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Optimal Design of Capsule Transporting Pipeline carrying Spherical Capsules

Taimoor Asim, Rakesh Mishra and Kuldip Ubbi
School of Computing & Engineering,
University of Huddersfield,
Queensgate, Huddersfield HD1 3DH, UK

E-mail: taimoor.asim@hud.ac.uk, r.mishra@hud.ac.uk, k.s.ubbi@hud.ac.uk

Abstract. A capsule pipeline transports material or cargo in capsules propelled by fluid flowing through a pipeline. The cargo may either be contained in capsules (such as wheat enclosed inside sealed cylindrical containers), or may itself be the capsules (such as coal compressed into the shape of a cylinder or sphere). As the concept of capsule transportation is relatively new, the capsule pipelines need to be designed optimally for commercial viability. An optimal design of such a pipeline would have minimum pressure drop due to the presence of the solid medium in the pipeline, which corresponds to minimum head loss and hence minimum pumping power required to drive the capsules and the transporting fluid. The total cost for the manufacturing and maintenance of such pipelines is yet another important variable that needs to be considered for the widespread commercial acceptance of capsule transporting pipelines. To address this, the optimisation technique presented here is based on the least-cost principle. Pressure drop relationships have been incorporated to calculate the pumping requirements for the system. The maintenance and manufacturing costs have been computed separately to analyse their effects on the optimisation process. A design example has been included to show the usage of the model presented. The results indicate that for a specific throughput, there exists an optimum diameter of the pipeline for which the total cost for the piping system is at its minimum.

1. Introduction

In the third generation of transport pipelines, hollow capsules of spherical (or cylindrical) shapes are used to transport materials such as minerals, powders, medicines etc. These capsules are injected into the pipeline and are carried to the desired pumping station where special facilities are installed to filter out these capsules from the pipeline. Advantages of capsule pipelines listed by Agarwal and Mishra [1] are as given below:

- Separation of fluid and solid medium is not required
- Fluid is not contaminated
- Material reaches the destination in a dry state
- There are no traffic jams or accidents involved

Nomenclature

A	Sum of the coefficients of head loss in pipe fittings (1/m)
C_1	Levelized net annual cost of power consumption per unit watt (£/W)
C_2	Levelized net annual cost of pipes per unit weight of pipe materials (£/N)
C_3	Levelized net annual cost of the capsules per unit weight of the capsule material (£/N)
D	Pipe/Bend Diameter (m)
d	Capsule Diameter (m)
g	Acceleration due to gravity (m/s^2)
H	Head Loss (m)
k	Capsule to Pipe diameter ratio (-)
ρ	Density (kg/m^3)
L	Length of the test section (m)
N	Number of Capsules (-)
n	Number of pipe bends (-)
η	Pump efficiency (%)
Qc	Solid Throughput (m^3/sec)
Q	Total discharge rate (m^3/s)
ΔP	Pressure drop (Pa)
Re	Reynolds number (-)
γ	Specific weight (N/m^3)
μ	Dynamic viscosity (Pa.s)
V	Flow velocity (m/s)
t_c	Thickness of Capsule (m)
θ	Bend Angle (°)

Subscripts

p	Pipe	w	Water
b	Bulk	m	Mixture

Numerous experimental studies have recently been carried out by Ulusarslan and Teke [2-4] where they have developed empirical models for the prediction of pressure drop in spherical capsule transporting straight pipes and pipe bends. The capsule diameter being analysed by Ulusarslan and Teke was kept constant to 80% of the pipeline diameter. Furthermore, Asim et. al. [5] has developed a semi-empirical model for the pressure drop calculations in a straight pipeline carrying spherical capsules. The range of diameters of the capsules analysed by Asim et al. [5] were 60% to 80% of the pipeline diameter. This study incorporates the effect of the diameter of the capsules on the pressure drop in the pipe bends using Computational Fluid Dynamics techniques. Based on least-cost principle, a methodology has been developed to optimise the pipeline.

