An Experimental Correlation for Friction Factor in Horizontal Pipe with Trapezoidal Section Inner Longitudinal Slots for Conveying of Solids

Karparvarfard, Sayed Hossein*+; ***Vakili Farahani, Azam***

Department of Farm Machinery, College of Agriculture, Shiraz University, Shiraz, I.R. IRAN

ABSTRACT: *In order to increase the efficiency of the conveyance of the granular solids, a new experimental set-up is designed. The test rig has longitudinal trapezoidal slots in its conveying pipes. Through experimentation, a correlation for friction factor in terms of solid mass flow rate, fluid flow rate and Froude number is presented. It is shown that the mixture friction factor for pipes with inner trapezoidal slots is 40% smaller than that of pipes with inner rectangular slots. As a result, the arrangement helps to convey materials to longer distances for a given pressure setting.*

KEY WORDS: *Dense Phase, Mixture friction factor, Dimensional analysis, longitudinal slots.*

INTRODUTCION

In the field of materials handling, the method of transporting particulate solids in pipes by means of a flowing gas, generally air, has been known as pneumatic conveying. Cheaper installations, more flexibility and less labor requirement as well as spillage-free, small chance of explosion and contamination-free operations along with the ease of automation are some of the advantages of this system.

Commercial scale application of the idea was started by Duckham in 1893, when he introduced the first floating pneumatic grain elevator for unloading grain ships. Research with particular attention to particulate agricultural materials was carried out by *Segler* over a period of twenty years. The results illuminated some of the aspects of pneumatic conveying but certainly opened a lot more areas to be explored [1]. Pneumatic conveyors, regardless of being pressure or vacuum operated, are generally classified under two major categories. These are dilute phase and dense phase conveyors. In the dense phase flow, particles are in continuous contact, with little mixing and both the solids and fluids are continuous and capable of transmitting force.

Almost all commercial conveyor units used for handling of agricultural materials operate under dilute phase flow conditions with particles having high impact velocities throughout the conveyor. This causes serious problems such as damage to the grains, reduction of storage life and delayed germination as well as the distribution of disease spores into the mass of grains [2].

Happel [3] has been one of the earliest investigators

** To whom correspondence should be addressed.*
+ E-mail: karparvr@shirazu.ac.ir
1021-9986/10/1/85 9/$/2.90

who rigorously studied the vertical down flow of dense beds , but studies of dense phase vertical up flow was initiated by *Berg* [4] , who patented several conveyor components to be used with pipes of varying cross sectional areas. To avoid high pressure losses, noticed in cylindrical tubes, he employed stepped pipes consisting of two or three tube sections having different diameters. To keep the dense phase flow intact, he provided expansion chambers at the outlet of the line to give the required opposition force to the out flowing solids.

Koons & Lauer [5] designed a completely new type of test rig for studying dense phase flow of oil shale having an average particle size of 0.31 mm. They showed that transporting solids as a dense moving mass was suitable for delivery points.

The formulation of horizontal dense phase flow has generally started with fluidized bed flow studies. One of the earliest works in this area has been reported by *Wen & Simons* [6]. A fluidized bed, under constant pressure, could be discharged into the conveying line of 6.1m length. The data of some 200 test runs resulted in the following correlations:

$$V_f \cong 2V_s \quad (1)$$

$$(\Delta P / e_s L)(D / d_p)^{0.25} = 2.5V_s^{0.45} \quad (2)$$

The total pressure drop ΔP in Eq. (2) was calculated as the sum of two components, ΔP_d due to drag and ΔP_{fs} due to internal solid friction and friction of solid particles against air using a modified fanning friction factor f_{fs} as follows:

$$\Delta P_d = \frac{C_d A_s e_f V_f^2}{2gA} \quad (3)$$

$$\Delta P_{fs} = \frac{0.5 f_{fs} V_s^2 e_s L}{gD} \quad (4)$$

where C_d and A_s are defined as drag coefficient and cross sectional area of solids, respectively. Their results indicated that for a 3-m section, ΔP_d was in no case larger than 1.0% of the total pressure dropΔP. It was concluded that the total pressure drop for long transport lines can be estimated by Eq. (4). It was also stated that the particle size and shape seem to have only slight effects on flow characteristics.

