FMFP2016–PAPER NO.

Life-Cycle Cost Modelling of Pneumatic Conveying Pipelines for the Lean Phase Transport Condition

Joshua Walker
University of Huddersfield
Queensgate, Huddersfield,
UK, HD1 3DH
U1163540@hud.ac.uk

Taimoor Asim
University of Huddersfield
Queensgate, Huddersfield,
UK, HD1 3DH
t.asim@hud.ac.uk

Rakesh Mishra
University of Huddersfield
Queensgate, Huddersfield,
UK, HD1 3DH
r.mishra@hud.ac.uk

Martin Adams
HR Blowers
Bridge Mills, Holmfirth,
UK, HD9 3TW
sales.mastercraft@virgin.net

Abstract

Determination of the pressure requirements, volumetric flow rate and optimal pipeline diameter is key to selecting a compressor for dilute-phase conveying. Thus, a new methodology has been developed for determining these attributes for pneumatic conveying systems. There are two key costs involved in the design of pneumatic conveying pipelines, i.e. operational cost and capital cost. The methodology calculates these costs and formulates the optimal pipeline diameter based on the minimum conveying costs plus capital cost. This methodology displays the relationship between pressure drop and volumetric flow rate for the conveying costs. This will also allow for an optimal life cycle cost prediction.

Keywords: *Pneumatic Conveying; Life Cycle Cost; Pressure Drop*

I. INTRODUCTION

Pneumatic Conveying is the transportation of materials through piping systems using pressurised air. Dilute phase transportation is the primary method of pneumatic conveying and accounts for 70% of systems [1]. The key characteristic of dilute phase systems is that the bulk solids are suspended in the air stream when conveyed. Typical dilute phase systems utilise low pressure and high velocity to move low particle concentrations. However, dilute phase systems are inefficient in transporting bulk solids.

The key to designing an efficient system is selecting the correct compressor for the duty, which is crucial as inappropriate compressor selection can lead to blockages and large unnecessary running costs.

The most accurate method for designing dilute phase systems is to use experimental data in a number of scaling equations. However, this is not always accessible to system designers around the world. Using theoretical calculations, it is possible to predict how pipeline layout can affect the cost of pneumatic conveying systems. In the present study, a critical review of the different theoretical calculations has been carried out to be utilised in the prediction of optimal pipeline design parameters.

II. THEORETICAL PREDICTIONS

This section of the study describes how existing methods are used to predict the pressure drop and the volumetric flow rate requirements in pneumatic conveying pipelines. The methodology will then be developed for optimal pipeline selection.

A. Saltation Velocity, Air Volumetric Flow Rate and Solid Loading Ratios

To calculate the saltation velocity (minimum velocity for holding the particles in suspension) whilst being conveyed, a methodology was developed by Rizk [2] based on empirical correlations. Research suggests that this methodology is the most accurate for predicting saltation velocity when compared to other existing methodologies (Gomes and Amarante Mesquita) [3]. The saltation velocity (u_{salt}) is expressed by Rizk as:

$$u_{salt} = \left(\frac{4\,\dot{m}_p\,10^a\,g^{b/2}\,D^{(b/2)-2}}{\pi\,\rho_g}\right)^{\frac{1}{b+1}} \quad (1)$$

where the saltation velocity is calculated using the particle mass flow rate ($\dot{m}_p$), gravitational acceleration (g), pipe diameter (D), gas density (ρ_g) and the particle size factors determined on the particle size (x) as:

$$a = 1440x + 1.96$$
$$b = 1100x + 2.5$$

A sufficient safety factor of 1.5 times the saltation velocity is more than adequate to ensure that the particles do not fall out of suspension. This factor of safety is known as the superficial gas velocity (u). The minimum required gas volumetric flow rate (v_g) inside the pipe can then be calculated by multiplying the superficial gas velocity by the cross sectional area of the pipe (A). In order to calculate the Free Air Delivered (FAD), the mass flow rate of the gas needs to be calculated as:

