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Optimisation of a Capsule Transporting Pipeline Carrying Spherical Capsules

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Pipelines carrying fluids and slurries are very 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. Researchers, so far, have used rather simplified empirical and semi-empirical methods for optimisation purposes, the range and application of which is fairly limited. This study uses a rigorous approach to predict pumping cost based on Computational Fluid Dynamics (CFD) analysis and hence optimise capsule pipelines. A numerical solution has been obtained for pressure drop from the equations governing the turbulent flow around a concentric spherical capsule train consisting of 1–4 equal density capsules in a hydraulically smooth pipe section. The diameter of the pipe used in the analysis is 0.1m while the capsules' diameters are in the range of 50 to 80% of the pipe diameter. The investigation was carried out in the practical range of 0.4 ≤bulk velocity≥ 1.6 m/sec. Obtained results of pressure gradient along the pipeline in presence of capsules were compared with the available experimental data to validate the model used. The results predicted by the model agree well with the experimental data. The computationally obtained data over a wide range of flow conditions has then been used to develop a rigorous model for pressure drop. The pressure drop along the pipe can be used to calculate the pumping requirements and hence design of the system. The least cost principle has been used for optimisation.

Keywords— **Spherical Capsules, Bulk Velocity, Computational Fluid Dynamics (CFD), Head Loss, Pressure Drop, Maintenance Cost, Manufacturing Cost, Optimisation**

Nomenclature

A	Sum of the coefficients of head loss in pipe fittings
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 (£/m)
C_3	Levelised net annual cost of the capsules per unit weight of the capsule material (£/N)
D	Pipe Diameter (m)
d	Capsule Diameter (m)
ε	Pipe surface roughness (m)
f	Friction Factor
g	Acceleration due to gravity (m/s^2)
H	Head Loss (m)
k	Diameter ratio of capsule to pipe (d/D)
ρ	Density (kg/m^3)
L	Length of the test section (m)
N	Number of Capsules
η	Pump efficiency (%)
Q	Discharge rate or throughput
ΔP	Pressure drop (Pa)
Re	Reynolds number
γ	Specific weight (N/m^3)
μ	Dynamic viscosity (Pa.s)
V	Velocity (m/s)
t	Thickness (m)

Subscripts

p	Pipe
b	Bulk
w	Water
c /cap.	Capsule
m	Mixture

I. 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:

1. Separation of fluid and solid medium is not required
2. There is no contact between the solid and the fluid phases
3. Fluid is not contaminated
4. Material reaches the destination in a dry state
5. Capsule pipelines are more economical than slurry pipelines

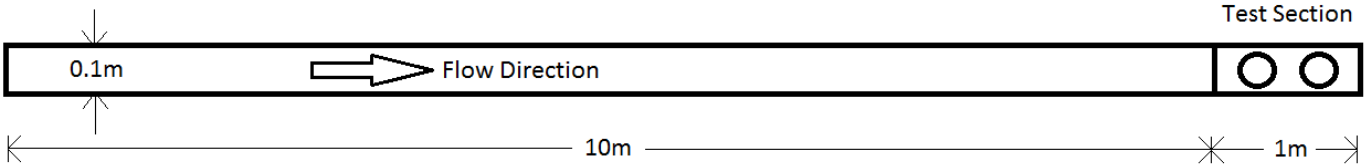

Fig. 1 Geometrical setup of the Capsules in the Pipeline

A model has been developed here, based on least-cost principle for optimal sizing of the capsule pipeline.

II. Numerical Solution

Commercial CFD package FLUENT has been used to obtain the pressure drop in the capsule carrying pipeline. A hydrodynamically smooth (i.e. $\varepsilon/D = 0$) test section similar to that of Ulusarslan and Teke [2] has been numerically modelled for L= 1m and D = 0.1m. According to Munson and Young [3], the minimum criterion to obtain a fully developed flow is 50*D; hence an additional pipe length of 100*D has been introduced before the test section. Capsules of various sizes i.e. d = 0.05, 0.06, 0.07 and 0.08m are introduced in the test section. Pressure drop investigations have been carried out in bulk velocities range of $V_b = 0.4–1.6$ m/s. Capsules trains with capsule numbers N = 1–4 have been used to carry out the analysis. Fig. 1 shows the geometrical setup for the case of N = 2 and d = 0.08m. Following assumptions have been made to solve the equations governing the turbulent flow in the capsule carrying pipeline:

1. Flow is steady
2. Capsule velocity has been taken to be equal to the velocity of water i.e. $V_w = V_c = V$ as suggested by Ulusarslan [4]
3. The pressure drop can be computed using a single phase method for the bulk velocity V_b=V
4. Capsules are made of polypropylene material which has the same density as water i.e. $\rho_w = \rho_c = \rho$

III. Optimisation Theory

The design procedure for a straight spherical capsule pipeline comprises 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.

A. *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. Various correlations have been developed to account for the pressure drop in a capsule transporting pipeline.

1) Pressure Drop: Using the aforementioned assumptions, the capsule throughput rate (Q_c), water discharge rate (Q_w) and the total discharge rate (Q) can be computed by the following expressions:

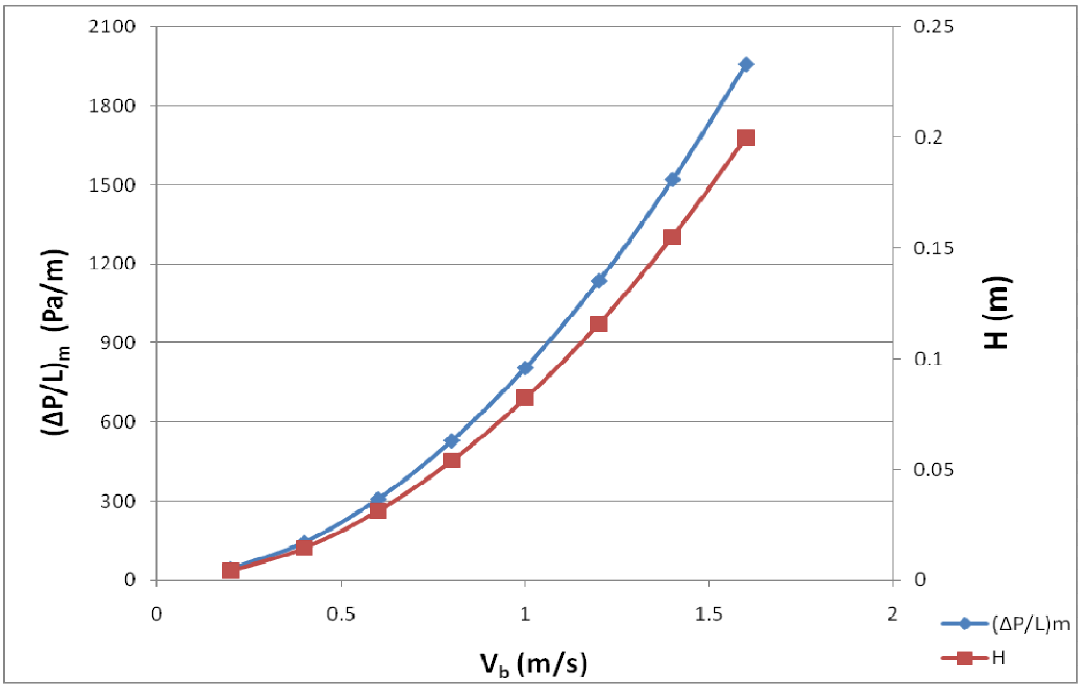

Fig. 2 Variation of Pressure Drop and Head Loss at different Bulk Velocities

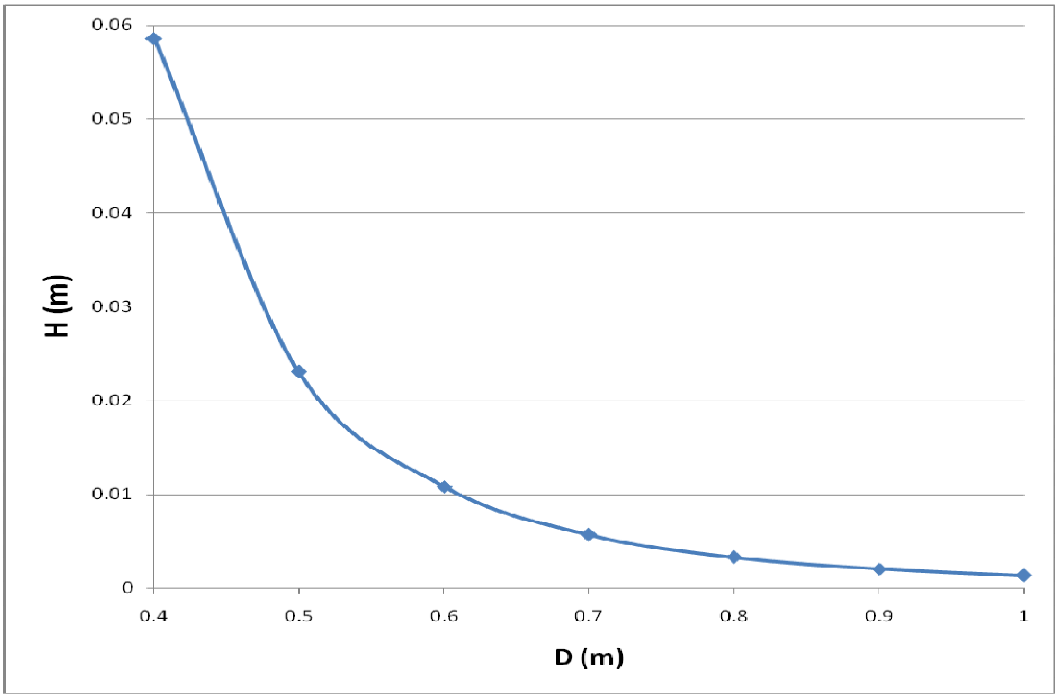

Fig. 3 Variation of Total Head Loss as a function of Pipeline diameter

Capsule throughput rate;

$$Q_c = \frac{\pi k^2 D^2 V}{6} \qquad [1]$$

Water discharge rate;

$$Q_w = \frac{\pi D^2 V}{4} \qquad [2]$$

Total Discharge rate;

$$Q = Q_c + Q_w = \frac{\pi D^2 V}{12} * (2k^2 + 3) \qquad [3]$$

Fig. 2 shows the variations in the pressure drop and the head loss in hydraulic capsule pipeline for the case shown in Fig. 1. The result shows that as the bulk velocity of the mixture increases, the pressure drop and the head loss in the pipeline increases exponentially. Using the results from numerical simulations, a rigorous correlation has been developed for the pressure drop per unit length in a spherical capsule pipeline.