Many investigators in the field of pneumatic conveying have tried to establish general relationships among various factors governing dense phase flow. Considering the advantage of conveying agricultural materials by low velocity dense phase transport system, *Jafari* [7] studied the dense phase flow of particulate materials in horizontal pipes of 38.1mm inside diameter and a total length of 11m. He identified the parameters which could affect the flow as

$$f_m = F(V_s, V_f, e_s, e_f, e_p, d_p, D, L, g, \mu, Z_s, \beta_s, E_e, F_c) \quad (5)$$

He left out some of the dimensionless factors including the particle shape factor Z_s, the factor describing the electrostatic effects E_e, particle size-distribution factor β_s and coefficient of dynamic friction F_c. Finally he arranged the remaining parameters into the following dimensionless groups:

$$f_m = F_1(M_s / M_f) F_2(\varepsilon_b) F_3(Fr) F_4(L / D) \quad (6)$$

Where

$$1 - (e_s / e_p) = \varepsilon_b \quad (7)$$

$$V_f^2 / gD = Fr \quad (8)$$

calculate the dependent group f_m, the modified form of equation (4) is:

$$f_m = \frac{(\Delta P / L) Dg}{0.5 e_s V_s^2} \quad (9)$$

This equation was transformed to a more convenient form and appropriate units and finally a new equation was concluded [7].

$$f_m = 25.92 \times 10^9 (De_s A^2 \Delta P / L M_s^2) \quad (10)$$

$$f_m = 10^{8.731} \left[(M_s / M_f)^{-2.180} \times (Fr)^{-0.5} \times 10^{-6.665\varepsilon_b - 1.694 \times (0.001)(L/D)} \right]^{0.989} \quad (11)$$

This equation could be used for scale-up purposes. To study the packed bed flow of agricultural particulates through bends of different radii, *Raoufat* [8] identified the parameters which could affect the flow as Eq. (12).

$$\frac{P}{e_f D} = F\left[\frac{M_s}{M_f}, \frac{V_f^2}{gD}, \frac{V_f e_f D}{\mu}, \frac{e_s}{e_p}, \frac{d}{D}, \frac{R}{D}, F\right] \quad (12)$$

where

$$V_f e_f D / \mu = R_e \quad (13)$$

The individual relationship between the independent dimensionless groups and the dependent group P/e_fD was calculated and the following relationship was obtained:

$$\frac{P}{e_f D} = 10^{3.73} + \left[(M_s/M_f)^{0.418} \times (Fr.R_e)^{0.140} \times 10^{2.821(d/D)+0.039(R/D)-1.766(F_c)}\right]^{0.445} \quad (14)$$

To optimize material handling in dense phase by decreasing friction, increasing the length of conveying and consequently, increasing skin drag of air on materials, *Karparvarfard* [9] designed and developed a test-rig and concluded a characteristic equation which was used for the basic design of a full scale dense-phase conveyor. A finned structure along the internal pipe was used to make air to accelerate more freely within the grooves resulting in high frictional skin drag on the particles and elimination of breaks with the continuous-bed flow.

In this formulation the new parameter H/D was included in the groups of dimensionless parameters and using Buckingham-pi theorem the following correlation was obtained:

$$f_m = F\left(\frac{M_s}{M_f}, Fr, \varepsilon_b, L/D, H/D\right) \quad (15)$$

$$f_m = 10^{4.757}\left[(M_s \times 3.6/M_f)^{-2.145} \times (Fr)^{-0.776} \times 10^{-0.069\varepsilon_b - 0.001(L/D) - 8.213(H/D)}\right]^{0.865} \quad (16)$$

To consider the effect of cross section of air passage slots, Torabi [10] introduced a new factor A_{air} / A_{pipe} in Eq. (15) and suggested the following relationship:

$$f_m = F\left(\frac{M_s}{M_f}, Fr, \varepsilon_b, L/D, H/D, \frac{A_{air}}{A_{pipe}}\right) \quad (17)$$

where

$$A_{air} = 40 \times 1.5 \times H \quad (18)$$

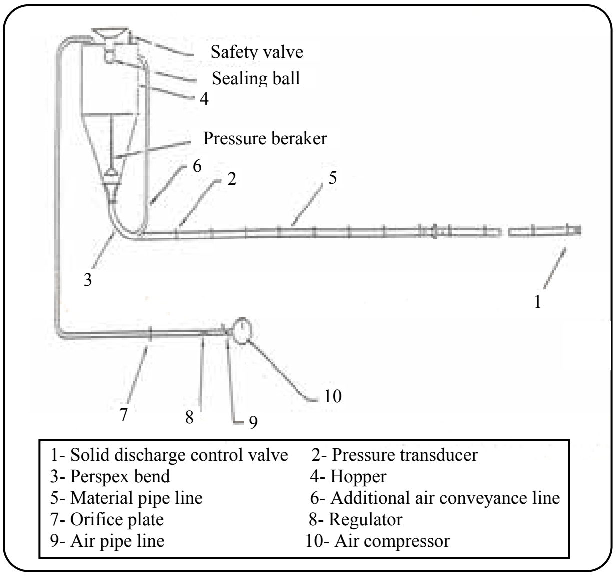

Fig. 1: General layout of the experimental test-rig.

