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Optimal Sizing and Life-cycle Cost Modelling of Hydraulic Capsule Pipelines

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*Abstract_* **Estimation of the total cost is essential for the planning and the designing of pipelines in a cost-effective way. As a result, the total cost modelling could go beyond the established objectives of least-cost design and optimization. This study incorporates a design methodology for pipelines transporting spherical capsules, which have variant sizes and densities. A methodology has been developed to determine the optimal size and lifetime of pipelines transporting solid–liquid mixtures (Capsule Flow). The methodology includes a model for the prediction of various life-cycle costs. The methodology provides a closed form solution to predict the optimal pipe diameter corresponding to the least total cost. Such solutions are obtained for different life-cycle costs, of which the one associated with minimum annual total cost provides the lifetime. The developed methodology has been used to obtain the optimal diameter of a pipeline for a practical case. The study reveals the interrelationship between the optimal pipe diameter and the corresponding minimum total cost.**

Index Terms: **Computational Fluid Dynamics (CFD), Hydraulic Capsule Pipelines (HCP), Least-Cost Principle (LCP).**

I. INTRODUCTION

The pipeline that carries the solid-liquid mixture has practical significance for many industries. Minerals are often transported through pipelines in the oil and mining industries [1], [2], this type of transport also plays an important role in the nuclear industry in the treatment of radioactive waste [3]. In such pipes, the solids are transported together with the carrier liquid in crushed form. Compared to other methods of conveying bulk solids, these pipes have proven cost-effective, reduce traffic and accidental hazards, and are environmentally friendly. In the life cycle of a pipeline that carries a solid-liquid mixture (including capsule transportation), several cost factors affect the total cost, including manufacturing and maintenance costs and the cost of pumping power that requires an estimated head loss.

In traditional optimization procedures, these costs are only determined based on the flow parameters, without considering their changes throughout the life cycle of the pipe. However, some of these cost items vary greatly over time; therefore, they should be considered as time-related parameters. Another factor that is not considered in most design methods is the capsule size. The size of the capsule, as well as the diameter of the pipe and the flow velocity are the most important parameters, because their combination determines the state of the flow. At low flow velocities, pipes carrying solid-liquid mixtures have obvious concentration gradients and asymmetric velocity distributions. For the same solid output, this heterogeneous flow regime usually corresponds to a lower pressure drop value. At higher operating velocities, the velocity distribution becomes symmetrical [4]. In this case, the pressure drop value is usually higher [1]. Traditional techniques for fluid analysis and optimization of hydraulic piping have had only limited success in the process of designing piping for conveying solid and liquid mixtures (capsule flow). Albertson et al. [5] proposed a method in which they considered the initial investment cost of pipelines and pumps and their interest, annual operating and maintenance costs during the pipeline's service life, and the residual value of the pipeline. Hatout et al. [6] and Cheremisinoff et al. [7] developed an optimization methodology in which some mathematical functions had been represent for the total annual cost of pipelines, the cost of pumps, and the cost of energy used to transport fluids. Franzini and others [8] found that the total annual cost of pipes carrying fluids is based on a linear combination of the power function of the pipe diameter; but it also depends on the coefficient of friction included in the analysis as a function of the Reynolds number and roughness of the pipe. Swamee [9] proposed an optimal sizing method for pipes for the transport of solid-liquid mixtures. He considered the functional form of the cost of pumping and the cost of the pipeline system. Agarwal & amp; Mishra [10] proposed a method to optimize multiphase pipe size in capsule processing.

Taking into account the cost of pumping power, the cost of the pipes and the cost of the capsule, the optimal size corresponds to the lowest total cost. In [11], a similar method was developed to determine the size of pipes carrying equilibrium solid-liquid mixtures. Estimating life cycle costs is essential for timely planning of pipeline

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replacement in a cost-effective manner. Therefore, life cycle cost calculation and life cycle management exceed the strict minimum cost optimization and design goals. Fillion et al. [12] carried out a life cycle energy analysis to quantify the energy costs incurred at each stage of the life cycle. Their analysis helps to select the pipeline replacement strategy that is relevant to the lowest cost. Pandey et al. [13] proposed a probabilistic corrosion loss model based on wall thickness measurement data and estimated the pipeline life distribution. The current work incorporates a pipeline design method that transports a mixture of solids and liquids with solid particles (capsules) of various sizes.