$$\dot{m}_g = \frac{p\,\dot{v}_g}{RT} \quad (2)$$

Eq.2 uses the volumetric flow rate ($\dot{v}_g$) of the gas, the pressure in the line (p), the specific gas constant (R) and the temperature (T) in the line to calculate the mass flow rate of the gas. Using the mass flow rate of the gas, the FAD volumetric flow rate of the gas can be calculated as:

$$\dot{v}_g FAD = \frac{\dot{m}_g \, R \, T_{atm}}{P_{atm}} \quad (3)$$

Eq.3 uses the mass flow rate of the gas, the specific gas constant, atmospheric temperature and atmospheric pressure (T_{atm} and P_{atm}) to calculate the FAD volumetric flow rate of the gas. The Solid Loading Ratio (SLR) can be calculated by dividing the mass flow rate of the solid phase with the mass flow rate of the gas. The maximum SLR can be used to validate a dilute phase system. It is recommended that dilute phase systems are limited to a maximum of 15 SLR as over this value particles start falling out of suspension, thus blocking the pipeline.

B. Pressure Drop Calculations

The total pressure drop in a pipeline comprises of pressure drop in horizontal pipes, vertical pipes and pipe fittings, such as pipe bends etc. The net force acting on the pipe contents is equal to the rate of increase of momentum of its contents. Thus, the net force (comprising of the pressure force, gas-wall friction, solid-wall friction, gravitational force) is equal to the rate of increase of momentum of gas and solids [4]. Thus can be expressed in terms of gas density, particle density (ρ_p), voidage (ε), superficial gas velocity gas (u_g), superficial particle velocity (u_p), gas friction factor (f_g), particle friction factor (f_p), gravitational acceleration, length of pipe run (L) and diameter of pipe as below in Eq.4:

$$\begin{aligned} p_1 - p_2 = {} & \frac{1}{2} \varepsilon \rho_g u_g^2 + \frac{1}{2} (1 - \varepsilon) \rho_p u_p^2 + \\ & 2 f_g \rho_g \varepsilon u_g^2 \frac{L}{D} + 2 f_p \rho_p (1 - \varepsilon) u_p^2 \frac{L}{D} + \\ & \rho_P L (1 - \varepsilon) g \sin\theta + \rho_f L \varepsilon g \sin\theta \end{aligned} \quad (4)$$

The pressure drop calculated using Eq.4 can be differentiated into its constituents, as shown in Table.1.

Table 1: Pipeline pressure loss equation breakdown

(I)	$\frac{1}{2} \varepsilon \rho_g U_g^2$	Pressure drop due to gas acceleration
(II)	$\frac{1}{2} (1 - \varepsilon) \rho_p U_p^2$	Pressure drop due to particle acceleration
(III)	$2 f_g \rho_g \varepsilon U_g^2 \frac{L}{D}$	Pressure drop due to gas-to-wall friction
(IV)	$2 f_p \rho_p (1 - \varepsilon) U_p^2 \frac{L}{D}$	Pressure drop due to solids-to-wall friction
(V)	$\rho_P L (1 - \varepsilon) g \sin\theta$	Pressure drop due to the static head of solids
(VI)	$\rho_f L \varepsilon g \sin\theta$	Pressure drop due to the static head of the gas

Some of these equations may be omitted when calculating for pressure drop in either vertical or horizontal pipe. For example, equations (V) and (VI) can be omitted from the horizontal pipe pressure loss calculations as there should be no static head losses. Equations (I) and (II) can be omitted in the vertical pipe sections as assumptions are made that the material is dispensed in the horizontal pipe, therefore, there should be no losses due to the acceleration of the material in vertical sections. In reality, the acceleration occurs after bends, however, this shall be predicted by scaling the vertical pipe pressure loss. Hence, pressure drop in horizontal and vertical pipes, and in pipe bends, can be computed as:

$$\begin{aligned} \Delta p_{Horizontal} = {} & \frac{1}{2} \varepsilon \rho_g u_g^2 + \frac{1}{2} (1 - \varepsilon) \rho_p u_p^2 + \\ & 2 f_g \rho_g \varepsilon u_g^2 \frac{L_H}{D} + 2 f_p \rho_p (1 - \varepsilon) u_p^2 \frac{L_H}{D} \end{aligned} \quad (5)$$