2. Optimisation Methodology

The design procedure for a spherical capsule transporting pipeline comprises the determination of that diameter of the pipeline and the associated fittings such as bends etc., for which the total cost is minimum. The total cost of the pipeline is the sum of the maintenance and manufacturing costs of the system. The step-by-step procedure of this methodology is discussed hereafter:

2.1. *Discharge Rates*

Capsule throughput (Qc) and the total discharge rate (Q) can be computed by the following expressions:

Capsule throughput;

$$Q_c = \frac{\pi d^2 V}{6} \tag{1}$$

Total Discharge rate;

$$Q = \frac{\pi D^2 V}{4} \tag{2}$$

2.2. *Major Head Loss*

Asim et. al. [5] developed a relationship for the determination of the pressure drop in a spherical capsule transporting horizontal pipeline. The relationship is:

$$\left(\frac{\Delta P}{L}\right)_m = \frac{\rho V^2}{2D} * \left[\left\{\frac{0.177}{{Re_w}^{0.2}}\right\} + \left\{\frac{((0.0032*N)-0.0011)}{{Re_c}^{0.2}} * e(7*k)\right\}\right] \tag{3}$$

Major head loss in a capsule transporting pipelines is due to the friction force between the capsule and the fluid and also between the adjacent layers of the fluid. It also accounts for the friction forces present between the pipe material and the fluid. Major head loss per unit length in terms of Qc can be computed using equation (4) as:

$$\frac{h_{major}}{L} = \frac{18{Q_c}^2}{\pi^2 g d^4 D} * \left[\left\{\frac{0.177}{{Re_w}^{0.2}}\right\} + \left\{\frac{((0.0032*N)-0.0011)}{{Re_c}^{0.2}} * e(7*k)\right\}\right] \tag{4}$$

2.3. *Minor Head Loss*

Using the results from the numerical simulations, a rigorous correlation has been developed for the pressure drop per unit length in spherical capsule carrying bends.

$$\left(\frac{\Delta P}{L}\right)_m = \frac{n\rho V^2}{2D} * f \tag{5}$$

Where the friction factor can be expressed as:

$$f = \left\{\frac{(0.06 * Sin\theta)+0.177}{{Re_w}^{0.2}}\right\} + \left[\{(0.0025 * N) + (0.0014 * Sin\theta) - 0.0021\} * \frac{e\,(7.5*k)}{{Re_c}^{0.2}}\right] \tag{6}$$

Minor losses are present in the pipelines due to different factors such as pipe bends etc. Minor head loss per unit length in terms of Q_c can be computed from equation (1) as:

$$\frac{h_{minor}}{L} = \frac{18{Q_c}^2 n}{\pi^2 g d^4 D} * f \tag{7}$$

2.4. *Total Head Loss*

Total head loss in the capsule pipeline is the sum of the head loss due to pipes (major head loss) and the pipe fittings (minor head loss). The total head loss thus can be expressed as:

$$H = \frac{h_{major}}{L} + \frac{h_{minor}}{L} \tag{8}$$

Figure 1 shows the variation of total head loss as a function of a 45^{o} bend's diameter for two spherical capsules with k=0.8. The result indicates that as the diameter of the pipeline increases, the total head loss decreases. The drop in the total head loss from D = 0.08 to 0.09 m is 65% as compared to D = 0.18 to 0.2 m which is 40%. The sharp decrease in the slope of the plot suggests that although the head loss decreases with increasing pipeline diameter, the change in the decrease of the head loss becomes smaller at higher high pipeline diameters.

2.5. *Pumping Power*

The power required per pumping unit can be computed using the following expression:

$$Power = \frac{\gamma_m Q H}{\eta} \tag{9}$$

Where the specific gravity of the mixture can be computed as:

$$\gamma_m = \rho_m \, g \tag{10}$$

Note that the capsules under consideration have the same density as that of the carrier fluid.