$$(\frac{\Delta P}{L})_m = \frac{\rho V^2}{2D} * f \qquad [4]$$

Where;

$$f = \left\{ \left(\frac{0.177}{Re_w^{0.2}} + \frac{(0.0032N - 0.0011)\, e^{7K}}{Re_c^{0.2}} \right) \right\} \qquad [5]$$

Where the Reynolds number of water is expressed as:

$$Re_w = \frac{\rho D V}{\mu} \qquad [6]$$

And the Reynolds number of capsules is calculated by:

$$Re_c = \frac{\rho d V}{\mu} \qquad [7]$$

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 per unit length in terms of Q_c can be expressed as follows:

$$\frac{h_{Major}}{L} = \frac{18 Q_c^2}{\pi^2 g k^4 D^5} * f \qquad [8]$$

Minor losses are present in the pipelines due to different factors such as fittings used in the pipelines, bends, sudden expansions or contractions etc. General relationship for minor head loss per unit length in terms of Q_c can be expressed as follows:

$$\frac{h_{Minor}}{L} = \frac{18Q_c^2 A}{\pi^2 g L k^4 D^4} \quad [9]$$

Where A is a constant representing the sum of the coefficients of head loss in pipe fittings etc. Total head loss in the capsule pipeline can be computed as:

$$H = h_{Major} + h_{Minor} = \left(\frac{18Q_c^2 L}{\pi^2 g k^4 D^5} * f\right) + \frac{18Q_c^2 A}{\pi^2 g k^4 D^4} \quad [10]$$

Fig. 3 shows the variation of total head loss as a function of the pipeline diameter at Q_c=0.05m^3/s for the case shown in Fig. 1. The results indicate that as the diameter of the pipeline increases, the total head loss decreases. The drop in the total head loss from D=0.4 to 0.5m is 150% as compared to D=0.9 to 1m which is 50%.