for 40 internal slots with 1.5mm width, and

$$A_{pipe} = \pi/4\left((38.1 + 2H)^2 - 38.1^2\right) - A_{air} \quad (19)$$

for pipes with 38.1mm internal diameter. Subsequently, Equation(17) was reduced to the following characteristic equation.

$$f_m = 10^{8.434}\left[(M_s \times 3.6/M_f)^{-2.145} \times (Fr)^{-0.776} \times 10^{-0.069\varepsilon_b - 0.001(L/D) - 8.213(H/D) - 2.413\left(A_{air}/A_{pipe}\right)}\right]^{0.981} \quad (20)$$

Since internal air passage grooves are crucial in decreasing friction of solids against air, the objective of the present work is to investigate general flow equation for pipe with internal longitudinal trapezoidal grooves and to compare the resulting friction factor with previous works at equal upstream pressure. For this purpose an experimental test rig was designed and manufactured.

EXPERIMENTAL SET

The solids discharge control valve (SDCV)

The apparatus has the following main features (Fig.1):

This component of the conveyor is provided for adjustments of the opening of the valve which could provide step change of 1.0mm. For randomization in the opening section and producing a long ratio band of solid mass to air mass, it was necessary to have a simple and yet effective means of fast selection and adjustment of opening. This was achieved by employing a spring rod, having a pin fixed at one end perpendicular to its axis and a number of grooves on a collar fixed to the pipe. The end of the spring was fastened to a sliding collar, which also carried the conical part, in such a way that its pin could radially be inserted into any groove of the fixed collar. The spring rod would stay in position and so does the conic, until some force be applied to lift the pin out for next adjustment (Fig.2).

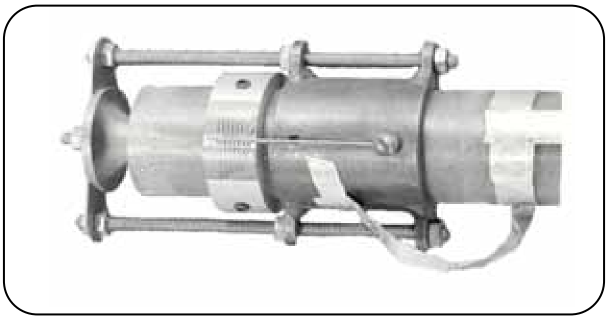

Fig. 2: Overall view of the solid discharge control valve.

The Pipeline

Taking note of the average dimension of polyethylene grains handled in this study, a pipe of 38.2mm I.D. and 5.9mm thickness seemed necessary to avoid arching at the hopper opening. The total pipe length measured 3.65m, comprising a horizontal section of 2.93m length, two fittings and a control valve at discharge end. The pipe material was polyethylene, readily machinable, reliably safe with sufficient tensile strength. Also a number of pipe supports to give a negligible pipe deflection was used.

For uniformity of the average static pressure readings at each section of pipe (both ends and middle), eight equally spaced holes (1mm drill) around the pipe were provided. Single transducer connection was then made to the calming collar which was connected and covered the holes at each section of the pipe (Fig. 3).

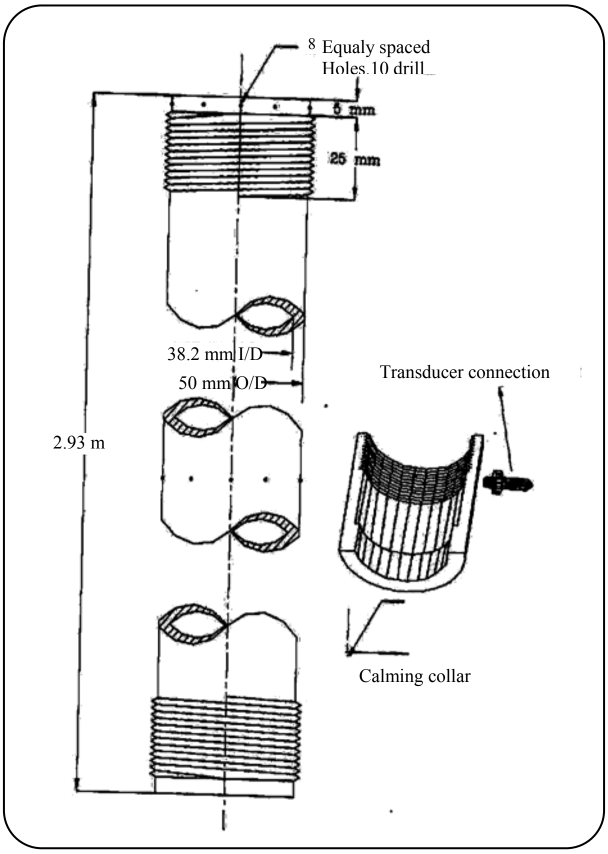

Fig. 3: Section of material conveying pipeline.