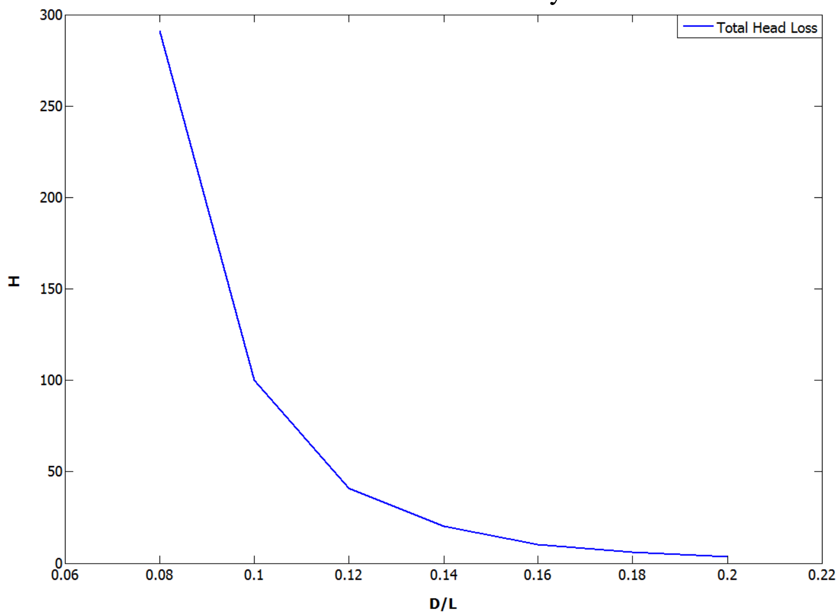

Figure 1. Variation of total head loss in a spherical capsule carrying 45^{o} hydraulic bend for a solid throughput of 50 kg/sec, or Qc=0.05 m3/sec, for capsule to pipe diameter ratio of k = 0.8.

2.6. *Maintenance Cost*

Maintenance cost corresponds to the cost involved in pumping the capsules and the carrier fluid in the pipe and the bends. Pumping power based on levelized net annual cost of power consumption per unit watt can be expressed as follows:

$$C_{Power} = C_1 * Power \tag{11}$$

2.7. *Manufacturing Cost*

The manufacturing cost for the capsule pipeline consists of the cost involved in the manufacturing of the pipeline (including bends) and the cost of the capsules.

2.7.1. Cost of Pipes. Cost of the pipes based on C_2 and C_c, where C_c is a constant of proportionality dependent on expected pressure and diameter ranges of pipe, can be computed from the following expression:

$$C_{Pipe} = \pi D^2 \rho g C_2 C_c \tag{12}$$

2.7.2. Cost of Capsules. Cost of N number of capsules, having a wall thickness of t_c, based on levelized net annual cost of the capsules per unit weight of the capsule material can be computed using the expression:

$$C_{Capsule} = \pi N k D \rho g t_c C_3 \tag{13}$$

2.8. *Total Cost*

The total cost is the sum of the maintenance cost and the manufacturing cost of the pipeline.

$$C_{Total} = C_{Maintenance} + C_{Manufacturing} \tag{14}$$

The maintenance cost corresponds to the cost of pumping power whereas the manufacturing cost accounts for the manufacturing of the pipe and the capsules. Hence, the total cost can also be expressed as:

$$C_{Total} = C_{Power} + \left(C_{Pipe} + C_{Capsule}\right) \tag{15}$$

$$C_{Total} = \frac{\gamma_m QHC_1}{\eta} + \pi D^2 \rho g C_2 C_c + \pi N k D \rho g t_c C_3 \tag{16}$$

Equation (16) accounts for the total cost of the capsule transporting pipeline system which includes the pipes and the associated fittings. Figure 2 shows the variations in various costs involved in the capsule transporting pipeline w.r.t. pipeline diameter for the case where Qc=0.05 m^3/s, number of spherical capsules is 2, diameter of the capsules is 80% of the pipeline diameter and a single bend of 45º. The maintenance cost has a trend similar to that of the total head loss i.e. as the pipeline diameter increases the maintenance cost decreases. This is due to the fact that for the same solid throughput in a pipeline an increase in the pipeline diameter will result into the decrease of the flow velocity inside the pipeline. As it can be clearly seen from equation (3) that the pressure drop, and hence the head loss, in a capsule transporting pipeline has a direct relation with the flow velocity, a decrease in the flow velocity will result in decrease in the total head loss.