B. 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 capsules Based on the pressure drop correlation and considering the market price of the materials, a robust formulation of total cost optimisation is presented here.

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

$$Power = \frac{\gamma_m Q H}{\eta} \quad [11]$$

$$Power = \frac{\pi \rho g V D^2}{12\eta} * (2k^2 + 3) * H \quad [12]$$

2) Cost of Pumping Power: Cost of the pumping power based on C_1 can be expressed as follows:

$$C_{Power} = C_1 * \frac{\gamma_m Q}{\eta} * \left(\frac{h_{Major}}{L} + \frac{h_{Minor}}{L}\right) \quad [13]$$

$$C_{Power} = \frac{C_1 \pi \rho g V D^2 * (2k^2 + 3)}{12\eta} * \left\{\left(\frac{18Q_c^2}{\pi^2 g k^4 D^5} * f\right) + \frac{18Q_c^2 A}{\pi^2 g L k^4 D^4}\right\} \quad [14]$$

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

$$C_{Pipe} = \pi D^2 \rho g C_2 C_c \quad [15]$$

4) Cost of Capsules: Cost of the capsules based on C_3 can be computed using the following expression:

$$C_{Cap.} = \pi k D \rho g t_c C_3 \quad [16]$$

5) Total Cost: The total cost than would be:

$$C_{Total} = C_{Maintenance} + C_{Manufacturing} \quad [17]$$

$$C_{Total} = C_{Power} + (C_{Pipe} + C_{Cap.}) \quad [18]$$

$$C_{Total} = \left[\frac{C_1 \pi \rho g V D^2 * (2k^2 + 3)}{12\eta} * \left\{\left(\frac{18Q_c^2}{\pi^2 g k^4 D^5} * f\right) + \frac{18Q_c^2 A}{\pi^2 g L k^4 D^4}\right\}\right] + \pi D^2 \rho g C_2 C_c + \pi k D \rho g t_c C_3 \quad [19]$$

