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Optimisation of a Horizontal Capsule Transporting Pipeline carrying Cylindrical Capsules

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Abstract. Pipelines carrying fluids and slurries are quite common. The third-generation pipelines carrying spherical or cylindrical capsules (hollow containers) filled with minerals or other materials including hazardous liquids are rather a new concept. These pipelines need to be designed optimally for commercial viability. An optimal design of such a pipeline results in minimum pressure drop in the pipeline. This corresponds to minimum head loss and hence minimum pumping power required to drive the capsules and the transporting fluid. This study uses a rigorous approach to predict pumping cost based on Computational Fluid Dynamics (CFD) and hence optimize the design of the capsule transporting pipelines. Pressure drop relationship developed has been incorporated to calculate the pumping requirements for the system. Based on the least-cost principle, a methodology has been developed for the determination of the optimal diameter of cylindrical capsule carrying hydraulic pipeline. This procedure can be applied to obtain the optimal size of the capsule pipeline for minimum pumping and capital costs.

1. Introduction

Cylindrical capsules have long been of interest for transportation purposes. Kroonenberg [1] developed a mathematical model based on the fact that friction factor in a capsule transporting pipeline increases due to the presence of solid phase in the pipeline. The mathematical model developed made use of the Moody's chart for the calculation of Darcy's friction factor. Recently, Khalil et. al. [2] has numerically modeled a cylindrical capsule in a horizontal pipeline and compared the results of pressure gradient and drag force on the capsule using different turbulence models. The results presented in both of these studies are for limited data sets. The present work focuses on the development of a design methodology for the determination of the optimal pipeline diameter at different throughput rates of the capsule. The flow in the vicinity of only one capsule has been considered in the present study.

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Nomenclature

A	Sum of the coefficients of head loss in pipe fittings (1/m)
a	Capsule to Pipe Length Ratio (-)
b	Capsule to Pipe Diameter Ratio (-)
C_1	Levelised net annual cost of power consumption per unit watt (£/W)
C_2	Levelised net annual cost of pipes per unit length of pipe materials (£/N)
C_3	Levelised net annual cost of the capsules per unit weight of the capsule material (£/N)
C_c	Constant of proportionality dependent on expected pressure and diameter range of Pipe [-]
D	Pipe Diameter (m)
d	Capsule Diameter (m)
f	Darcy Friction Factor (-)
g	Acceleration due to gravity (m/s^2)
h_{major}	Major head loss (m)
h_{minor}	Minor head loss (m)
H	Total Head Loss (meter of water / meter of pipe length)
L	Length of the test section (m)
ρ	Density (kg/m^3)
η	Pump efficiency (%)
Q	Total Flow Rate (m^3/sec)
Q_c	Solid Throughput (m^3/sec)
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)

Subscripts

p	Pipe	c	Capsule
m	Mixture	w	water

2. Optimisation Theory

The design procedure for a straight spherical capsule pipeline consists of the determination of the diameter of the pipeline such that the total cost should be at minimum. The total cost of the pipeline is the sum of the pumping, pipe and capsule costs.

2.1. Operational Cost

While designing a hydraulic pipeline in engineering practices, head loss calculations play a vital role in the selection of the pumping power, distance between the pumping stations and the optimisation of the complete pipeline system. Various correlations have been developed to account for the pressure drop in a capsule transporting pipeline.

2.1.1. Pressure Drop. The capsule velocity has been taken to be equal to the velocity of water as suggested by Ulusarslan [3]. The volumetric flow rate of the capsule (Q_c) and the total discharge rate (Q) can be computed by the following expressions

Capsule flow rate;

$$Q_c = \frac{\pi d^2 V}{4} \quad [1]$$

Total flow rate:

$$Q = \frac{\pi D^2 V}{4} \quad [2]$$

Using the results from the numerical simulations [4], a rigorous correlation has been developed for the pressure drop per unit length in cylindrical capsule carrying pipelines.

$$\left(\frac{\Delta P}{L_p}\right)_m = \frac{\rho V^2}{2D} * (f) \quad [3]$$

Where the friction factor f can be computed as:

$$f = \left[\left\{\frac{0.177}{Re_w{}^{0.2}}\right\} + \left\{(0.012a - 0.004) * \frac{e(9b)}{Re_c{}^{0.2}}\right\}\right] \quad [4]$$