To this end, functional relationships have been developed for various cost elements that appear in the pipeline life cycle. These factors include pumping energy costs, pipe fabrication costs, and pipe maintenance costs. The model takes into account changes in pumping costs and pipeline maintenance costs over time. A solution has been proposed that gives a useful life related to the lowest annual cost and obtains the best pipe diameter at the lowest total cost throughout the entire life cycle. Finally, a practical example of design is presented, revealing the variation of the optimum diameter of the pipe with the capsule size and the specific gravity of the capsule material. Since maintenance costs are not considered when estimating the total cost, the conventional optimization models are limited. In addition, the expressions of friction coefficient and loss coefficient in this study include starting energy requirements. Startup has been considered by averaging the pressure drop during the movement of the capsule from a stationary state to a constant flight phase.

II. MATHEMATICAL MODELLING

The total cost consists, shown in Equation (1), of the costs of operating and pipe repair [14].

$$C_{Total} = C_{Operating} + C_{Repair} \qquad (1)$$

The total cost of capsule pipeline includes the cost of operating (energy requirements), the cost of pipe repair, which is dependent on the cost of pipe and the capsules (manufacturing cost). Following is the breakdown of the total cost components [15].

Cost of Energy Requirements

From the literature, T. Asim [16], the cost of power consumption per unit watt is given by.

$$C_{Operating} = C_1 P \qquad (2)$$

Where P, is the power requirement of the pipeline transporting capsules, and C_1 refers to the net annual cost of the energy consumed per unit power, and it is variable. In this study, the effect of inflation on the energy unit price has been also considered. The power can then be expressed as.

$$P = \frac{Q_m \ \Delta P_{Total}}{\eta} \qquad (3)$$

Where Q_m is the flow rate of the mixture, ΔP_{Total} is the total pressure drop in the pipeline transporting capsules and η is the efficiency of the pumping unit. Generally, the efficiency of industrial pumping unit ranges between 60% and 75%. The total pressure drop can be calculated from the friction factor relations developed by S. Abushaala [17]. The mixture flow rate has been expressed according to a relation reported by Liu [18] as follows.

$$Q_m = \frac{\pi D^2}{4} V_{av} \qquad (4)$$

The total pressure drop in a pipeline can be expressed as a sum of the major pressure drop and minor pressure drop resulting from pipeline and pipe fittings, respectively.

$$\Delta P_{Total} = \Delta P_{Major} + \Delta P_{Minor} \qquad (5)$$

The major pressure drop can be expressed as follows for hydraulic pipes as.

$$\Delta P_{Major} = f_w \frac{L_p}{D} \frac{\rho_w V^2}{2} + f_c \frac{L_p}{D} \frac{\rho_w V^2}{2} + \rho_w g h \qquad (6)$$

Similarly, the minor pressure drop can be expressed as follows for hydraulic bends as [16].

$$\Delta P_{Minor} = K_{lw} \frac{n \rho_w {V_{av}}^2}{2} + K_{lc} \frac{n \rho_w {V_{av}}^2}{2} \qquad (7)$$

Where *n* is the number of bends in the pipeline. The term f_w indicates the friction factor which can be obtained by the following equation.

$$f_w = 0.0055 + \frac{0.55}{{Re_w}^{\frac{1}{3}}} \qquad (8)$$

Reynolds number Re_w in Equation (8) can be expressed by $Re_w = \frac{\rho_W V_{av} D}{\mu}$, where V_{av} refers to the main flow average velocity [4]. Semi-empirical expression for the friction factor of spherical capsules were developed by S. Abushaala et al [22].