The inner longitudinal trapezoidal slots were carved in the pipe with an special device which moved through the pipe by tractor pulling. The assembly is shown in Fig.4. This was made of ten steel disks with 44mm O.D. 25mm I.D. and 10mm thickness. They were tightened on a 25mm O.D. shaft.

A slope of 1.7 degree was selected for machining and conical shaping. Longitudinal trapezoidal slots were made by sparking method along the separated disks with the minimum and maximum depth of grooves, 0 and 2.4mm, respectively. In this way, by changing the disks, the depth of grooves with 0.3mm increment was selected for nine pipes.

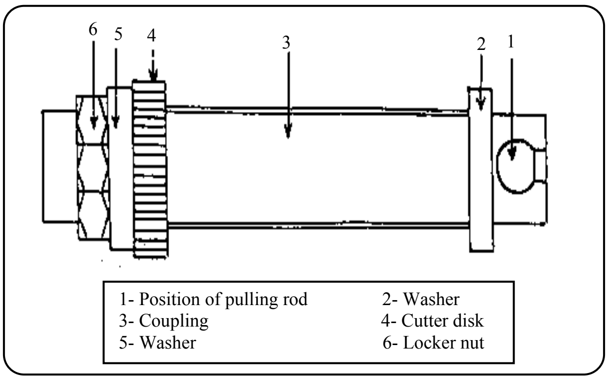

Fig. 4: General layout of the mechanical groover.

The blow hopper

This section is made of a steel pipe having a nominal diameter of 35cm and a wall thickness of about 4mm. A side wall slope of 58 degrees was selected for the bottom part of the hopper and to maintain a fairly constant head of solids in the hopper, a pressure breaker was designed

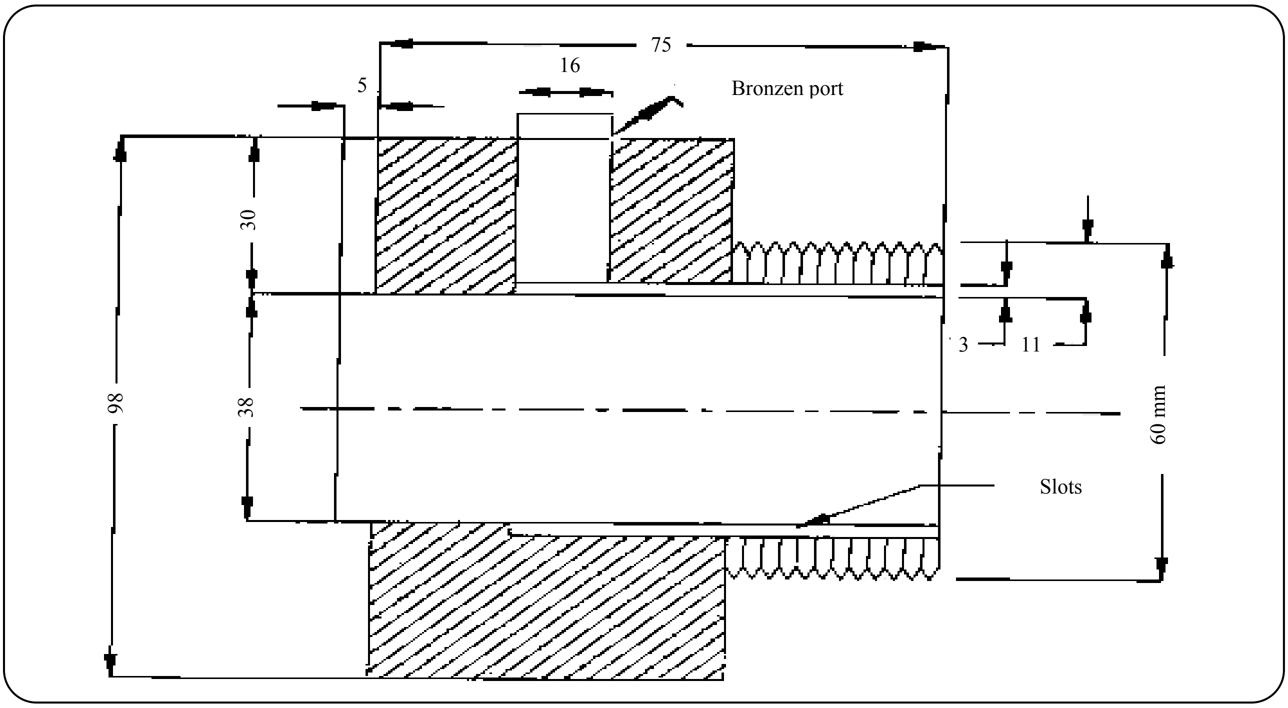

Fig. 5: Special adaptor for air intaction to slot pates.