2.1.2. Head Loss. Head loss is the reduction in the total head of the fluid as it moves through a fluid system. Pressure drop can be expressed as head loss. There are two major types of head losses:

1. Major Head Losses
2. Minor Head Losses

Major head loss in the 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 in a pipeline can be computed as:

$$h_{major} = \frac{f L_p V^2}{2gD} \quad [5]$$

Substituting *V* in terms of Q_c, the equation for the major head loss per unit pipe length is obtained:

$$\frac{h_{major}}{L_p} = \frac{8 Q_c{}^2}{\pi^2 g D d^4} * \left[\left\{\frac{0.177}{Re_w{}^{0.2}}\right\} + \left\{(0.012a - 0.004) * \frac{e(9b)}{Re_c{}^{0.2}}\right\}\right] \quad [6]$$

Minor losses are present in the pipelines due to different factors such as pipe bends etc. Minor head loss per unit length of the pipeline, in terms of Q_c, can be expressed as follows:

$$h_{minor} = \frac{A L_p V^2}{2g} \quad [7]$$

Where *A* is the sum of coefficients of head loss in various pipe fittings being installed in the pipeline. Note that *A* is a function of the pipeline diameter and the range of operational pressures in the pipe.

$$\frac{h_{minor}}{L_p} = \frac{8{Q_c}^2 A}{\pi^2 g d^4} \qquad [8]$$

Total head loss in the capsule pipeline than can be computed as:

$$H = \frac{h_{major}}{L_p} + \frac{h_{minor}}{L_p} \qquad [9]$$

Substituting the values of major and minor head losses per unit pipe length from equations (5) and (7) into equation (9), the total head loss in the pipeline due to carrier fluid, capsule and the pipe fittings can be computed. The total head loss in the pipeline dictates the choice of the pumping unit for the pipeline.

As can be seen in equation (5), pipeline diameter has an inverse relationship with the major head loss in the pipeline. Hence, increase in the pipeline diameter decreases the head loss and vice versa. Figure 1 depicts the typical variations of total head loss as a function of the pipeline diameter for cylindrical capsule transporting pipelines. The curve indicates that as the diameter of the pipeline increases, the total head loss decreases. The percentage decrease in the head loss from 0.06m pipe diameter to 0.07m is 51% while the percentage decrease in the head loss from a pipe diameter of 0.12m to 0.13m is 26%.

2.2. Least Cost based Optimisation

While designing a capsule transporting pipeline, the optimisation parameter that needs to be considered is the total cost of the pipeline including the manufacturing cost of the capsule. Based on the pressure drop correlation and considering the market price of the materials, a robust formulation of total cost optimisation is presented here.

2.2.1. Pumping Power. The power required per pumping unit can be computed using the following expression:

$$Power = \frac{\gamma_m Q H}{\eta} \qquad [10]$$

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

$$\gamma_m = \rho_m\, g \qquad [11]$$

As the capsule under consideration has the same density as that of its carrier fluid, the density of the mixture is the same as that of the capsule.

