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## **Air Flow Resistance through a Packed Bed of Selected Grains**

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Static pressure of rough rice, wheat, corn, milled rice and soybean were investigated at different moisture contents and airflow rates. The pressure gradient along the depth of the packed bed was found to vary linearly. The static pressure was also found to depend on the airflow rate and moisture content of the materials, increasing with increase in any of the parameters. The static pressure was observed to satisfy the Ramsin equation. However, the constant,  $\alpha$  was observed to be dependent on the moisture content of the material, hence the moisture content was added to this equation. Taking into account of the moisture content of the material enabled the variation of the static pressure between the materials to be explained to a reasonable accuracy.

### INTRODUCTION

The air flow resistance in grain packed bed is an important parameter in determining the static pressure requirements of a fan for drying, cooling and ventilation such as in insecticide application. The air flow rate through the packed bed will determine the rate of drying or cooling. The higher the flow rate the faster the operations can be carried. In some operations, such as ventilation of vegetables and fruits in a cold storage facility for the reduction of heat pockets, low flow rates will be desirable in order to reduce moisture losses from the products. Low air flow rates are also used in grain ventilation for the removal of odors, reduction of respiration rates, inhibition of molds and for controlling moisture migration.

Air flow rate that can be attained by any given fan capacity will depend on the depth of the bed through which the air has to be forced through. The deeper the bed the lower the flow rate will be attained. The depth of the bed will have an important bearing on the operation and will in some cases affect the end product's quality. For example too deep beds during drying will give rise to dry and wet zones, which if maintained for a long time will lead to spoilage of the products. To avoid this spoilage, the depth of the bed and the corresponding air flow rate should be established. On the other hand, the depth of the bed and the air flow rate will be very important for the design and cost evaluation of the equipment to be used in the supply of air to the bed. Cost of the equipment will mainly be based on the size of the fan to be used and this can be accurately be estimated if the static pressure drop

through the bed at different moisture contents has been determined.

Pressure drop through grains has been investigated by many researchers such as Husain and Ojha (1969), Farmer *et al.* (1981) and Patterson *et al.* (1971). The results reported by these researchers have shown that the resistance of airflow varies not only from material to material, but also with the variety of the material. Moreover, disagreeing results on the effect of moisture content on the flow resistance have been reported. The study was therefore carried in order to obtain comprehensive data that will be used synonymously with the previous data for the design and construction of a grain storage facility as stated earlier, Chuma *et al.* (1981).

### LITERATURE REVIEW

The resistance to air flow through rough rice has been investigated by Husain and Ojha (1969). The researchers reported a parabolic relationship between air flow and static pressure of the grain bed and reported a linear relationship when the two parameters were plotted on a log-log paper. The relationship between these parameters were represented by the equation,

$$Ps = KQ^n,$$

where,

$Ps$  : static pressure,  
 $Q$  : air flow rate,  
 $n$  : constant.

The constant,  $n$  was reported to decrease with increase in depth of the bed. The researchers further reported a linear relation between the static pressure and the distance from the top of the bed.

Farmer *et al.* (1981) stated that for an initially packed bed if undisturbed during drying, because of reduction of particle size, it can become less resistant to air flow at low moisture contents. The researchers reported a decrease in static pressure as the moisture content of bluestem grass seeds increased from 17.5 % to 42.6% and an increase in the static pressure as the moisture content increased from 47.8 % to 78.6 %. However, the effect of moisture content was not observed in freshly harvested seeds which although a difference of moisture content up to 30 % was investigated, there was almost no difference in the air flow resistance at different moisture contents. The authors further more represented their data as in the above given equation and reported that the constant,  $K$  was mainly affected by moisture content while the constant,  $n$  was affected by the bulk density of the seeds. Air flow resistance was reported to be inversely affected by bulk density of the seeds by the same authors.