which could be assembled readily inside the hopper through the lower opening. A large size opening of 10cm diameter was provided at the discharge end of the hopper. For the sake of rapid loading and sealing of the hopper, a simple valve system was provided at the intake. Other necessary components such as safety valve, valve for quick air discharge and a gate valve for injecting the additional air are also provided for the hopper (Fig. 5). For discharge from hopper to the horizontal pipe line, a 90 degrees pipe bend was attached to the end of hopper. For visual observations and ease of machining, it was made of clear Perspex material.

The orifice plate flow meter with D and D/2 tappings

Two more pieces of equipment were required for instrumentation purposes, air flow meter and several pressure transducers. For the range of about 25kg/h air flow rate, recommendations of the British standards [11] indicated the use of orifice meters with D-and-D/2 pressure tapping. For this purpose a minimum steel pipe size of 2.54cm I.D. is allowed. Choosing that, the standards were followed in design of the required meter.

The upstream pressure of the orifice and the pressure drop across the orifice were recorded through two pressure transducers at the rate of 16Hz at 10s intervals. The upstream temperature was checked by attaching a thermometer at the vicinity of the tapping. The discharged air was also found to have humidity, however, outside the resolution of the wet-and-dry-bulb thermometer.

To accommodate the temperature and humidity of the outside air, the following equations were used for the air flow rate calculations [11]

$$M_f = 2.202\sqrt{e_f \Delta P} \tag{21}$$

where

$$e_f = \frac{62.774}{1.8T_c + 491.67}\Big(\big[7.638\Delta P + 0.022P_b\big] + \big[70.566 - 34.679T_c\big]_c RH \times 10^{-4}\Big) \tag{22}$$

and

$$\Delta P = P_1 - P_2 \qquad P_1 > P_2$$

(Pressure drop across orifice plate)

$$\Delta P = P_3 - P_6 \qquad P_3 > P_6$$

(Pressure drop across the conveyor pipe)

An analog Input/Output Interface Card, computer and a number of software items were used to sample the Piezo-electric pressure transducers installed throughout the four points of rig and across the orifice plate.

Air compressor and pressure control valve (Regulator)

A two-stage piston type air compressor with air capacity of 2 cubic meters was used to supply air to the test rig at working pressure in the range of 276-760 kPa. A pressure control valve was installed in the supply line to regulate air pressure levels envisaged in the study. The tests were carried out at four pressure levels; 50, 100, 140, 180 kPa.

ANALYSIS

Obviously, there are too many parameters in Eq. (17) and a thorough study of all would be tedious. Thus it was decided to use dimensional analysis to correlate the experimental data. Accordingly, a basic model was proposed in which all the variables were grouped in such a way to produce sets of independent dimensionless ratios. For ease of application, it would also be advisable to select group forms which produce linear relationships with the dependent variable group. The selected model has the following form

$$f_m = C\left(F_1\left[\frac{M_s}{M_f}\right] F_2[Fr] F_3[\varepsilon_b] F_4[L/D] F_5[H/D] F_6\left[\frac{A_{air}}{A_{pipe}}\right]\right)^K \quad (23)$$

Taking logarithm of both sides, equation (23) can be written as

$$\mathrm{Log}[f_m] = \mathrm{Log}C + K(\mathrm{Log}F_1[{}^{M_s}/_{M_f}] + \mathrm{Log}F_2[Fr] + \mathrm{Log}F_3[\varepsilon_b] + \mathrm{Log}F_4[L/D] + \mathrm{Log}F_5[H/D] + \mathrm{Log}F_6[\frac{A_{air}}{A_{pipe}}] \quad (24)$$

in which LogC is the vertical intercept and K is the slope of the straight line. However, these two constants were not determined until all functional relationships were found.

Since the relative scattering of data is not sensitive to the starting assumptions we let LogC=0 and K=1 and use the following definitions.