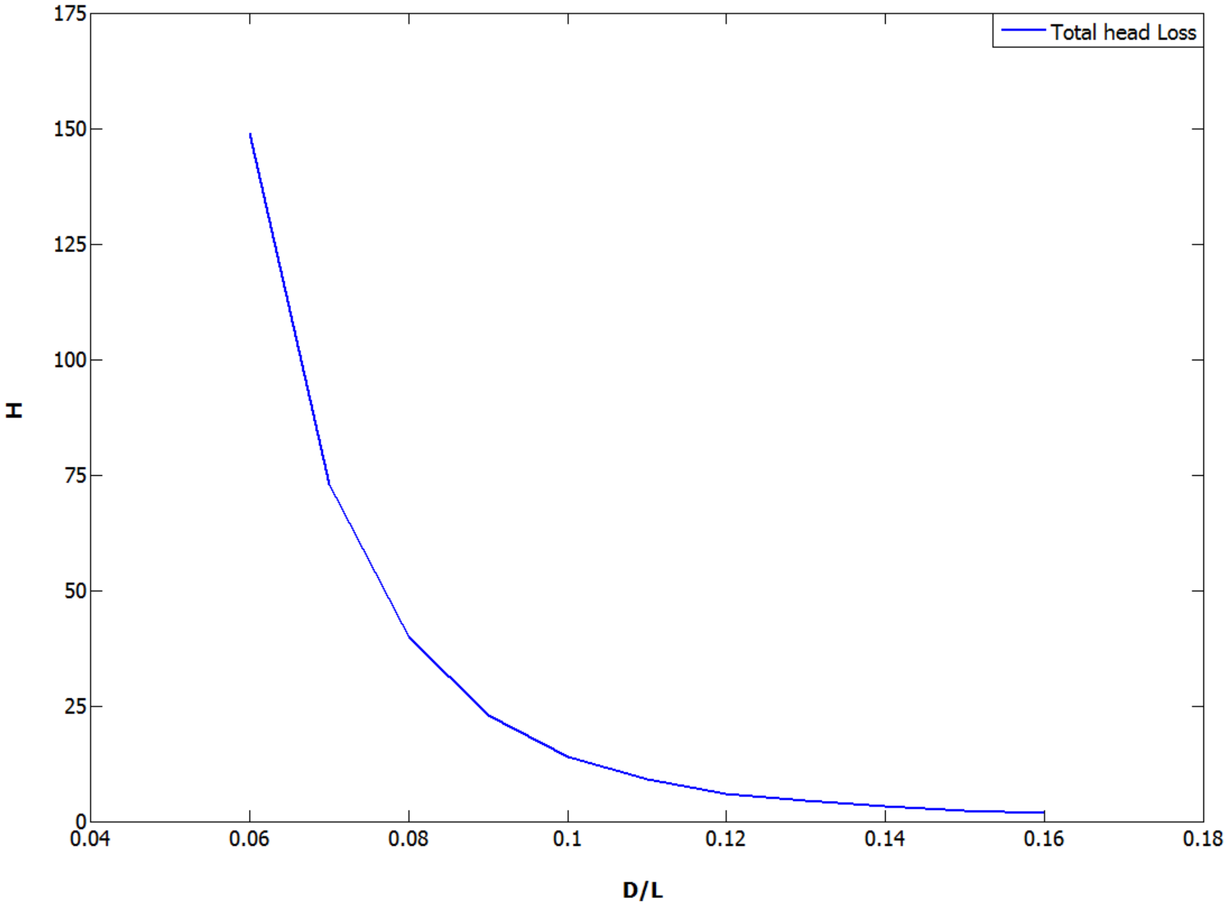

Figure 1. Variation of total head loss in a cylindrical capsule carrying hydraulic pipeline for a solid throughput of 50 kg/sec, or Qc=0.05 m^3/sec, for capsule to pipe diameter ratio of b = 0.8.

2.2.2. Cost of Pumping Power. Cost of the pumping power based on the levelised net annual cost of power consumption per unit watt C_1 can be expressed as follows:

$$C_{Power} = C_1 * Power \qquad [12]$$

or:

$$C_{Power} = C_1 * \frac{\gamma_m Q H}{\eta} \qquad [13]$$

2.2.3. Cost of Pipes. Cost of the pipes based on the levelised net annual cost of pipes per unit length of pipe materials C_2 and the constant of proportionality dependent on expected pressure and diameter range of the pipe C_c, can be computed from the following expression:

$$C_{Pipe} = \pi D^2 \rho g C_2 C_c \qquad [14]$$

2.2.4. Cost of Capsules. Cost of the capsule based on the levelised net annual cost of the capsules per unit weight of the capsule material C_3, can be computed using the expression:

$$C_{Capsule} = \pi k D \rho g t_c C_3 \quad [15]$$

2.2.5. Total Cost: The total cost then would be:

$$C_{Total} = C_{Maintenance} + C_{Manufacturing} \quad [16]$$

$$C_{Total} = C_{Power} + \left(C_{Pipe} + C_{Capsule}\right) \quad [17]$$

Figure 2 shows the variations in maintenance, manufacturing and total costs w.r.t. pipeline diameter at a solid throughput of 5kg/sec for a capsule to pipe diameter ratio of 0.8.