Patterson *et al.* (1971) observed an increase in the static pressure of a packed bed of corn when the moisture content was increased from 16 % to 19 %, but the static pressure was not greatly affected by the moisture content between 19 % and 24 % moisture contents. For navy beans, the researchers

reported a decrease in the static pressure as the moisture content increased. Due to the slower moisture transfer process, moisture content changes during data reading was reported to be negligible.

Bakker-Arkema *et al.* (1969) found out that the static pressure and hence the air flow rate is not affected by the temperature and humidity of the flowing air.

Akritidis and Siatras (1979) reported the air flow resistance on pumpkin seeds not to be significantly affected by moisture content at low flows. However, at flow rates greater than  $10 \text{ m}^3/\text{min}/\text{m}^2$  the resistance decreased with decrease in moisture content to a minimum and then increased.

### MATERIALS AND METHOD

The experimental apparatus is shown in Fig. 1. A plastic pipe of internal diameter of 204mm and 1,780 mm in height was used as the packed bed chamber. At intervals of 320 mm, four small holes of 1 mm in diameter at equal intervals around the perimeter of the chamber were bored for static pressure transmittance. Stainless steel syringes, 1 mm thick cut to a length of the thickness of the chamber wall were inserted into the holes. The syringes were connected to water manometers through which the static pressure could be measured to an accuracy of 0.1 mm. The static pressure holes at the same height were connected to one manometer tube on which the average static pressure could be read directly. The static pressure at six different heights could therefore be read on the manometer at the same time. Air flow to the packed bed chamber was delivered from a turbo fan, SANCO L1192, through plastic pipes of internal diameter of 76mm. The fan had an air flow delivery capacity of  $8 \text{ m}^3/\text{min}$  and had a static pressure head of 700 mm of water and 3,600 rpm. The air flow rate was varied by adjusting a butterfly valve placed immediately before the fan. An orifice meter was used to measure the air flow through a pressure differential transmitter, MODEL 6501-1010 which was manu-

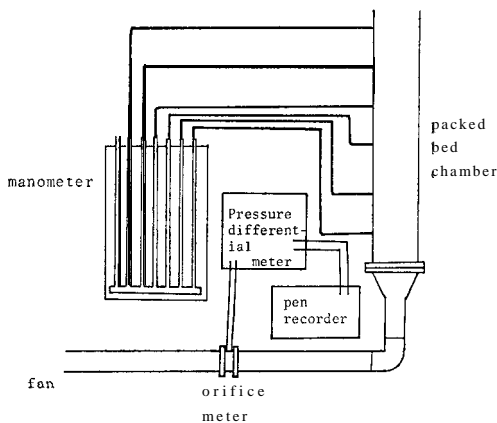


Fig. 1. Schematic diagram of experimental apparatus.

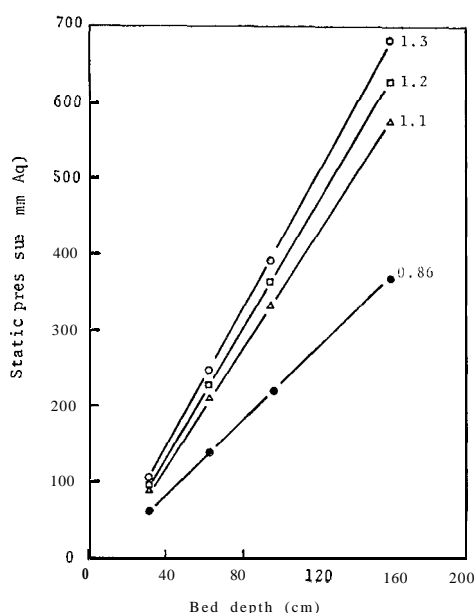
factured by Yokogawa Electrical Works. The air flow was then recorded on a pen recorder.