$$f_c = 32.28 \times 10^{-6} \left(\frac{k^{4.511} * (s+1)^{1.998}}{{R_{ec}}^{1.881}}\right) \qquad (9)$$

This expression has been implemented into the optimisation model in this study. Reynolds number Re_c can be expressed by $Re_c = \frac{\rho_c V_c D}{\mu}$, where V_c refers to the capsule average flow velocity and D is pipe diameter. The loss coefficient of bends due to water flow K_{lw} is presented by Asim [16] as.

$$K_{lw} = \frac{\left(3.05 - 0.0875\frac{r}{R}\right)}{Re_w^{1/5}} \qquad (10)$$

Where *r* is the radius of the pipe and *R* is the radius of the pipe curvature. The solid throughput is the amount of a certain material that flows per unit time in m^3/sec. The solid throughput has been considered as the main input to the model introduced in this study. This input has been used to replace the velocities in the designing process.

The solid throughput for a pipeline transporting spherical capsules has been used as [16].

$$Q_c = \frac{\pi d^3 V_c}{6L_p} \ x \ \frac{L_p}{L_c} \qquad (11)$$

Where L_p, L_c represent the pipeline length and the capsule length respectively. Expression for the loss coefficient of bends K_{lc} was based on S. Abushaala et al study [22].

$$K_{lc} = 113.5 * \left[\frac{(\theta+1)^{0.331} * k^{0.462} * (s+1)^{0.417}}{Re_c^{0.527}}\right] \qquad (12)$$

Cost of Manufacturing

The manufacturing cost can be further divided into the cost of the pipeline and the cost of the capsules as follows.

$$C_{Manufacturing} = C_{Pipe} + C_{Capsule} \qquad (13)$$

The cost of pipe per unit weight of the pipe material is C_2 in dollars, thus the pipeline cost C_{Pipe} can be expressed by.

$$C_{Pipe} = \pi D t \gamma_p C_2 L_p \qquad (14)$$

Where t is the thickness of the pipe wall and γ_p is the specific weight of the pipe. According to Davis and Sorenson [19] and Russel [20], the pipe wall thickness can be expressed as.

$$t = C_c D \qquad (15)$$

Where C_c is a constant of proportionality depends on expected pressure and diameter ranges of the pipeline and it is suggested to be around 0.12 in T. Asim [21, 23]. Hence, the cost of the pipe becomes.

$$C_{Pipe} = \pi D^2 \gamma_p C_2 C_c L_p \qquad (16)$$

The cost of spherical capsules per unit weight of the capsule material can be calculated as [16].

$$C_{Spherical\ Capsules} = \pi k^2 D^2 t_c N \gamma_{Cap} C_3 \qquad (17)$$

Where C_3 is the cost of capsules per unit weight of the capsule material ($/N), t_c is the thickness of the capsule, N is the total number of capsules in the pipeline and Υ_{cap} is the specific weight of the capsule material.

Cost of Repair

The calculation of cost of repair is obtained based on the study published by T. Asim et al [14] as follows.

$$C_{Repair} = C_{Break} \sum_{i=1}^{t_T/\Delta t} N(t_i) \qquad (18)$$

Where, C_{Break} is the cost of repairing a single break ($/break) and i represents the year in which the calculations are made. The cost of repairing a single break is calculated by multiplying a typical break length L_b with the manufacturing cost per unit pipe length. It is assumed that repairing a break requires the same activities as replacing a pipe; thus, the typical break length (m/break) is obtained by dividing pipe repair cost ($/break) by pipe replacement cost ($/m). The typical pipe-break length is assumed as much as 9 m/break for pipes in the size under consideration in this study [12]. The other term $N(t_i)$ in Equation (16) is the sum of break rates in each year (breaks/km); hence, the break rate (breaks/km/year) can be obtained from.

$$N(t_i) = N(t_1) e^{\phi(t_i - t_1)} \qquad (19)$$

Where t_1 is time of replacement, $N(t_1)$ is the initial break rate (at the time of replacement), and ϕ is the breakage growth rate. According to Asim et al [14], typical values for initial break rate and breakage growth rate are 0.04 breaks/km/year and 0.07/year, respectively.