Figure 2 further suggests that the manufacturing cost increases as the pipeline diameter increases. This is due to the fact that the pipes and associated pipe fittings of larger diameters are more expensive. The results presented here are in accordance with the current market price of PVC pipes and fittings. It can be seen that at a particular pipeline diameter, the total cost of the capsule transporting pipeline is at its minimum. This pipeline diameter corresponds to the optimal diameter of the pipeline for which the total cost involved is minimum.

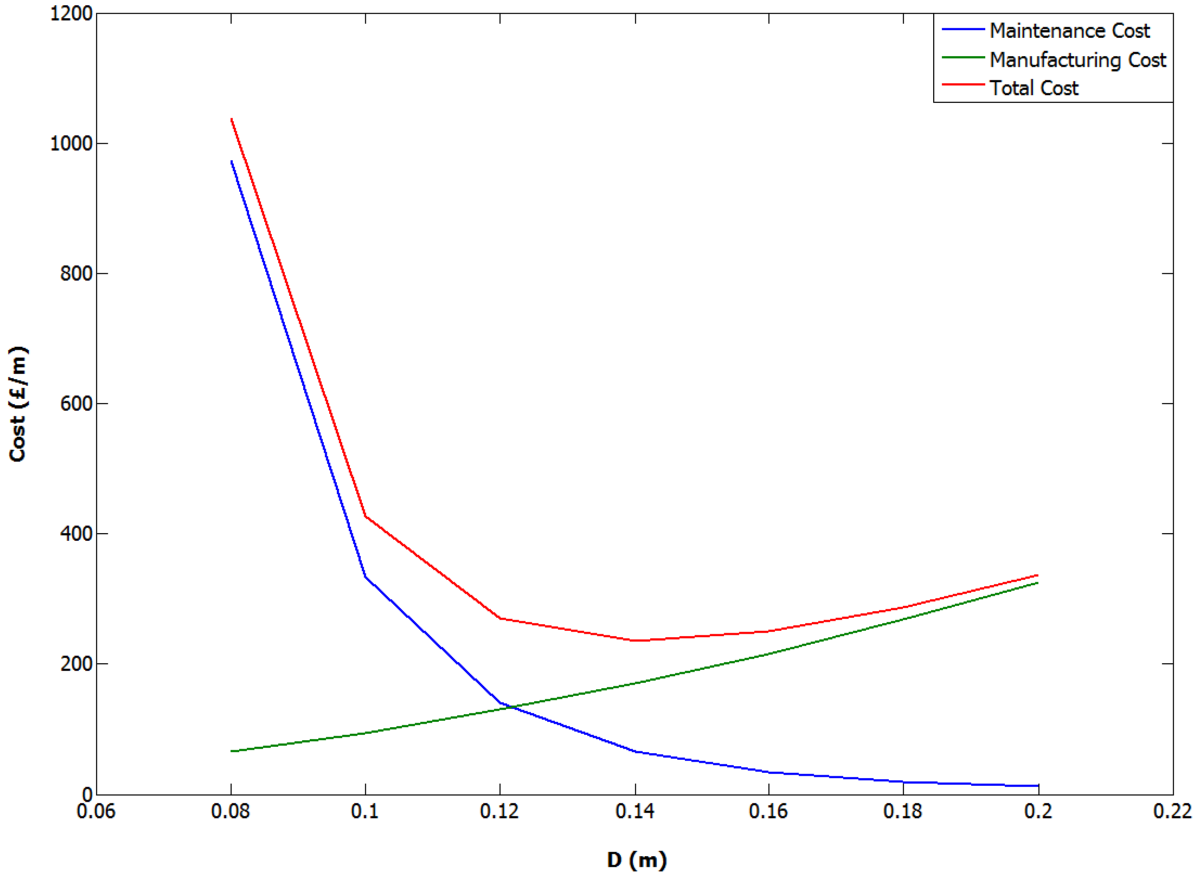

Figure 2. Variations in pipeline costs w.r.t pipeline's diameter.

3. Design Example

Find out the optimum diameter of the pipeline consisting of a horizontal pipe and a 45° bend for a solid throughput of 5, 10, 15, 20 and 25 Kg/sec. Use the following data to calculate total head loss as well:

Pump Efficiency = 60%	C_1 = 1.1 £/W
Capsule's thickness = 10mm	C_2 = 1.1 £/N
k = 0.8	C_3 = 1.1 £/N
Number of Capsules = 2	C_c = 0.2

The values for the cost coefficients have been taken from different sources. However, the current market values should be used in designing the pipeline.

