PNEUMATIC AND HYDRAULIC CONVEYANCE SYSTEM FOR SOLIDS

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ABSTRACT

The effecient design of a hydro or pneumatic transport system depends on a large number of parameters affecting the behaviour of such system. Some of the parameters key in the design and the method of their optimization has been outlined in the present paper. A new mathematical relationship for pressure drop and critical velocity has been described.

NOMENCLATURE

A	Cross sectional area of pipe
C_D	drag co-effecient of solid particle
D	Pipe diameter
d	solid particle diameter
f	Darcy-Weisbach fraction factor
g	acceleration due to gravity
h_{Tot}	Total head loss per unit length of pipe
R_{ep}	Partcile Reynolds number
V_c	Critical velocity
V_f	average velocity of fluid
V_T	Terminal velocity of solid particle
w_f	flow rate of fluid by weight
w_s	Flow rate of fluid by weight
ρ_f	density of fluid
P_p	density of solid
μf	Viscosity of fluid

1. INTRODUCTION

Pipe lines are used to handle not only water, gas or oil but chemicals, wood chip, sewage, solid-fluid mixtures etc. There are number of slurry pipe-lines, pneumatic pipe-lines and pneumo-capsule pipe-lines that are successfully competing with rail, roads etc. for solid transportation.

Solids of different sizes can be transported through pipe lines using fluids like water and air as carrier. The two types of transportation systems namely hydro-transport and pneumo-transport system have wide range of applications in industries like mining, chemical and petro-chemical, iron and steel, thermal power plants etc. Pneumatic conveying of grains has been common for many years. The process is also used for the movement of dry chemicals, fertilizers and other finely divided solids particularly within process plants. Shot peening and surface preparation are other applications of this process.

The flow of solids in a solid-fluid mixture may be either homogenous or heterogenous depending on large number of parameters such as diameter, fluid velocity, density and viscosity, particle size, shape, size distribution, density and concentration of solids etc. Due to large number of parameters affecting the flow, it is not possible to develop the expression purely on theoretical basis for the design parameters like head loss, minimum transport velocity, critical velocity etc. However, semi-empirical and empirical correlations are available from the important contributions of Gasterstad (1924), Wilson (1942), Zenz (1949), Newitt et. al (1951), Clark et. al (1952), Durand (1953), Rose & Duckworth (1969), Jones and Leung (1978), Toda et. al (1979), and Michaelides (1987). These studies provide a better insight to the mechanism of flow of solid - liquid / gas mixture in pipes.

In the heterogenous flow of mixture of solid-liquid/gas, the deposition velocity and the critical velocity play very important role for deciding the optimum operating condition from the view-point of energy consumption. Many investigators have obtained critical velocity experimentally for different flow rates. The empirical correlation thus obtained for the critical velocity fail to predict the actual values under the changed flow conditions. A comparison of such correlations has been made by Widenroth and Kirchner (1972).

In the present paper an attempt has been made to optimise theoretically few design parameters from the point of view of energy consumption.

2. ANALYTICAL APPROACH

A general relationship for the critical velocity is derived starting from the first principle. Considering a large number of independent variable such as ρ_p, d, C_D, W_s, V_T, W_p, D, V_f, ρ_f, g and θ and assuming uniform distribution of particle across a pipe section, the additional head loss (h_s) due to solids in the mixture is

$$h_s = [0.5\, C_D \cdot \rho_f \cdot A_p \cdot V_T^2 + W_p\,(1 - \rho_f / \rho_p)\,\sin\theta]\,(W_s / W_p)\;1 / W_f \qquad (1)$$

Neglecting the losses due to friction between the solid particles and the pipe surface for the flow of solids under fully suspended condition, the total head loss

($h_{Tot.}$) per unit length is obtained as

$$h_{Tot.} = h_f + h_s \qquad (2)$$

where h_f is the head loss per unit length due to friction between fluid and pipe surface under identical flow situation.

By Darcy-Weisbach equation,

$$h_f = \frac{f V_f^2}{2gD} \qquad (3)$$

Then, the total head loss could be written as

$$h_{Tot.} = [0.5\, C_D \,.\, \rho_f \,.\, A_p \,.\, V_T^2 + W_p (1 - \rho_f / \rho_p) \sin\theta]\, (W_s / W_p)\, 1 / W_f + f V_f^2 / 2gD \qquad (4)$$

For a horizontal pipe, it reduces to

$$h_{Tot.} = \frac{f V_f^2}{2gD} + 0.5\, C_D \,.\, \rho_f \,.\, A_p \left(\frac{V_T^2}{W_f}\right) \left(\frac{W_s}{W_p}\right) \qquad (5)$$

where,

$V_T = \sqrt{4gD\,(\rho_p - \rho_f) / 3\, C_D\, \rho_f}$

$C_D = 18.5\, Rep^{-0.6}$, for $0.1 < Rep < 500$

$C_D = 0.44$ for $500 < Rep < 2 \times 10^5$

and $Rep = \frac{P_f V_T d}{\mu f}$

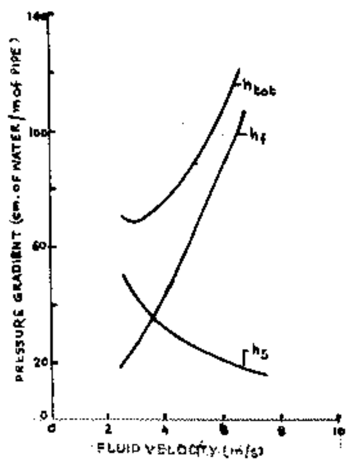

Fig. 1. h_f, h_s & $h_{Tot.}$ V_s V_f

The velocity of the carrier fluid for which the head loss is minimum is termed as critical velocity. Fig. 1 shows a plot of head loss (pressure drop) versus the velocity of flow. Differentiating eq. (1) with respect to the carrier fluid velocity (V_f) and equating it to zero gives an expression for critical velocity as -