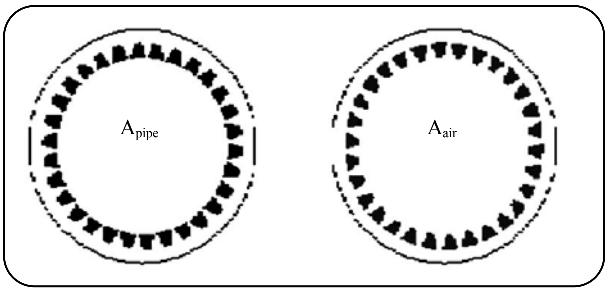

Fig. 6: Pipe cross section.

$$\text{First residuals} = \mathrm{Log}(f_m) - \mathrm{Log}F_1[M_s/M_f] \quad (25)$$

$$\text{Second residuals} = \text{first residuals } - \mathrm{Log}F_2[Fr]$$

$$\text{Third residuals} = \text{second residuals - } \mathrm{Log}F_3[e_b]$$

$$\text{Sixth residuals} = \text{Fifth residuals } - \mathrm{Log}F_6[A_{air}/A_{pipe}]$$

Functional relationships for F_1 through F_5, were already obtained in [9] and are recorded here

$$\mathrm{Log}F_1\left[{}^{M_s}/_{M_f}\right] = -2.145\mathrm{Log}\left[M_s \times {}^{3.6}/_{M_f}\right] \quad (26)$$

$$\mathrm{Log}F_2(Fr) = -0.776\mathrm{Log}(Fr) \quad (27)$$

$$Fr = 156.757\times10^{-3}\left[{}^{M_f}/_{e_f}\right]^2 \quad (28)$$

$$\mathrm{Log}F_3[\varepsilon_b] = -0.069[\varepsilon_b] \quad (29)$$

$$\mathrm{Log}F_4[L/D] = -0.001[L/D] \quad (30)$$

$$\mathrm{Log}F_5[L/D] = -8.213[H/D] \quad (31)$$

Also

$$A_{air} = 30[[1+x]/2]\times H \quad (32)$$

for 30 internal slots with 1mm and x mm bases of a trapezoid (small and long respectively), Fig.6, and

$$A_{pipe} = \frac{\pi}{4}\left[[38.1 + 2H - 38.1^2]^2\right] - A_{air} \quad (33)$$

for pipes with 38.1mm internal diameter.

Equation (24) is written in the following linear form:

$$\mathrm{Log}F_6[\frac{A_{air}}{A_{pipe}}] = \mathrm{Log}[f_m] - \mathrm{Log}F_1[\frac{M_s}{M_f}] - \mathrm{Log}F_2[Fr] - \mathrm{Log}F_3[e_b] - \mathrm{Log}F_4[L/D] - \mathrm{Log}F_5[H/D] \quad (34)$$

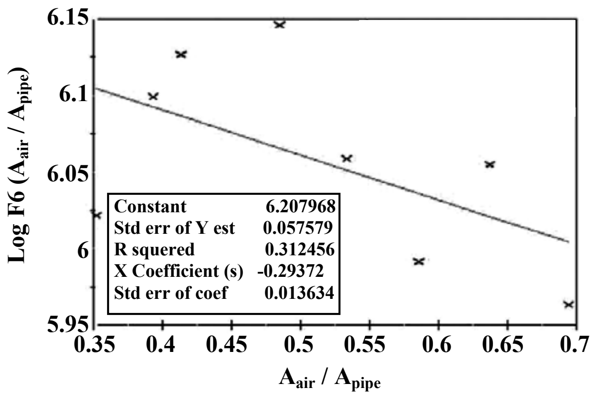

Fig. 7: Graph relating Log F6(A_{air} / A_{pipe}) to (A_{air} / A_{pipe}).

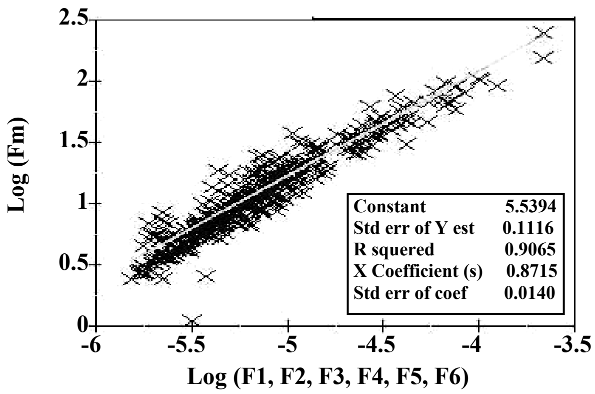

Fig. 8: Graph relating Log(F_m) to the dimensionless groups of importance for all experimental test runs.

