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Economic Pipe Size Selection by Using Graphical Method

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The graphical method for determining optimum conditions based on piping and pumping system. As an example, consider the case where was made calculation of the optimum pipe diameter necessary to handle a given flow, fluid density and viscosity, cost of electricity and efficiency of pump as a pumping cost. However for considering piping cost authors have developed optimization procedure for turbulent flow of conduit size by using pipe density and wall thickness which can be determined by piping specification.

1. Introduction

Piping systems are normally designed to deliver fluid at required head and flow rate in a cost effective manner and they are one of the lowest cost means of transportation, with notable applications in oil and gas as well as water distribution systems.
The main purpose of this article is to calculate the economic pipe diameter for pipes carrying fluid under pressure. Graphical method to calculate the economic pipe diameter for pipe system was engaged in this article.
For any given set of flow conditions, the use of an increased pipe diameter will cause an increase in the fixed charges for the piping system and a decrease in the pumping charges. Therefore, an optimum economic pipe diameter has to exist. The value of the optimum diameter can be determined by combining principles of fluid dynamic with cost considerations.
The most economical pipe size for a distribution system is found at the point at which the total cost of the piping system including fixed charges based in this article on the pipe density and thickness of a pipe and pumping costs, is a minimum.
The graphs presented in the article may be used as a guide by engineers for the economic design of piping system.

2. Literature review

The head losses in piping installations include the energy or head required to overcome resistance of pipeline and fitting in the pumping system. Friction exists on both the discharge and suction sides of a pump and energy loss in pipe flow depends on fluid velocity, density, viscosity, and size of pipe. A number of equations governing fluid flow in pipelines have been developed by Peters and Timmerhaus (1991). The most widely used ones include the Scobey, Darcy-Weisbach, Mannings and Hanzen-Williams formula.
Many previous research papers had dealt with optimum designs of piping systems. Some workers considered combining cost factors with hydraulic problems, but others failed to consider cost factors. Since it is the cost which forms the principal concepts of economic designing, it is important to consider all cost factors that might be involved.
In the literature for pipe laying in a trench the earliest cost analysis was reported by Maurey (1922), who created a diagram for the cost of laying pipe in a trench and showed that the cost of pipe installed was as follow as Eq(1):

$$T = (0.055 + 0.0145D)dW + 0.00159dL + 0.00006dY \quad (1)$$

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where:
T – pipe laying cost,
L – cost of lead,
d – diameter of pipe in inches,
Y – cost of yarn,
D – depth of trench,
W – wages rate for common labor.
Babbitt and Donald (1939) were used this information in their work and has summed the cost of pipe and pumping to give total annual fixed charges of pipe, as follow as Eq(2):

$$\text{Annual fixed cost} = Tr + 2ard^{1,5} + 236PQS \tag{2}$$

where:
a – cost of iron,
Q – rate of pumping water through pipe line,
S – slope of hydraulic grade line,
P – cost of pumping,
$2ard^{1,5}$ - term for pipe cost,
$236PQS$ – term for pumping cost,
r – annual rate of interest plus depreciation and other charges,
d – diameter of pipe .
They have substituted the head loss term, S, as a function of flow rate, Q, and diameter, d, as follow as Eq(3):

$$S = 100 \cdot \frac{Q^{7/4}}{d^{19/4}} \tag{3}$$

and substituted Eq(2) and Eq(3) and differentiated yielding the following equation for minimum cost pipe size as shown Eq(4):

$$d = 6.5 \cdot \left[\frac{P}{r(T + 3a)} \right]^{1/16} \cdot Q^{11/24} \tag{4}$$

Lischer (1944) applied the principles developed by Camp and showed the effect on economic pipe sizes with various values of parameters. Pumping capacity, pipe size, elevated reservoir and pumping head were combined to find the most economical pipe size.
The method of balancing equivalent pipes has introduced (Tong, 1961) to solve a pipe network by using the hydraulic analysis to give an optimal solution. But the cost factors were failed to consider.
The method of designing a water distribution network by using the theory of linear programming opens new perspectives (Karmeli et al., 1968). They included the cost of pipes, pumping and annual operating cost in the total cost of the system. The method of linear equations to solve economic pipe diameters was based on trial and error methods and digital computer was employed to solve the problem.
In the same year was proposed to formulate the pipe network problem as a nonlinear optimization problem of minimizing the total cost of the system (Jacoby, 1968).
Deb and Sarker (1971) regarding to a method of solving economic pipe diameters in pipe network actually combined the works of Tong, Karmeli and Jacob to solve the problem.
The problem of selecting economic pipe diameter is proposed by Genic (2012) as a new model of optimization based on simple economic balance approach Good practice in investigation of economic pipe size selection can be read in Towler (2013).
In summing up the previous work, hydraulic analysis was the main approach used to solve a pipe network system while the cost analysis was considered to be less important. All the cost information was formulated as being exact function of pumping head, or flow rate and pipe sizes whereas in actual fact, cost factors are much more irregularly related to pumping head, flow rate and pipe sizes, and consequently the formulated relationships may greatly deviate from the actual conditions.
It was not possible to get a clear picture of the exact method and details of cost calculations. Nor did the previous authors show a comparison between model results and the results from calculations using actual