$$V_C = [C_D V_T^2 d^2 W_S D^{C-1} \rho_f^C / (2-C)K W_p \mu_f^C]^{1/3-C} \quad (6)$$

where K and C are the constants to be obtained from the plots of friction factor (f) against Reynolds number (R_e) for pipe flow which can be expressed as -

$$f = \frac{K}{Re^C} \quad (7)$$

3. RESULTS AND DISCUSSION

In conveying solids through pipe line with a carrier fluid, the head loss depends on various characteristics of carrier fluid, pipe and solid particles. It is, there fore, necessary to optimize these variables in order to minimise the head loss. The selection of the following factors are vital for the optimal design of the solid-liquid/gas transportation system.

3.1 Mean Particle Diameter

The mean particle diameter of solid is one of the important parameters as it affects the drag co-efficient and terminal velocity of particle, thus affecting the pressure drop. Eqs. (2) and (6) can be used to optimize the mean particle diameter. Experimental results on transporting spherical glass beads of different sizes 2.11 mm, 2.72 mm and 3.18 mm in air, in a horizontal pipe of diameter 50 mm showed that the head loss is minimum for the glass beads of diameter 2.11 mm and maximum for diameter of 2.72 mm.

3.2. Pipe diameter

Selection of an optimum pipe diameter is important not only from the fixed cost point but also from energy consumption point of view. A larger diameter pipe would result in less pressure drop but at the same time cause higher cost of pipe. Hence, a compromise between the two should be made for an overall economy of the system.

3.3. Transport Velocity

A minimum velocity of carrier fluid is required in order to keep the particle under suspended condition. However, the head loss increases as the fluid velocity increases. So, it is important to select a fluid velocity for which the head loss is minimum. Using eqs. (1) to (7), the critical velocity of fluid and terminal settling velocity have been calculated and tabulated in Table 1. From the results, it is seen that no solid can be transported at a fluid velocity lower than the terminal velocity of the particle. Further, the critical velocity is usally higher than the terminal velocity of the particle in case of hydro-transport where as it generally not the case with pneumo-transport. Thus, a knowledge of critical velocity is important to decide the minimum transport velocity for pipe line conveyance of solid.

Table 1. Comparison of Theoretical and Experimental Values of Critical Velocity

Sl. No.	References	θ Deg.	Fluid used	Solid used	dx10³ m	V_T m/s	W_s N/s	V_C(Theo) m/s	V_C(Exp.) m/s
1.	Shrivastava & Kar	90	Air	Glass Beads	1.080	1.080	0.2452	9.53	9.76
2.	- do -	90	Air	Do	1.080	1.080	0.3550	9.48	9.36
3.	Rose & Duckworth	0	Water	Lead Shots	2.400	0.850	7.784	2.75	2.56
4.	- do -	0	Water	Do	2.400	7.550	15.301	3.30	3.28
5.	Rose & Duckworth	0	Water	Lead Shots	2.400	0.850	11.120	3.08	2.98
6.	Shrivastava & Kar	0	Air	Glass	1.080	8.000	0.6570	8.60	8.93

3.4. Entrance length

The entrance effect in the design of solid transport system is the one associated with the acceleration of solids from essentially zero velocity to some stabilized pipe velocity. For this, the procedue recommended is -

i) Calculate the travel distance and the pressure drop required to accelerate the solids to a steady velocity using the expression -

For the acceleration distance :

$$L_A = 6\left[\left(\frac{M_S}{\rho_f\, g^{1/2}\, D^{5/2}}\right)\left(\frac{D}{d}\right)^{1/2} S^{1/2}\right]^{1/3} \qquad (8)$$

where L_A = Length of pipe required for full acceleration of solids.

M_s = Mass flow rate of solid

S = Density ratio (ρ_s / ρ_f).

ii) The pressure drop due to the acceleration of solids over the length, L_A -

For the acceleration pressure drop due to the solids,

$$\frac{2\,\Delta P_{KES}}{P_f\, V_{SF}^2} = \frac{1.12}{g} \cdot \frac{M_S}{M_f} \cdot \phi_1\, \phi_2 \qquad (9)$$

where ϕ_1 is function of V^2_{SF} / gd_s^2

and, ϕ_2 is the function of angle of inclination of pipe. For horizontal pipe $\phi_2 = 1$.

3.5. Acceleration Effects

Acceleration effects over the stabilized flow portion of the pipe are usually small but they may be significant for gas-solid mixture if the pressure drop is significant.

4. CONCLUDING REMARKS

An economical and effecient design of a solid-liquid/gas transportation system need a critical selection and optimization of various parameters such as particle size and size distribution, pipe diameter, transport velocity etc. The mathematical expression given in this paper are very helpful in designing a solid transportation system.

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