The materials were loosely packed into the chamber by pouring them slowly in to the chamber. The pressure readings were not taken until the fan attained an optimum speed. For each test run, the air flow was varied to six levels and at each air flow rate, the static pressure was recorded. The weight of the material as well as the depth of the bed were taken before and after the pressure readings were taken. The temperature and relative humidity of the air was also measured.

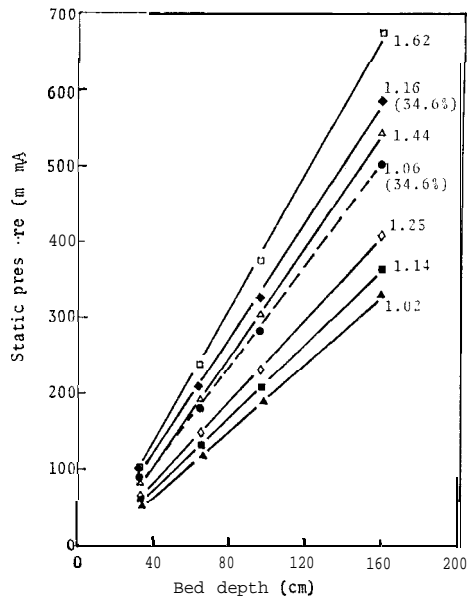
The method used for attaining the different moisture contents of the materials as well as the properties and history of the materials has been explained elsewhere, Chuma *et al.* (1981).

## RESULTS AND DISCUSSION

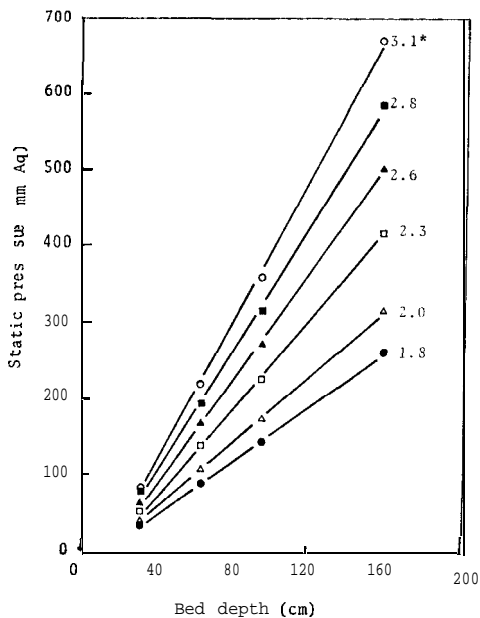
The relationship between the static pressure and depth of the bed is shown from Figs. 2 to 6 for rough rice, wheat, corn, soybean and milled rice, respectively, at different air flow rates. In all the materials as the air flow rate increases the static pressure also increases. Except for soybeans at a high moisture content of 53.1%, the static pressure was found to increase linearly with increase in depth of the bed. These results are in agreement to those reported by Husain and Ojha (1969) on rough rice. The parabolic



**Fig. 2.** Variation of pressure drop with bed depth and air velocity ( $\text{m}^3/\text{m}^2/\text{sec}$ ) at 16.6% moisture content.



**Fig. 3.** Variation of pressure drop with depth of bed and air velocity for wheat at 13.7% moisture content (w.b.).



**Fig. 4.** Variation of pressure drop with bed depth and air velocity for corn at 12.9% moisture content (w.b.). \*: Velocity in  $\text{m}^3/\text{m}^2/\text{sec}$ .

increase in the static pressure with increase in depth of the bed in soybeans at high moisture content is yet to be investigated further.