costs. All equations in this chapter were presented only for information purpose and were not used for any calculation because of English units were defined.

3. Cost affecting factors

An overall consideration of cost affecting factors is necessary before proceeding with the analysis of economy pipe diameters.

3.1 The capital cost
The capital cost is composed of the cost of materials, cost of pipe installation and in some cases may be excavation cost as well.
Material cost included the cost of pipe, valves, crosses, tees and other fittings. In the case of the supply lines we may consider no crosses and tees are required while in the case of main pipes, tees and other types of branch connections.
Pipe cost itself could vary widely from manufacturer to manufacturer as other factors other than profits are involved. The cost consists of the cost of materials such as cost iron or ductile iron or concrete pipe or duplex and the cost of freight, tax rate and etc. Whether the pipe is lined or unlined also affects the cost as does the pressure rating or class of pipe.
Pipe installation cost is usually fixed by local conditions and there may be huge differences form country to country and continent to continent and place to place for example offshore on onshore installation. Various types of pipe and joints will give different working conditions and thus different cost.

3.2 Capital recovery consideration
In economic considerations the amortization cost is determined by employing one of the uniform series factors as capital recovery factor (CRF) or sinking fund factors (SFF). By using these two factors has the convenience of obtaining the annual fixed charges. In cost analysis, annual cost is the most commonly used unit, so that any factors which introduce cost in yearly basis is convenient to use.
The uniform series factors are functions of interest rate and the life period of amortization. Both interest rate and life period are determined by local conditions.

3.3 Pumping cost
The pumping costs influenced by pumping head, flow rate, pipe constant, cost of electricity and the efficiency of pumping. Optimum pumping head and flow rate can be obtained by hydraulic analysis. The cost of electricity may vary from place to place and is fixed by local electrical power commission.

3.4 Total annual cost
Total annual cost is gained by simply adding up the annual capital recovery cost and operation and maintenance costs. The latter two terms will include according to the above statement only the pumping cost. Thus the total annual cost will be equal to the capital recovery cost plus the pumping cost.

4. Methods of analysis

There are basically two methods which can be used for analysis; one is termed graphical method, the other mathematical method. Both methods are based on the same principles. The procedures involved in the analysis can be listed as following:

- The piping cost
- The pumping cost.

Analysis is then made to find the minimum cost among all pipe sizes, and the size corresponding to the minimum cost is called economic pipe diameter. Graphical is described separately below as a reliable economic pipe size method.
The pumping cost and piping cost are computed for each pipe for given flow. Then the total cost is obtained by adding up these two costs for each pipe size. A curve is then drawn to fit all the plotted points of total cost. Usually a U-shaped curve is formed and the point at the bottom of the curve gives a minimum cost. Then the pipe diameter corresponding to this point is the pipe which gives minimum cost and the size is referred to as the economic pipe diameter.
In this method, the piping cost is expressed by cost of one meter of pipe and the pumping cost is calculated by cost of electricity times the power consumed. All costs are expressed in terms of unit pipe length.
The calculations referred to above would give one economic pipe size corresponding to one flow while other economic diameters are obtained by changing the flow rate. In cost analysis the capital cost is fixed and is a function of pipe diameter but pumping cost which is a function of pumping head, is set up as a

function of diameter and flow rate so that the total cost becomes a function of both pipe diameter and flow rate.

This can be expressed as total annual cost as summary of pumping cost and piping cost.

$$TAC = f\left(d^n, \frac{Q^x}{d^m}\right) \tag{5}$$

Eq(5) indicates that the total annual cost is a function of both flow rate and pipe size when other factors are constant as x and m. Thus the various flow rates will yield a series of economic pipe sizes. A figure plotted with flow rate against economic pipe size will give a curve which represents minimum total annual cost.

