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The use of dimensional analysis and optimization of pneumatic transportation operations and operating parameter

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Abstract: An attempt has been made with the help of Buckingham π theorem to correlate different variables of pneumatic transportation. Different variable are grouped into dimensionless number using dimensional analysis. Therefore the variables are explained in group not an individual transport operating parameters.

Keywords: Dimensional analysis, pneumatic transportation, sedimentation, Optimization.

I. INTRODUCTION

Pneumatic conveying is the art of transporting granular materials through a closed pipe by either positive or negative air pressure stream. The transport was essentially limited to free flowing materials. But, it was not possible for heavy abrasive materials. It is a good replacement of open system conveying (e.g. belt conveyor, flight conveyor etc.) which eliminates the hazard of falling solid material. It is a useful and economical way of transporting very light material which may be lost in the atmosphere in open system of conveying. Also it reduces the possibilities of chemical reaction of the material to be transported, due to atmospheric contamination, which is evident in open system of conveying. Thus, the purpose of doing any research on pneumatic conveying system is very exploring and beneficial for the concerned industry. New development in this field took place for transporting fragile material and other material sensitive to friction like coal dust, spray dried fertilizes and others. The abrasion in conveying line due to friction and impact of particle on the wall can be reduced by reducing air velocity. As a result of low air velocity and small air volume, the cost of operation is reduced. But in full-scale operation, the decrease of air velocity and increase of loading factors of the conveying fluid are limited. From the point of drawing and reliability, higher cost for investment is usually acceptable (e.g. compressor and blower etc.). Pneumatic transport of solids is widely used due to many of its advantages. Many studies have been carried out to explore the details of the transport of solids with pneumatic conveying with the aim to develop enhanced operations. The flow pattern seen in pneumatic conveying can vary widely depending on the gas velocity, the solid feed rate, and the characteristics of the solid.

II. LITERATURE REVIEW

Dhole et al.[1] studied suction effect using venturi-feeding in the pull and push pneumatic conveying system, thereby developing the suction effect at the venturi throat. This will help to create the automatic suction of the material into the system through the inlet provided at the throat. The maximum quantity of air used for the experimentation purpose was 0.521 m^3/min and maximum suction effect achieved was 0.9831 bars. They observed that by increasing the quantity of air and by changing the dimensions suction effect can be increased. They have not predicted any correlation between variables. Mishra[2] studied the effect of upstream inclination on sedimentation formation in pneumatic transportation and found the minimum inclination to the pipe is 450 for effective coal handling process and minimum sediment formation. But there is no correlation among the variables in available research work. Peng et al.[3] studied the flow regimes of high-pressure and dense-phase pneumatic conveying system. Quartz powder was chosen as conveyed material to study the flow regime and found that with the decrease in superficial gas velocity, three distinguishable flow regimes observed are stratified flow, dune flow and plug flow but they have not formed any mathematical relationship. Kuang et al.[4] studied the vertical pneumatic conveying by a combined approach of discrete element model for particles and computational fluid dynamics for gas. The approach is verified by comparing the calculated and measured results in terms of particle flow pattern and gas pressure drop. Then forces governing the behaviour of particles are analysed in detail and did not find any interrelationship. Liu[6] suggested trends of particle velocity and pressure drop along pipe were given experimentally and theoretically. According to experimental data, resistance properties along pipeline were performed experimentally and transport mechanism in dense-phase pneumatic conveying was analysed. Based on dynamic balance of gas-solid two-phase flow pressure drop calculation equation of horizontal pipe in dense-phase pneumatic conveying was established. Hilton et al.[7] conducted experimental and computational studies on horizontal and vertical dense conveying, investigated the effect of gas flow velocity and pressure on the bulk particle flow rate.

They compared both slug formation and the movement of slugs to the spherical case and showed that the bulk flow is highly sensitive to particle shape.