EXPERIMENTAL PROCEDURE

After filling the hopper with polyethylene particles and sealing the hopper top, air flow was started to fill the pipe with particles, while an adjustable SDCV was set to a position so that no solids could be discharged into the catch pan. The air pressure was set to the required level by a regulator and then the flow control valve was opened to pressurize the hopper. The air could pass through the porous solids and along the pipe internal slots accelerating more freely and resulting in high skin drag on particles and low friction of solids with inner pipe wall.

After the pressure reached equilibrium, for each required pressure level, the range of solid flow rates by the positions of SDCV was recorded. Because of importance of flow parameters, mainly solid flow rates M_s and air flow rates M_f, four levels of M_f, along with nine slot depths were considered. However, it was decided to leave the solid flow rate as a floating factor depending on the depth of slots. The effect of different depth of grooves is included in the dimensionless factor H/D. Accordingly, few numbers of observations were made for different depths. The minimum solid flow rate corresponded to the minimum gap setting of SDCV which could maintain a continuous dense flow of solids. This was known to be independent of the air flow rate. The maximum flow rate considered was limited to the rate for which a smooth dense flow condition could be maintained. This was identified by visual observations of the flow on the clear Perspex bend and also vibration pulses shown on the conveyance pipe. Accordingly, four levels of M_s were considered on average.

In order to calculate friction factor using Eq. (10), several quantities are needed for different slot depths. Values of pressure drop ΔP were recorded directly by computer through pressure transducers which were installed throughout the rig. After the SDCV was opened and fixed at the desired position, a period of 10 s was required to collect the solids and then the values of M_s were determined. Also, pipe internal diameter, pipe length, solid bulk density, internal pipe cross sectional area, relative humidity and upstream air temperature of the orifice-plate of the outside air pressure were also recorded.

In three replications, 432 data points were collected. In order to determine the functional relationship for the group $\mathrm{Log}F_6\left[A_{air}/A_{pipe}\right]$, the values of the fifth residual, as defined by equation (34), were plotted against their corresponding values of $\left[A_{air}/A_{pipe}\right]$ as shown in Fig. 7.The fitted linear relationship for this pipe was:

$$F_6\left[A_{air}/A_{pipe}\right]=10^{-0.293\left[A_{air}/A_{pipe}\right]} \quad (35)$$

THE OVERALL FLOW CALCULATIONS

After calculating the sixth residuals as defined by Eq. (35), the final correlation of the data using the model of Eq. (24) was determined. For this purpose, equation (24) was rewritten as

$$\mathrm{Log}f_m=\mathrm{Log}C+\mathrm{Log}\left[F_1\times F_2\times F_3\times F_4\times F_5\times F_6\right] \quad (36)$$

The values of the quantities in brackets in Eq.(23) were plotted against the corresponding values of the mixture friction factor for all available data as shown in Fig.(8) . The regression coefficients were found to be:

$$C=5.539 \quad \text{and} \quad K=0 \quad (37)$$

Table 1: Range of dimensionless groups considered in the present investigation.

Variable groups	Range of variation
M_x / M_f	21.877-1096.478
Fr	0.014-86.201
ε_b	0.445-0.494
L/D	95.80-253.28
H/D	0.000-0.068
A_{air} / A_{pipe}	0.352-0.694

If equation (24) is rearranged with the values of these constants it takes the following form:

$$f_m = 10^{5.539}\left([M_s \times 3.6/M_f]^{-2.145} \times [Fr]^{-0.776} \times 10^{-0.069\varepsilon_b - 0.001[L/D] - 8.213[H/D] - 0.293[A_{air}/A_{pipe}]}\right)^{0.871} \quad (38)$$

The permissible range of each group of variables is given in Table 1.

CONCLUSIONS

Inspection of the data used in this study indicated that for a given value for pressure drop, any increase in mass flow rate of solids was associated with corresponding decrease in frictional pipe wall stress. Also it can be concluded that the value of solid stress acting normal to the pipe wall decreases. This phenomenon is further supported by the fact that mixing at high velocities, results in looser contacts among the solid particles. This phenomenon could be visualized as a coring tendency, for which the solid particles prefer to move along the pipe center at higher velocities and leave more space between themselves and the pipe wall in which air can flow. The flowing air in the boundary layer has lubricating effect which in turn results in less frictional stress between moving solids and pipe inner wall. In other words, the value of mixture friction factor f_m decreases. Comparison of f_m values calculated from experimental data for both rectangular [10] and trapezoidal inner slots indicated that for similar conditions of conveying length and upstream pressure, the mixture friction factor for pipes with trapezoidal slots was 40% less than that of pipes with rectangular slots. Moreover, higher values of solid-to-air mass flow ratios could be achieved using friction pipe material for a given exit opening. Furthermore, this arrangement helps to convey materials to longer distances at a given pressure setting.