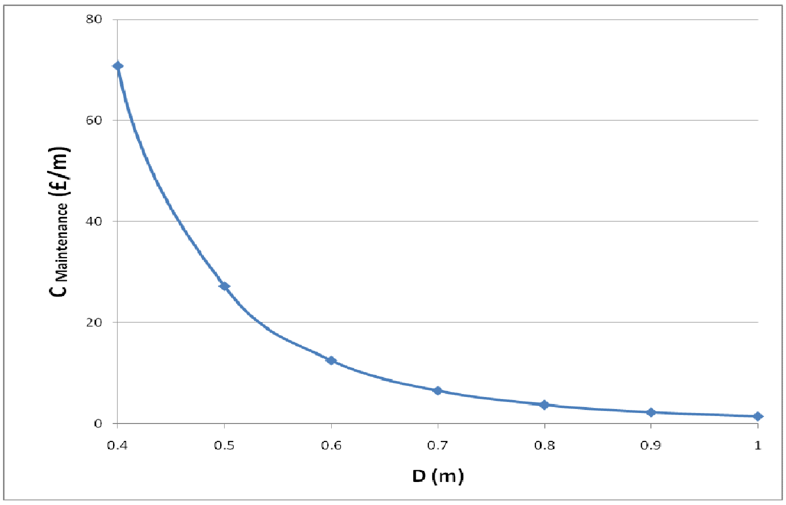

Fig. 4 Variation of Maintenance Cost as a function of Pipeline diameter

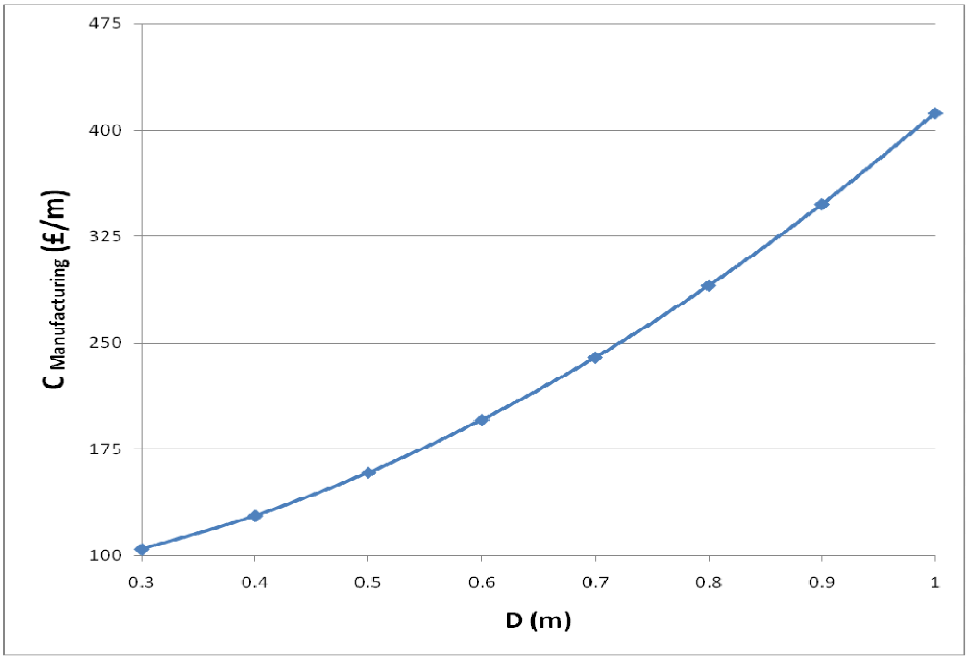

Fig. 5 Variation of Manufacturing Cost as a function of Pipeline diameter

IV. Design Example

At Q_c=0.05m^3/s for the case shown in Fig. 1, what is the effect of the hydraulic pipeline's diameter on the maintenance, manufacturing and total costs using the following parameters:

$\eta = 65\%$
$C_1 = 8$ £/W
$C_2 = 1.1$ £/m
$C_3 = 12$ £/N
$C_c = 0.01$
$t_c = 10$mm

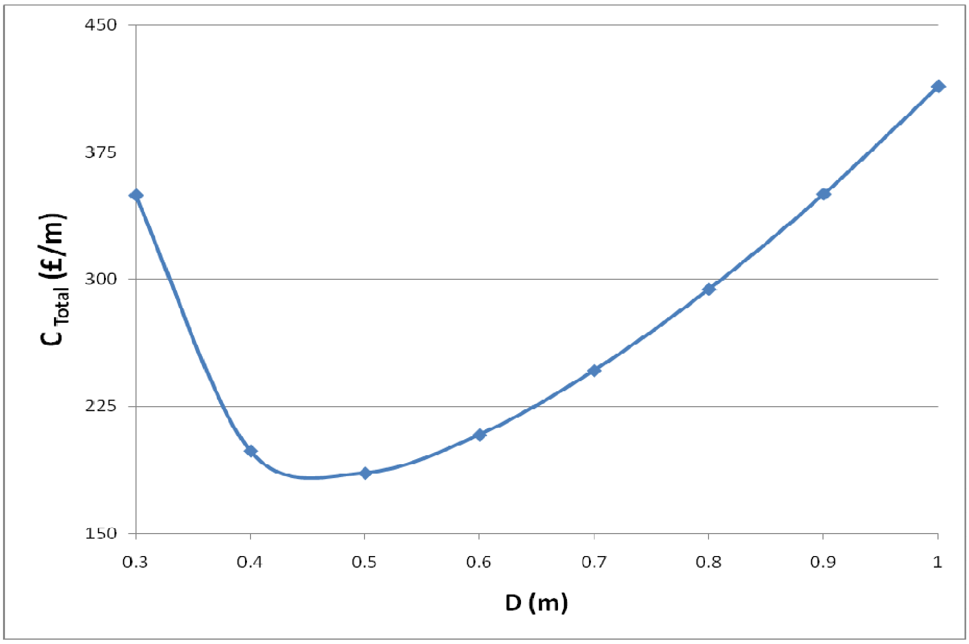

Fig. 6 Variation of Total Cost as a function of Pipeline diameter

TABLE I
HEAD LOSS AND COSTS OF HYDRAULIC CAPSULE PIPELINE

D (m)	H (m)	$C_{Maintenance}$ (£/m)	$C_{Manufacturing}$ (£/m)	C_{Total} (£/m)
0.3	0.196	245.2	104.2	349.5
0.4	0.058	70.82	127.9	198.7
0.5	0.023	27.25	158.4	185.6
0.6	0.010	12.55	195.6	208.1
0.7	0.005	6.544	239.6	246.1