Mishra[8] studied stationary bed and asymmetric suspension two phase flow pattern in pneumatic transportation and correlate different variables affecting on pneumatic coal injection system. Experimental readings were taken by keeping mass flow rate of coal and air flow rate constant sequentially. He found that different variables responsible for coal handling process.

Barbosa and Pinho[9] worked on pneumatic conveying of cork stoppers used in the cork processing industries. Design and built of equipments purely on an empirical basis. A simple correlation for the pressure drop in the steady state region of the conveying pipe is proposed. The correlation is a function of dimensionless parameters used to characterize the two phase flow under analysis. Three standard stoppers sizes and a single pipe diameter were used in the experiment; all experiments are carried out at ambient temperature.

Therefore, in this work, the correlation between all the variables with the help of dimensional analysis is made.

III. EXPERIMENTAL PROCEDURE

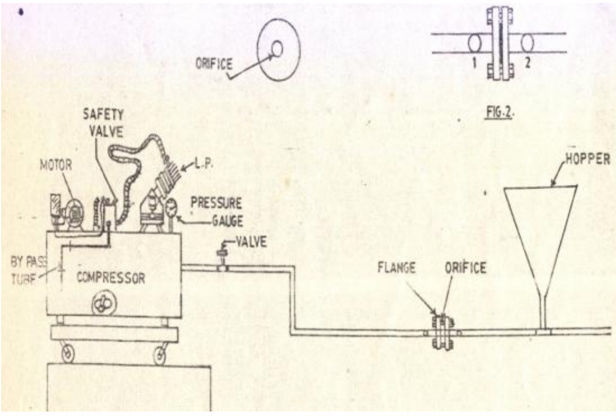

Figure 1. Experimental Setup

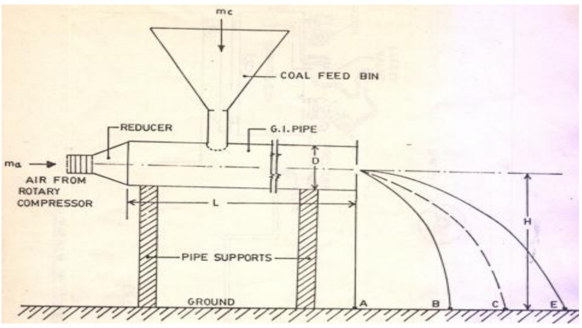

Figure 2. Experimental set up

An experimental set of was made at Birla Institute of Technology, Mesra, Ranchi to developed inter-relationship of pneumatic transportation parameter of coal injection systems. From one end of the pipe, air was supplied by a two stage reciprocating air cooled compressor through an orifice plate and coal was fed to the pipe beyond the orifice plate and orifice plate at different flow rate through a vertical hopper. The experimental arrangement is shown schematically in Figure 1. Compressor droves air through the pneumatic conveying circuit. The particles were injected through the hopper there; it fell by gravity and was controlled by the adjustable flap. The air – solid mixture flowed along the piping conduit of internal diameter 1 inch. The pressure measurements were made from the pressure tapping at location 1 and 2 volumes as shown in Figure 2. An orifice meter measured the air – volume rate. The air velocities the mean air velocities at the main branch were measured by pitot static probes, to determine the solid mass, constant volume coal was collected for a known time interval. Now, air was supplied by the stage reciprocating compressor at the rate of 32 kg/hr., 38 kg/hr and 48 kg/hr. for each air flow rate coal was fed into the coal throwing pipe at the rate of 20 kg/hr, 24kg/hr, 26.5 kg/hr and 28 kg/hr. For each coal flow rate, the throwing distance of the injected coal and the spreads were measured. Size of the coal used for the experimental trial was 3 – 1.75 mm and bulk density of coal was 1500 kg/m^3.