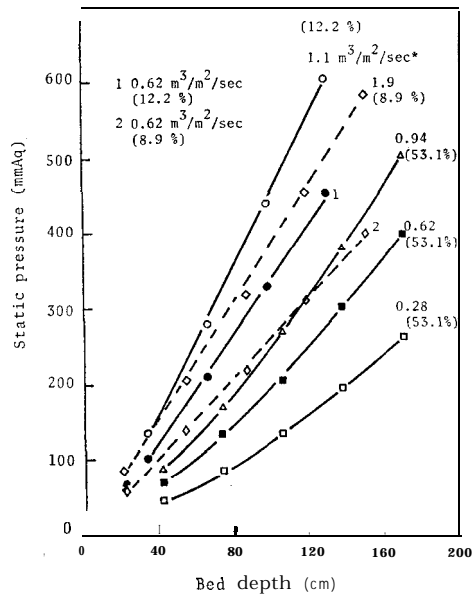


Fig. 5. Variation of pressure drop with depth of bed for soybeans at different moisture contents and air velocities. \*: All velocities are in these units.

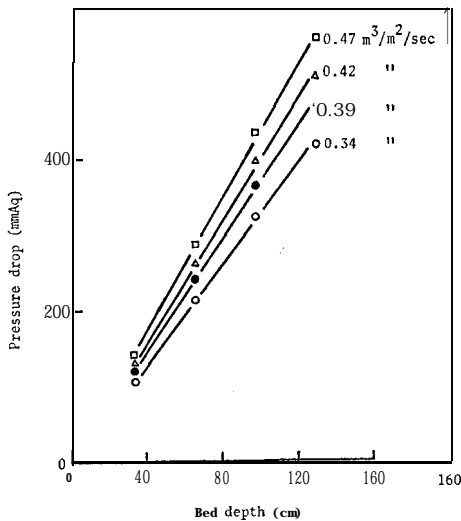
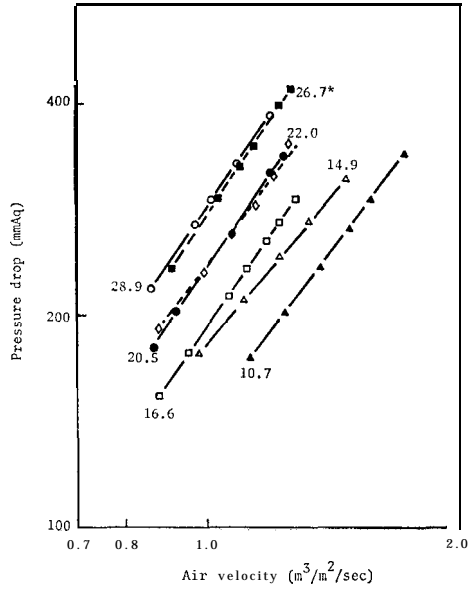
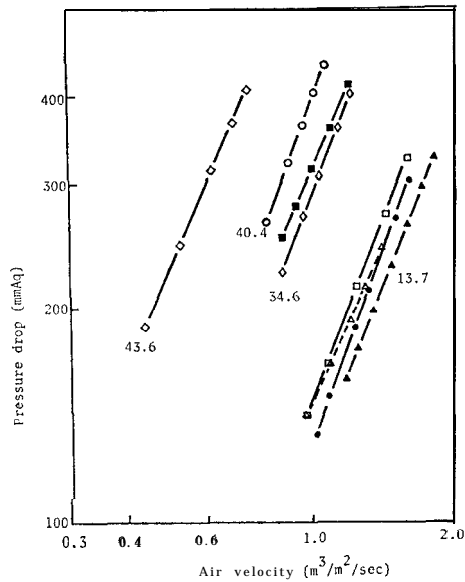


Fig. 6. Variation of pressure drop with bed depth and air velocity for milled rice at 13.0 % Moisture content. (w.b.).

