Since $T_g < T_{gi}$ the left hand side of the above equation is negative. So for given values of T_g, T_B and T_{gi}, the jet to bed heat transfer coefficient is directly proportional to the orifice gas velocity and orifice diameter. This explains why the drying rate is higher with larger orifice diameter in the high Reynolds number region as suggested by equation 7.

As for McGaw's work[3], the bed heights used were relatively short and reducing the bed height to orifice diameter ratio improves the steadiness of jets formed[8]. This shows that the gas discharge mode in McGaw's work was predominantly jets; this is why the heat transfer coefficient was favoured by the increase in orifice diameter, as he concluded.

The values of gas to particle heat transfer coefficient obtained from this work varied from 0.72 to 25.16 W/m^2K and the corresponding Nusselt number varied from 0.10 to 3.6. When compared to other workers as given by Zabrodsky[10], results of this work fall between that of Federov, who worked with coal and cardboard particles of diameter 5 to 10mm and those of Kettering who worked with Silica gel, diameter 0.4 to 1mm. This agrees with the trend that the heat transfer coefficient increases with an increase in particle diameter.

A comparison of the present correlation to that of McGaw[3] shows little similarity apart from the fact that both correlations demonstrate that distributor plate parameters have a significant effect on the heat transfer coefficient. The discrepancy is due to the differences in the process and material used. In McGaw's work the particles were being cooled from 130 °C to room temperature. The particles were already dry and there was no disturbance of the heat transfer layer by moisture vapour as is the case with wet particles. Also, the design method for distributor plates used in McGaw's work did not consider the hole pitch to be a function of the orifice diameter. Otherwise the last two term in his correlation would be a linear combination of each other and the statistical model would lose one degree of freedom. Furthermore, the open area ratio, which influences the distributor pressure drop and hence the stability of fluidization, was not included in his correlation.

CONCLUSIONS

From this study, the following the can be concluded:

i The distributor plate parameters have a significant effect on the gas to particle heat transfer coefficient in fluidized beds of coarse particles; thus the drying rates are also significantly influenced by these parameters. These effects, however, depend on the Reynolds number. At low Reynolds number, a decrease in orifice diameter favours an increase in heat transfer, whereas at high Reynolds number the opposite is the case.

ii The change in the effect of distributor parameters with Reynolds number suggests that there is a change in the mode of gas discharge into the bed from a chain of bubbles at low gas velocities to jet at higher velocities. Since the jet to bed heat transfer is enhanced by an increase in gas velocity and orifice diameter, the jet discharge mode is predominant in the case of high Reynolds number.

iii The distributor pressure drop alone has been found not to contribute significantly towards higher drying rates, although it is theoretically known that a high pressure drop distributor gives more stable fluidization. This suggests that the distributor parameters, in collaboration with the distributor pressure drop, together contribute towards better performance of the bed.

iv The values of gas to particle heat transfer coefficient obtained in this work were in the range of 0.8 - 25.2 W/m^2 °C and the corresponding Nusselt number varied from 0.1 - 3.6. These values are relatively higher than those reported for spouted beds [11], which were in the range of 3.4 - 17.0 W/m^2 °C.

v When compared to other researchers, results of this work on the gas to particle heat transfer coefficient fall between those of Federov, who worked with coal and cardboard particles of diameter 5 - 10mm and those of Kettering, who worked with Silica gel of diameter 0.4 - 1mm. This agrees with the trend that the heat transfer coefficient increases with an increase in particle diameter.

vi With respect to the gas to particle heat transfer correlation, this work shows that the effect of the distributor plate parameters on heat transfer is very significant. There is, however, a limited agreement between the correlations developed in this work and that of McGaw[3]. The difference is due to the fact that different materials were used in different processes (i.e cooling Vs drying).

vii Finally we can say that coarse particles can be dried in fluidized bed driers provided a suitable distributor is used and the bed height is limited to avoid slugging.

NOMENCLATURE

a = particle surface area per unit volume of bed, m^2/m^3
C_p = Specific heat of particle, J/kg°C
C_g = Specific heat of gas, J/kg°C
C_g = Specific heat of gas, J/kg°C
d_p = particle diameter,mm
h_{jb} = Jet to bed heat transfer coefficient, W/m°C
h = Distance above the distributor, m
h_o = Model parameter
h_{gp} = gas to particle heat transfer coefficient, W/m^2°C
L = Penetration length, m
M_p = amount of material in drier per unit area of grid. kg/m^3
Nu = Nulsset number
Re = Reynolds number
T_B = Bed temperature, °C
T_{gi} = Inlet temperature, °C
T_{go} = Outlet gas temperature, °C
U = Superficial gas velocity, m/s
U_{or} = Gas velocity at the orifice, m/s

ρ_g = Density of gas, kg/m^3
θ = Jet half angle, rad.
ε = bed voidage
μ = dynamic viscosity

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The manuscript was received on 9th January 1994 and accepted for publication on 5th May 1995.