The above mentioned data was re-examined once more for effect of air flow rates at an approximately similar solid flow rate. In general, as the air flow rate M_f increases, the value of friction wall stress will increase. This phenomenon could be explained by the fact that the increase of air flow rate depends on the applied pressure or the values of pressure drop, resulting in higher solid compaction in the longitudinal pipe direction. This in turn gives rise to the radial stress within the solid acting normal to the surface of the pipe, resulting in higher frictional stress. Higher air flow rates result in more frictional drag on the pipe wall. Deeper slots tend to increase the velocity of air however, the increasing rate of velocity of solid-air mixture is not proportional to air-flow velocity.

Comparison of the experimental data indicated that as the pipe inner wall shape changes from rectangular slots to trapezoidal slots, the air flow velocity and solid-air mixture velocity increase 66% and 26%, respectively.

Nomenclatures

$A(mm^2)$	Pipe cross sectional area
A_{air} (mm^2)	Air pass cross section of pipes slot
A_{pipe} (mm^2)	Cross section of pipe without slot
D(mm)	Pipe diameter
d_p(mm)	Mean particle diameter
E_e	Factor describing electrostatic effects
$e_f(kgm^{-3})$	Fluid density under flow conditions
$e_p(kgm^{-3})$	Solid true density
$e_x(kgm^{-3})$	Solid bulk density under flow conditions
F	Symbol for function
F_c	Coefficient of dynamic friction
f_m	Mixture friction factor
Fr	Froude number
$G(ms^{-2})$	Gravitational acceleration
H(mm)	Depth of slot
L(mm)	Length of Pipe
$M_f(kgh^{-1})$	Fluid mass flow rate
$M_s(kgh^{-1})$	Solid mass flow rate
P_b(pa)	Barometrix pressure
P_1(pa)	Upstream pressure tapping for orifice
P_2(pa)	Downstream pressure tapping for orifice
Re	Reynolds number
RH(%)	Relative humidity

T_c(°C)	Upstream air temperature for orifice
V_f(ms^{-1})	Solids velocity
Z_s(ms^{-1})	Solids velocity
Z_S	Factor describing particle shape
β_S	Particles size-distribution factor
ε_b	Voidage of the bed
ΔP(Ncm^{-2})	Pressure difference
μ(N.sm^{-2})	Dynamic viscosity of fluid

Received : Nov. 13, 2007 ; Accepted : Aug. 17, 2009

REFRENCES

[1] Segler G,, "Pneumatic Grain Conveying with Special Reference to Agricultural Application". N.I.A.E. Wrest Park. Silsoe. Beds. England (1951).

[2] Marcuse R.D., "Conveying of Solids", Chapman and Hall.11 New Letter Lang, London (1990).

[3] Happel J., Pressure Drop Due to Vapor Flow Through Moving Beds, *Ind. Eng. Chem*., **41**, p. 1161 (1949).

[4] Berg C.H.O., "Conveyance of Granular Solids", United States Patent Office, No2684868 (1969).

[5] Koons D.E., Lauer B.E., Continuous Solids Feed, *Ind.Eng.Chem*., **53**, p. 970 (1961).

[6] Wen C.Y., Simons H.P., Flow Characteristics in Horizontal Fluidized Solids Transport, *A.I.Ch.E. Journal*, p. 263 (1959).

[7] Jafari J., "Characteristics of Dense Phase Pneumatic Transport of Grains in Horizontal Pipes", Ph.D. Thesis. National College of Agricultural Engineering, Silsoe. UK. 254 P (1976).

[8] Raoufat M.H., Pneumatic Conveying of Grain, A New Approach, *International Conference of Agr.Eng*., Uppsala, Sweden, Paper No.9201-20 (1992).

[9] Karparvarfard S.H., "Characteristics of Dense Phase Pneumatic Transport of Grains in Horizontal Pipes Having Internal Air Passage Slots", .Ph.D. Thesis. Tarbiat Modarres University. Tehran, (1997)

[10] Torabi A.R., "An Investigation in the Slot Cross Sectional Area Effect in the Pipe for Pneumatic Transportation of Granular Materials", M.S.Thesis. Shiraz University. Shiraz (2000).

[11] British Standards Institute; BS-1042 Pt.1, "Methods for Measurement of Fluid Flow in Pipes, Orifice Plates, Nozzles and Venture Ttubes", **222** (1964).