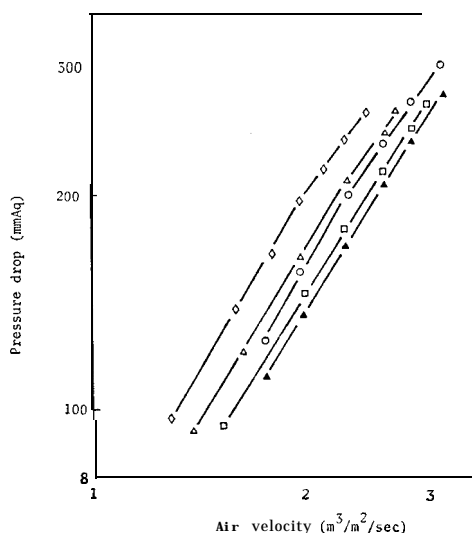


**Fig. 1.** Relationship between pressure drop and air velocity for rough rice at different moisture contents (% w.b.). \*: Moisture contents.



**Fig. 8.** Relationship between pressure drop and air velocity for wheat at various moisture contents. ■, 38.1 % M.C.(w.b.); □, 23.8 % M.C.(w.b.); △, 20.6 % M.C.(w.b.); ●, 17.3 % M.C.(w.b.).





**Fig. 9.** Relationship between static pressure drop and superficial air velocity for corn at different moisture contents.  $\diamond$ , 33.3 % M.C.(w.b.);  $\triangle$ , 23.2 % M.C.(w.b.);  $\circ$ , 16.8 % M.C.(w.b.);  $\square$ , 15.3 % M.C.(w.b.);  $\blacktriangle$ , 13.3 % M.C.(w.b.).

Figs. 7 to 9 show a log-log plot of the static pressure against air flow rate at different moisture contents for rough rice, wheat and corn. For all the grains investigated, as the moisture content increases, the static pressure increases also. At low moisture contents, that is at 10.7 % and 14.7 % for wheat, there was no significant difference in the static pressure between these moisture contents. The increase in the static pressure was more noticeable when the moisture content increased from 23.8 % to 38.1 %, compared to a small increase when the moisture content increase from 13.7 % to 23.8 %. A drastic increase in the static pressure was also observed when the moisture content increased from 40.4 % to 43.6 %. These results are in contrast to those reported by Shedd (1953) but in agreement to those reported by Patterson *et al.* (1971).

The pressure-velocity relations for wheat and rough rice were observed to be represented by a straight line at any given moisture content. For corn, except at 13.3 % moisture content, the relation was partitioned into two straight lines, that is between low and high flow rates. This might have indicated a transition between laminar and turbulent flow. This phenomenon has also been reported by Akitidis and Siatras (1979). The failure to observe this phenomenon in the other materials needs further investigation.

The effect of the depth of the bed and air flow rate on the static pressure was determined using Ramsin equation, Bakker-Arkema *et al.* (1969),

$$P = aV^n H^m,$$

**Table 1.** Material constants derived from the equations,  $P = aV^nH^m$  at different moisture contents.

Material	M. C. (% w. b.)	Bed depth (m)	B. D. (kg/m <sup>3</sup> )	<i>a</i>	<i>n</i>	<i>m</i>
Rough rice	28.9	1.62	687.7	282	1.61	1.11
	26.7	1.65	675.2	273	1.62	1.04
	22.0	1.72	648.3	245	1.09	0.96
	20.5	1.59	634.9	200	1.43	1.11
	16.3	1.54	648.3	159	1.61	1.15
	14.9	1.59	608.1	173	1.53	1.09
	10.7	1.56	622.3	128	1.34	1.11
Wheat	40.4	1.70	870.2	247	1.54	1.25
	38.1	1.64	744.1	124	1.69	1.30
	34.6	1.54	770.6	225	1.50	1.07
	23.8	1.60	688.3	204	1.51	1.00
	20.6	1.69	716.6	183	1.54	1.03
	17.3	1.65	674.4	136	1.54	1.10
	13.7	1.64	685.9	142	1.54	1.17
Corn	33.3	1.75	711.4	62	1.69	1.03
	23.2	1.68	683.3	42	1.66	1.09
	16.8	1.65	679.9	31	1.53	1.05
	15.3	1.54	700.1	18	1.59	1.17
	12.9	1.47	706.9	22	1.72	1.29
Soybean	53.1	1.75	644.6	52	1.10	1.07
	12.2	1.72	679.7	27	1.25	1.24
	8.9	1.64	640.9	27	1.15	1.13
Milled rice	13.0	1.73	838.8	522	0.86	1.12