A. Solution

Fig. 4-6 shows the variation of maintenance, manufacturing and total costs as a function of the pipeline's diameter. Fig. 4 indicates that at lower pipeline diameters, the maintenance cost is significantly higher. As the pipeline diameter increases, the maintenance cost decreases. Fig. 5 shows that as the pipeline diameter increases, the manufacturing cost, as expected, increases due to more material being used for the pipeline and the capsules. Fig. 6 shows that at lower pipeline diameters the total cost is significantly higher and it decreases as the pipeline diameter increases. At a specific pipeline diameter, the total cost reaches its minimum value after which, as the pipeline diameter increases, the total cost again increases.

That pipeline diameter, for which the total cost is at its minimum, is the optimum diameter for the hydraulic capsule pipeline. Table I summarises the Total Head Loss and the costs involved in designing the hydraulic capsule pipeline for some of the pipeline diameters. The table clearly shows that the optimum pipeline diameter is 0.5m in this design example as its total cost is at minimum. Fig. 7 shows the variations in Total Head Loss and Total Cost of the hydraulic capsule pipeline as a function of Pipeline's diameter listed in Table I.

V. CONCLUSIONS

A versatile and robust method for the optimisation of capsule transporting pipelines has been presented here. Pressure drop correlation for equal density spherical capsule train in a hydraulic pipeline 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.

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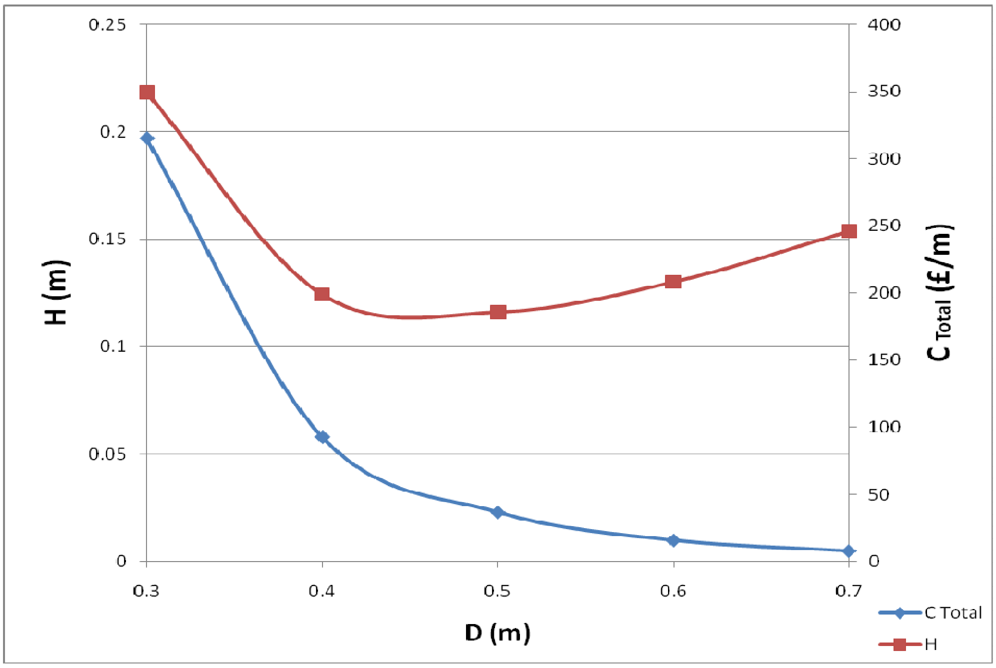

Fig. 7 Variation of Total Head Loss and Total Cost as a function of Pipeline diameter