$$\begin{aligned} \Delta p_{Vertical} = {} & 2 f_g \rho_g \varepsilon u_g^2 \frac{L_V}{D} + 2 f_p \rho_p (1 - \varepsilon) u_p^2 \frac{L_V}{D} + \\ & \rho_P L_V (1 - \varepsilon) g \sin\theta + \rho_g L_V \varepsilon g \sin \end{aligned} \quad (6)$$

$$\Delta p_{Bend} = \frac{\text{No. of Bends} \cdot 7.5 \cdot \Delta p_{Vertical}}{L_V} \quad (7)$$

Using the pressure loss and volumetric flow rate, the power consumption of the system can be calculated [5].

III. COST OF POWER CONSUMPTION

To calculate the cost of power consumption in a pipeline (also known as operational cost) for a range of pipe diameters, the volumetric flow rate and the pressure need to be calculated for each diameter using the calculations from sections 2A and 2B. Thus, the power consumption can be computed using:

$$P = \frac{p \dot{v}_g FAD}{\eta} \quad (8)$$

where P is the Power required for the flow to take place at a given pressure multiplied by the volumetric flow rate of the material over η the volumetric efficiency of the compressor. To calculate the cost of the power consumption the power needs to be converted from Watts to kWh. Thus by knowing the energy consumption in kWh, and the average cost per unit kWh, the cost of power consumption can be calculated.

IV. COST OF PIPE MATERIAL

The cost of the piping material (also known as the manufacturing cost) can be computed as:

$$C_{Manuf} = \frac{C_2 \, \pi \, D \, t \, \gamma_p}{\dot{v}_g} \quad (9)$$

Agarwal and Mishra [6] have expressed the pipe manufacture cost in terms of the net cost of pipe per unit weight of material (C_2), the specific weight of pipe material (γ_p), the pipe diameter, the pipe wall thickness (t) and the gas volumetric flow rate. The pipe wall thickness can be calculated using a coefficient (C_c), (which is dependent on the operating pressure within the pipeline) multiplied by the pipe diameter.

V. COST OF COMPRESSOR

The cost of the compressor can be calculated using the FAD volumetric flow rate requirement as this is the determining factor for the size of a compressor. However, the relationship between pipe diameter and compressor cost can be predicted using:

$$\dot{v}_g FAD < 4000 \, m^3/hr \quad (11)$$

$$C_{Compress} = \frac{0.3057\pi D^2 upT_{atm}}{P_{atm}T} + 1828$$

$$\dot{v}_g FAD > 4000\,m^3/hr \quad (12)$$

$$C_{Compress} = -3E\text{-}05 \times \left(\frac{\pi D^2 upT_{atm}}{4P_{atm}T}\right)^2 + \frac{1.1289\pi D^2 upT_{atm}}{P_{atm}T} - 15252$$

VI. TOTAL PIPELINE COST

The total cost of a pipeline can be calculated as:

$$C_{Total} = C_{Operational} + C_{Manuf} + C_{Compress} \quad (13)$$

where the total cost is calculated by summing the operational cost, the manufacturing cost and the cost of the compressor.

VII. OPTIMAL PIPELINE SIZING

In order to predict the optimal size of the pipeline, the total cost of the pipeline should first be represented in terms of the pipeline diameter. The optimal pipeline diameter can then be calculated by differentiating the total cost of the pipeline with respect to the pipeline diameter. The results can then be summarised graphically where the relationship between total cost and pipe diameter can be depicted to find a local minima. This methodology only applies for a pressure of less than 1200mBarG and SLR less than 15.

VIII. DESIGN EXAMPLE

A pneumatic conveying system is being designed to carry 10tonnes/hour of caster sugar (density of 1590kg/m³, and mean particle size of 300µm) from a storage silo to a lorry loading silo. This system needs to run for 4 hours a day, 5 days a week and 48 weeks a year. The pipeline consists of a 10m vertical section, a 60m horizontal section and 4 pipe bends. Assume that a roots type blower will be used to convey the material with a volumetric efficiency of 70%. The gas will have an average density of 1.36kg/m³ in the pipeline. (Assume i = 12ppkWh, C_2 = 0.0358£/N, Cc = 0.01 and γ_p = 77008N/m³)

The results summarised in table 2 depict that by increasing the diameter of the pipeline, the saltation velocity and the total pressure drop within the pipeline decreases, whereas the FAD volumetric flow rate of the gas increases.