IV. USE OF DIMENSIONAL ANALYSIS

Often, dimensional analysis is reported to when the process is very complex. This technique is used widely in solving engineering problems and scientific disciplines which enables researchers to take several parameters into account affecting a particular process or phenomenon and when detailed modeling is not available. Pneumatic transportation is one such complex process and in this study dimensional analysis was used to point out the most significant parameters, using the dimensionless groups derived from the analysis. Its application is dependent on listing of all dimensional variables affecting the process. These methods can also be helpful in correlating experimental data and developing functional relationship between dimensional variables. Previously the researchers suggested that the derived model using dimensional analysis, which gives some of the dimensionless groups.

Complex engineering problems in many field's notably fluid mechanics and heat transfer are amenable to dimensional analysis. The technique has been successfully applied in the mechanics of solids in the study of elastic deformation and vibration of complex engineering structures. It was used to establish the modeling criteria for the scale model testing of coal-face production system. Its use in subsidence modeling was referred to by various scientists. Backed by these literature supports, the author decided to reapply this technique (Buckingham π Theorem[10]) to the analysis of the sedimentation in pneumatic transportation with the intention of deriving a set of dimensionless groups, so that the results could be used to correlate the experimental data and develop appropriate functional relationships. As mentioned above, there are many formation and pneumatic transportation parameters that affect the main parameter, i.e. sedimentation, based on published theoretical and experimental work.

4.1 The Buckingham π theorem

The Buckingham π Theorem[10] states that physical equation in general form

$$f(x_1, x_2, x_3, x_4, ... x_n) = 0 \qquad (1)$$

Where the 'x' terms 'are the physical quantities involved, can be reduced to one having n_m dimensionless variables where m is the number of dimensions, such that:

$$f(\pi_1, \pi_2, \pi_3, \pi_4, ... \pi_n) = 0 \qquad (2)$$

The procedure involved in reducing the original functional to one containing the dimensionless variables can be described as follows.

Step 1: Determine the number of π terms given by n_m

Step 2: Select the repeating variables according to the following rules.

Step 2.1: The repeating variables must include among them all of them fundamental dimensions. The dependent variable should not be used as a repeating variable.

Step 2.2: The dependent variable should not be used as repeating variable.

Step 3: Assign to each value of π terms (Not included those selected as reporting variables in step 2)

Step 4: Find exponent in each π terms

Step 5: Write the equation in terms of π terms and perform such algebraic operations as may be necessary to rearrange the terms.

TABLE 1. PARAMETERS USED IN THE PRESENT WORK

Name	Symbol	Dimensions
Throwing Distance	L_1	L
Spread of flow	δ	L
Friction factor	F	-
Height of fall	H	L
Depth of bed	h_b	L
Total length of pipe	L_4	L
Distance between hopper joint to injection end	L	L
Air flow rate	m_a	MT^{-1}
Coal flow rate	m_c	MT^{-1}
Pressure drop along length	ΔP	$ML^{-1}T^{-2}$
Velocity of solid	V_s	LT^{-1}
Pipe Diameter	D	L
Mix Density	ρ_m	$L^{-3}M$
Terminal setting velocity	V_0	LT^{-1}

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4.2 Formulation of Problem

According to Buckingham π Theorem[10] there should 14-3 =11 dimensionless groups which describe the process. Accordingly to develop the π groups, the process suggests 3 repeating variables. The variables themself do not form a dimensionless groups and these are $D \times V_0 \times \rho_m$ following standard procedures of dimensional analysis 9 groups can be constructed which are given in Table 2 as a result it was found that