The Overall Pressure Drop

The total cost of the pipeline per unit length per unit volume of transported capsules throughout the lifetime of the pipeline is the sum of the cost of operating and the cost of pipe repair as mentioned in Equation (1). The corresponding diameter to minimum total cost is considered to be the optimal diameter for a given solid throughput of capsules with a given size.

The following steps should be followed to run the optimisation model:

1. Assume an initial value of the pipe diameter D.
2. Specify the life cycle in years.
3. Specify the specific gravity of the capsule and the pipe materials.
4. Specify t_c, C_1, C_2, C_3, C_c, η and the material properties of the pipeline.
5. Specify solid throughput requirements Q_c.
6. Compute Q_m using Equation (4).
7. V_c is defined from the solid throughput in Equation (10).
8. Compute Re_w and Re_c.

For the life cycle, calculate the following:

9. Compute the cost of pipe and the capsules (cost of manufacturing).
10. Calculate friction factors and loss coefficients for both water and the capsules.
11. Compute the power requirement for the system using Equation (3) and the cost of power using Equation (2).
12. Calculate the total cost of the pipeline.
13. Repeat the steps from 1 to 7 for various values of the life cycle until the optimum value of the pipe diameter is achieved.

Figure 1 presents the flow chart for the design methodology proposed in this research. A programming language MATLAB® has been used to execute the mathematical model.

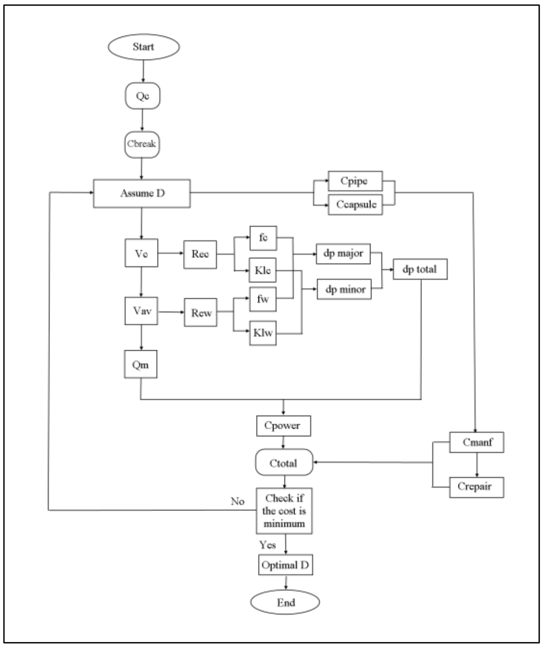

Figure 1 Flow chart of the design methodology

III. PRACTICAL CASE

As a practical case, the diameter of the pipe will be determined to understand the optimisation methodology and how can this be used in the design process? For this case, Polypropylene needs to be transferred from the processing plant to the storage area of the factory a half kilometre away in the form of spherical capsules of k = 0.7 in a mainly horizontal cast Iron pipeline. The required solid throughput of Polypropylene is $0.001 m^3/sec$. It is required to determine the pipe diameter, which can deliver the mentioned throughput for the lower cost per unit pipe length when the pipeline has five bends in various lifetime cycles for the following data.

$$\mu = 1.003 \times 10^{-3}\ Pa.s;\ \rho_c = 905 kg/m^3;\ \rho_w = 998.2 kg/m^3;$$
$$k = 0.7\ ;\ \eta_w = 0.6;\ ER = 0.95;\ \eta_m = 0.9;\ C_{1,i} = 1.4\$/W/year;\ C_2 = 0.95\$/N;\ C_3 = 1.1;\ C_c = 0.12$$

The pipe surface is assumed hydro-dynamically smooth. The inflation rate of the energy unit price is assumed to be at 3% growing yearly, and this will affect the operating cost only as it depends on the cost of the energy unit. The manufacturing cost of the whole system is time-independent, where it is functionally dependent on the pipeline diameter. Following the steps for optimisation of pipeline transporting capsules for only one year.