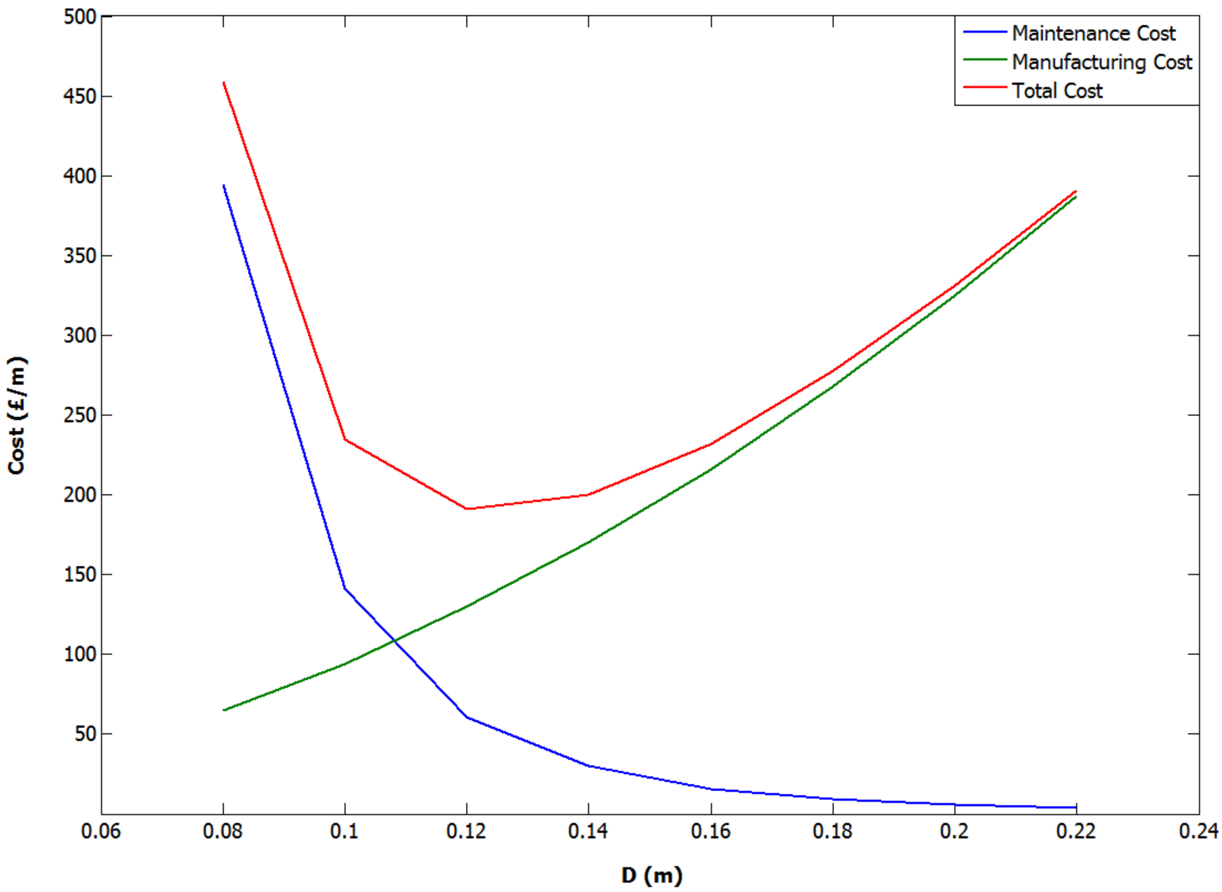

Figure 2. Variation of various costs w.r.t. the pipeline diameter.

It can be seen in figure 2 that as the diameter of the pipeline increases, the maintenance cost decreases. This is due to the fact that for the same solid throughput, increase in the pipeline diameter decreases the velocity of the flow. It can also be seen in figure 2 that as the pipeline diameter increases, the manufacturing cost increases. This is due to the fact that the pipes of larger diameters have a higher market price than the ones of smaller diameters. Furthermore, in order to keep the ratio of the capsule to pipe diameter same, the capsule size increases which accounts for the increase in the cost of the capsule. This adds to the increase in the manufacturing cost of the system.

It can be seen in figure 2 that the total cost curve shows a minimum value at 0.12m pipeline diameter. This corresponds to the optimal diameter of the pipeline.

3. Design Example

What is the optimum diameter of the pipeline consisting of a cylindrical capsule for a throughput of 5, 10, 15, 20 and 25 kg/sec using the following data?