Table 2: Pipeline Saltation, Volumetric flow rate and Pressure Loss

Pipe Dia. (mm)	Saltation Velocity (m/s)	FAD Volumetric flow rate (m³/hr)	Total Pressure Drop (mBarG)
25	22.1	71	28570
50	19.9	257	4538
100	17.9	923	989
150	16.8	1953	432
200	16.1	3322	245
300	15.1	7026	113

Figure 1 depicts the cost breakdown against the pipe diameter with a trend line plotted on the total cost. It can be seen that as the pipe diameter increases, the cost of the compressor and the manufacturing cost of the pipeline increases, however, the cost of power consumption (operating cost) decreases. The decrease in the operating cost is due to the fact that for the same gas flow rate through the pipeline, when the pipe diameter increases, the volume of gas required to maintain the gas velocity increases, hence decreasing the operational cost of the pipeline. A local minima in the total cost of the pipeline is noticed at a pipe diameter of 115mm, which is the optimal pipeline diameter. Thus, the optimum pipe diameter based on capital and operational costs is 125mm diameter pipe.

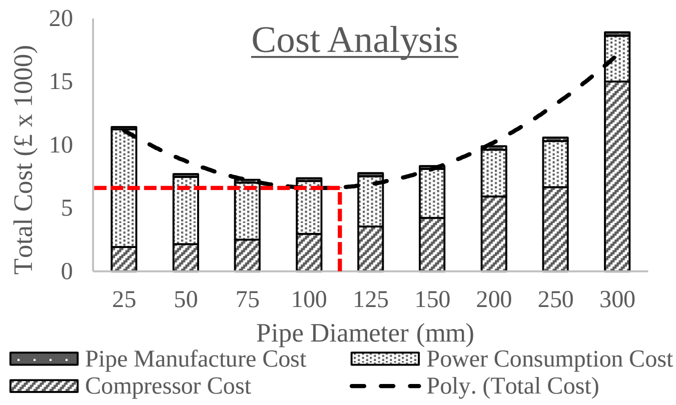

Fig.1 Predicted total cost

IX. CONCLUSIONS

The life-cycle cost methodology developed in this paper utilises theoretical calculations for the selection of an optimal pipe diameter in lean phase pneumatic conveying systems, transporting bulk solids. Utilising existing methodologies for the calculation of pressure and flow rates to calculate the operational cost through power consumption, combined with the cost of the pipe manufacture and compressor, this new methodology allows for an optimal pipe sizing to be selected on least cost principle. This can be achieved without the use of an expensive test facility.

REFERENCES

[1] Pneumatic conveying system market worth $30.67 billion by 2022: Grand view research, inc. (2015). PR Newswire Europe Including UK Disclose.

[2] Rizk, F. (1976). *Pneumatic conveying at optimal operation conditions and a solution of Bath's equation* (1st ed.). Bath, England: Proc Pneumotransport.

[3] Gomes, L.M. & Amarante Mesquita, A.L. (2014). On the prediction of pickup and saltation velocities in pneumatic conveying. *Brazilian Journal of Chemical Engineering. 31* (01), 35-46.

[4] Holdich, R. G. (2002). Fundamentals of particle technology. Shepshed, Leicestershire: Midland Information Technology and Publishing.

[5] Rhodes, M. (Ed.). (2008). Introduction to Particle Technology (2nd Edition). Chichester, GBR: Wiley. Retrieved from http://www.ebrary.com

[6] Agarwal, V. C., & Mishra, R. (1998). Optimal design of a multi-stage capsule handling multi-phase pipeline. International Journal of Pressure Vessels and Piping, 75(1), 27-35. doi:10.1016/S0308-0161(98)00003-9.