For the case considered, the optimal pipe diameter is calculated by solving equation (1) by trial and error for different lifetimes that is varied in 4-year intervals. The lifetime is determined as 4 years when the annual total cost has a minimum which is \$180,000. In this case, the optimal pipe diameter is 6 cm which corresponds to the minimum total cost throughout the lifetime. For this optimal diameter, the corresponding flow velocity is 2 m/s.

Table 1. Variations in optimal pipeline diameter with lifetime

Lifetime (years)	Minimum total cost (\$)	Corresponding pipeline diameter (m)
0-4	180,000	0.06
4-8	353,800	0.06
8-12	707,000	0.04

Figure 2 shows the variation of different cost elements with pipeline diameter. The total cost is the sum of operational or pumping cost and capital cost or cost of pipe including manufacturing and repair costs.

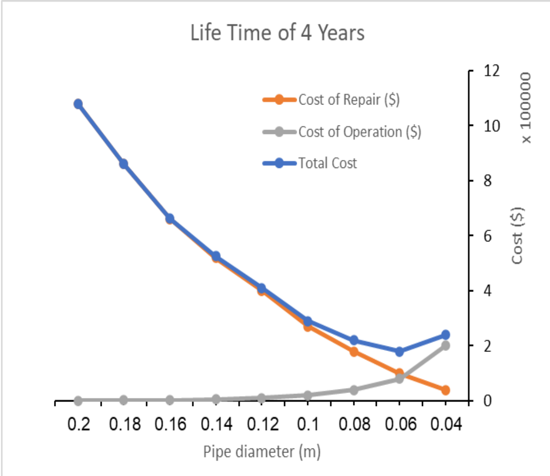

Figure 2. Total cost vs pipeline diameter for 4-years lifetime

Figure 3 shows variation of derivative of total cost with pipe diameter. The value of pipe diameter for which this derivative is reaching zero, i.e. when the corresponding curve crosses the x-axis, is the optimal diameter, and the total cost has a minimum for that diameter.

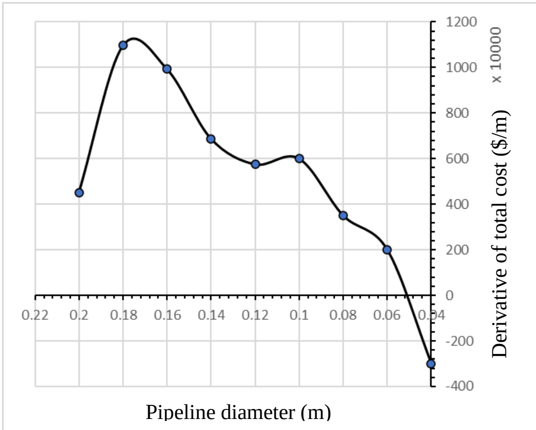

Figure 3. Derivative of total cost vs pipeline diameter for 4-years lifetime

The above calculation was repeated with increasing the lifetime to 12 years. The optimal pipe diameter is slightly different from the previous case: 4 cm, and the corresponding minimum total cost is 707,000 throughout the lifetime.

IV. CONCLUSIONS

A methodology has been developed to determine the optimal size of pipelines transporting spherical capsules. The pressure drop was estimated using the expressions developed for the friction factor and the loss coefficient. The proposed model is an improvement on simple pipe-cost optimisation. Consideration of the break cost and replacement cost in optimisation results in different optimal pipe diameters. The example presented has shown the importance of considering the break cost and replacement costs in optimisation model. The optimal pipe diameters depend on the break growth rate and initial break rate in addition to the life time. This indicates that there is a proportional relationship between the cost of break and the optimal pipe diameter. It can be concluded that the increase in the pipeline diameter decreases the operating cost and increasing the repair cost of the pipeline for a certain life time.

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