3.1. Solution

Using the methodology described the results in figure 3 and table 1 show the variations in the optimal diameter of the pipeline and flow velocity for various solid throughputs. Figure 3 shows that as the solid throughput in the capsule transporting pipeline increases, the optimal diameter increases. Furthermore, as the solid throughput increases, the flow velocity increases. These results can be used as a design chart for the optimal designing of a spherical capsule transporting hydraulic pipeline consisting of the pipes and the associated pipe fittings.

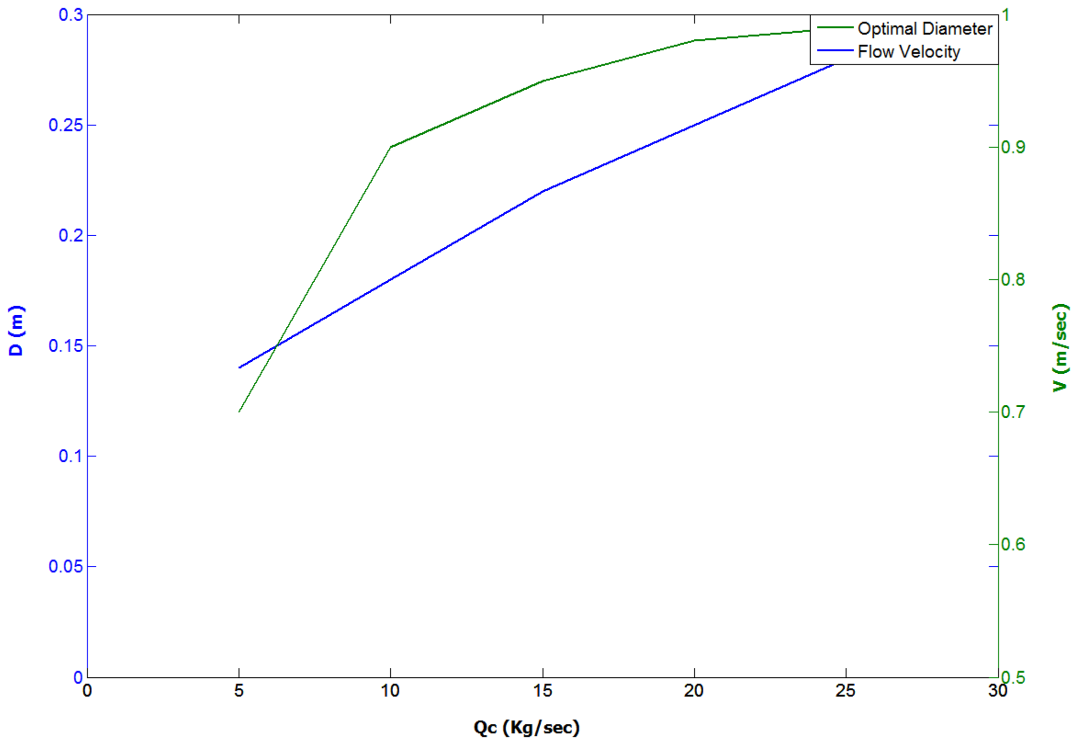

Figure 3. Variation in optimal diameter and flow velocity w.r.t. the solid throughput.

Table 1. Optimal diameter and the total cost variations.

Qc	D	V
(Kg/s)	(m)	(m/sec)
5	0.14	0.7
10	0.18	0.9
15	0.22	0.95
20	0.25	0.98
25	0.28	0.99

4. Conclusions

A versatile and robust methodology for the optimisation of capsule transporting pipelines has been presented here. Pressure drop correlations developed for equi-density spherical capsules in a hydraulically smooth pipeline and its associated bends have been used as the inputs to the model. Head losses, both major and minor, were then calculated based on these correlations. The individual costs involved in the manufacturing and the maintenance of the capsule transporting pipelines were calculated. The outputs of this model are the optimum diameter of the pipeline and the total cost involved. A design study has also been included to show the effectiveness of the model.

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