where,

**P**: pressure drop per unit depth (mmAq),

**v**: superficial air velocity (m<sup>3</sup>/m<sup>2</sup>/sec),

**H**: depth of grain (m),

**a, n and m**: constants.

The values for these constants are shown in Table 1, where it can be observed that the constant, **a** increases with increase in moisture content. The value of this constant was found to be larger in milled rice followed by rough rice, wheat, corn and soybeans, in descending order, respectively. As the increase was almost linear, and the apparent density was not kept constant at all moisture contents, a correlation between the constant and these parameters was investigated. A plot of the constant, **a** against bulk density gave almost a linear relation, but with a low correlation coefficient, the highest being 0.685 for rough rice. High correlation coefficients between the constant and moisture content were found, being 0.962, 0.956 and 0.987 for rough rice, wheat and corn, respectively. Addition of the bulk density parameter in the moisture content-constant plots and plotting the constant versus moisture content/bulk density increased the correlation coefficient to 0.978 and 0.994 for rough rice and corn. This increase would indicate that bulk density affected the pressure drop inversely, which is in agreement to Farmer *et al.* (1981)

observations. However, the increase in correlation coefficient could be assumed to be negligible and hence the main factor can be taken to be moisture content. From the results, the effect of moisture content on the constant was highest on rough rice followed by wheat and corn, respectively.

Constants,  $n$  and  $m$  were found to vary slightly with moisture content and that this variation was non uniform. Hence the constants were assumed not to be affected by the moisture content of the materials and therefore average values for each material was calculated. Apart from the failure to observe any variations in the  $m$  constant with moisture content, the constant varied slightly among the materials. This constant was therefore, averaged for all the materials and its value was found to be 1.1. This value could also be approximated to 1.0 depending on the importance of the accuracy in the calculation. For the constant,  $n$  it was assumed not to be affected by moisture content, therefore, average values of 1.46, 1.55 and 1.64 for rough rice, wheat and corn, respectively, were obtained.

From the above observations, Ramsin's equation was therefore, modified and the air flow resistance was represented by the following equations,

$$\begin{aligned} P &= (7.55 MC + 28.48) V^{1.46} H^{1.1} && \text{for rough rice,} \\ P &= (3.45 MC + 74.91) V^{1.55} H^{1.1} && \text{for wheat,} \\ P &= (2.87 MC - 17.26) V^{1.64} H^{1.1} && \text{for corn,} \end{aligned}$$

where,

$P$ : air flow resistance (mmAq/0.64 m),  
 $V$ : superficial air velocity ( $\text{m}^3/\text{m}^2/\text{sec}$ ),  
 $MC$ : moisture content (% w.b.),  
 $H$ : depth of packed bed (m).

From the above equations, it could clearly be observed that the difference in the air flow resistance between the materials could be explained by the role played by the moisture content in the individual materials.

## CONCLUSION

The air flow resistance in a packed bed of grains was found to vary linearly with depth of the bed. However, this might not hold true at very high moisture contents as observed in wheat and soybeans. This phenomenon needs further investigation. Although Ramsin equation can explain the variation of air flow resistance in grain packed beds, its omission of moisture content of the grains reduces the accuracy in determining the actual air flow resistance in the packed beds. Therefore, for accurate air flow resistance estimations, the moisture content of the material should be taken into account. It was observed that moisture content affects the air flow resistance more in rough rice followed by wheat and corn, respectively. For all the investigated materials, the highest air flow resistance was observed in milled rice followed by wheat, rough rice, corn and soybeans, in descending order, respectively.

## ACKNOWLEDGEMENTS

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