$$\pi_1 = D^{a_1} \times V_0^{b_1} \times \rho_m^{c_1} \times L_1$$

$$\pi_1 = [L]^a \times [LT^{-1}]^b \times [ML^{-3}]^c \times [L]$$

$$m = c_1 + 0 + 0 + 0 = 0$$

$$L = a_1 + b_1 - 3c_1 = 0$$

$$T = -b_1 = 0$$

$$a_1 = 0, b_1 = 0, c_1 = 0$$

Table 2. Estimation of various dimensionless groups

Estimation	Coefficient			Dim. Group
$\pi_1 = D^{a_1} \times V_0^{b_1} \times \rho_m^{c_1} \times L_1$	$a_1=0$	$b_1 = 0$	$c_1=0$	$\pi_1 = L_1$
$\pi_2 = D^{a_2} \times V_0^{b_2} \times \rho_m^{c_2} \times \delta$	$a_2=0$	$b_2 = 0$	$c_2=0$	$\pi_2 = \delta$
$\pi_3 = D^{a_3} \times V_0^{b_3} \times \rho_m^{c_3} \times f$	$a_3=0$	$b_3=0$	$c_3 = 0$	$\pi_3 = f$
$\pi_4 = D^{a_4} \times V_0^{b_4} \times \rho_m^{c_4} \times H$	$a_4=0$	$b_4=0$	$c_4 = 0$	$\pi_4 = H$
$\pi_5 = D^{a_5} \times V_0^{b_5} \times \rho_m^{c_5} \times L_4$	$a_5=0$	$b_5=0$	$c_5=0$	$\pi_5 = L_4$
$\pi_6 = D^{a_6} \times V_0^{b_6} \times \rho_m^{c_6} \times L$	$a_6=0$	$b_6=0$	$c_6=0$	$\pi_6 = L$
$\pi_7 = D^{a_7} \times V_0^{b_7} \times \rho_m^{c_7} \times m_a$	$a_7=-2$	$b_7=-1$	$c_7=-1$	$\pi_7 = \frac{m_a}{D^2 \times V_0 \times \rho_m}$
$\pi_8 = D^{a_8} \times V_0^{b_8} \times \rho_m^{c_8} \times m_c$	$a_8=0$	$b_8=0$	$c_8=0$	$\pi_8 = \frac{m_c}{D^2 \times V_0 \times \rho_m}$
$\pi_9 = D^{a_9} \times V_0^{b_9} \times \rho_m^{c_9} \times \Delta P$	$a_9=0$	$b_9=-2$	$c_9=-1$	$\pi_9 = \frac{\Delta P}{V_0^2 \times \rho_m}$
$\pi_{10} = D^{a_{10}} \times V_0^{b_{10}} \times \rho_m^{c_{10}} \times V_m$	$a_{10} = 0$	$b_{10}=-1$	$c_{10}=0$	$\pi_{10} = \frac{V_m}{V_0}$
$\pi_{11} = D^{a_{11}} \times V_0^{b_{11}} \times \rho_m^{c_{11}}$	$a_{11}=0$	$b_{11}=0$	$c_{11}=0$	$\pi_{11}=1$

$$\frac{\Delta P}{V_0^2 \times \rho_m} = f\left(L_1, \delta, f, H, L_4, L, \frac{m_a}{D^2 \times V_0 \times \rho_m}, \frac{m_c}{D^2 \times V_0 \times \rho_m}, \frac{V_m}{V_0}, 1\right)$$

$$\Delta P = V_0^2 \times \rho_m \times f\left(L_1, \delta, f, H, L_4, L, \frac{m_a}{D^2 \times V_0 \times \rho_m}, \frac{m_c}{D^2 \times V_0 \times \rho_m}, \frac{V_m}{V_0}, 1\right)$$

The required relationship between all the variables is as:

$$\Delta P = V_0^2 \times \rho_m \times f\left(\frac{L_1 \times \delta \times f \times H \times L_4 \times L \times m_a \times m_c \times V_m}{D^4 \times V_0^3 \times \rho_m^2}\right)$$

V. CONCLUSION

The correlation of different variables of pneumatic transportation was made and following conclusions are drawn.

1. The pressure difference ΔP through a pipe of certain length and diameter due to viscous flow directly proportional to terminal velocity V_0 and mixture density ρ_m.The pressure difference ΔP through a pipe of certain length and diameter directly proportional velocity of mixture Vm.
2. The pressure drop ΔP varies with respect to different air and coal flow rate. (m_a, m_c)

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