Pump Efficiency = 60%	C_1 = 5.5 £/W
Capsule's thickness = 10mm	C_2 = 1.1 £/N
Capsule to pipe diameter ratio = 0.8	C_3 = 1.1 £/N
Length of Capsule = 0.5m	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

Figure 3 shows the variation in optimal pipeline diameter and flow velocity in the pipeline for the solid throughputs mentioned. It can be seen that as the solid throughput in the pipeline increases, the optimal diameter, which corresponds to the minimum total cost of the pipeline system, increases. Furthermore, as the solid throughput increases, the flow velocity increases. This plot can be used as a design chart for the optimal designing of horizontal pipelines carrying water and cylindrical capsules. Table 1 summarises the results presented in figure 3.

Table 1. Variations in the optimal diameter and flow velocity in the pipeline for different solid throughputs.

Solid Throughput	**Optimal Diameter of the Pipeline**	**Flow Velocity**
(Kg/sec)	**(m)**	**(m/sec)**
5	0.12	0.5
10	0.17	0.68
15	0.2	0.74
20	0.23	0.75
25	0.25	0.79

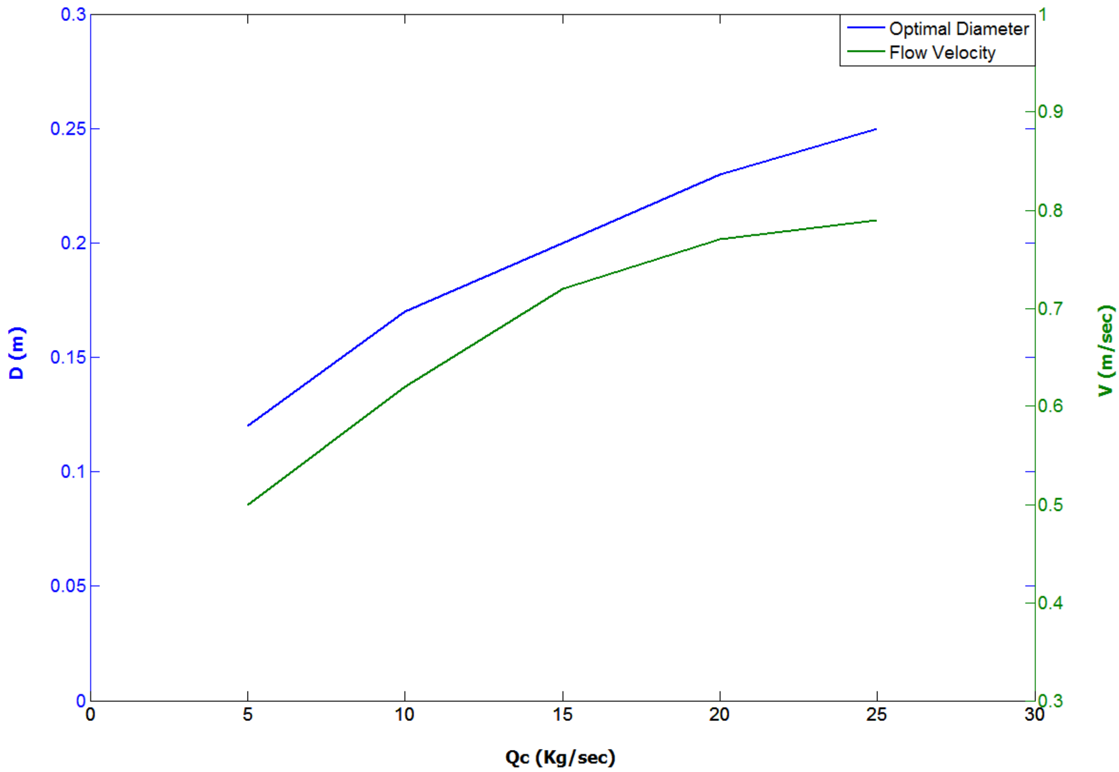

Figure 3. Variation of optimal diameter and the flow velocity w.r.t. the solid throughput.

4. Conclusions

A versatile and robust methodology for the optimisation of capsule transporting hydraulic pipelines has been presented here. Pressure drop correlation for equal density spherical capsule in a pipe has been developed. From this correlation, head losses, maintenance, manufacturing and total costs of the pipeline can be computed for any diameter and number of capsules. The methodology and the model developed for the calculation of pressure drop in the pipeline covers a wide range of important flow and geometric parameters.

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