5. Model of analysis

For any given operating conditions involving the flow of a non-compressible fluid through a pipe of constant diameter, the total mechanical energy balance can be reduced to the following Eq(6):

$$Work = \frac{2 \cdot m \cdot f \cdot V^2 \cdot L \cdot (1+J)}{D_i} + B \tag{6}$$

where:

$Work'$ – mechanical work added to system from an external mechanical source, J,
m - mass, kg,
f – Fanning friction factor,
V – average linear velocity of fluid, m/s,
L – length of pipe, m,
J – frictional loss due to fittings and bends expressed as equivalent fractional loss in a straight pipe,
D – inside diameter of pipe, m,
B – a constant taking all other factors of the mechanical energy balance into consideration.
In the region of turbulent flow, f may be approximated for pipes by the following Eq(7):

$$f = \frac{0.04}{\mathrm{Re}^{0,16}} \tag{7}$$

By combining Eq(6) and Eq(7) applying the necessary conversion factors, the following equation can be obtained representing annul pumping cost when the flow is turbulent as Eq(8):

$$C_{pumping} = \left[\frac{0.000125 \cdot \mu^{0.16} \cdot Q^{2.84} \cdot \rho^{0.84}}{D_i^{4.84}} \cdot (1+J)\right] \cdot \frac{K \cdot H_y}{E} + B' \tag{8}$$

where:

$C_{pumping}$- pumping cost when flow is turbulent, \$/year
Q - fluid flow rate, m^3/s,
ρ - fluid density, kg/m^3,
μ_c - fluid viscosity, centipoises,
K - cost of electrical energy, \$/kWh,
H_y - hours of operation per year, h/year
E - efficiency of motor and pump expressed as a friction,
B' - a constant independent of diameter.
The purchase cost for piping may be represented by the following Eq(9):

$$C_{piping} = \pi \cdot X \cdot \rho_{pipe} \cdot \left[D_i t + t^2\right] \tag{9}$$

where:

C_{piping} - piping cost, \$/m,

X - cost of pipe, \$/kg,

ρ_{pipe} - pipe density, kg/m^3

t - wall thickness, m.

The cost of piping consists of the cost of pipe and pipe density and wall thickness.

The total annual cost for the piping system and pumping can be obtained by adding Eq(8) and Eq(9). This procedure gives the following results as Eq(10):

$$C_{total} = C_{pumping} + C_{pipe} \tag{10}$$

The following equation was presented in one example.

Table 1: Input data for Eq(8) and Eq(9)

Medium	Condensate	Units
Flow rate	1,545	m^3/h
Flow rate	0.0009	Pa*s
Fluid density	546	kg/m^3
Pipe density	7,850	kg/m^3
Pipe price	0.80	\$/kg
Electricity price	0.15	\$/kWh
Hours of operation	8,760	h/y
Pump efficiency	0.5	-
Frictional loss due to fittings and bends	0.3	-
Pipe material	Carbon steel	-
Existing pipe size	0.610	m

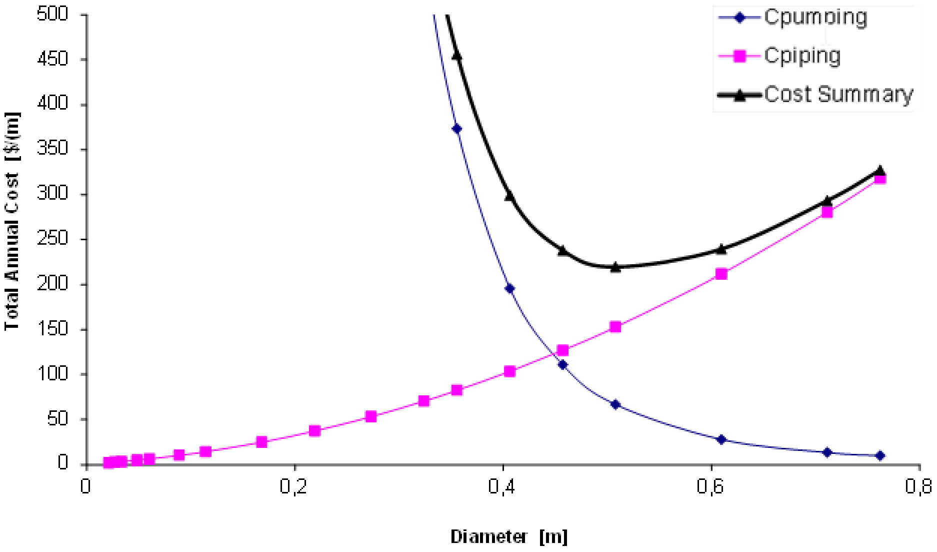

Figure 1: Economic pipe size selection according to piping and pumping cost

Figure 1 shows the relationship between pumping and piping cost for the case which has presented. Summary curve of both costs shows at minimum point where economic pipe diameter and the nominal pipe diameter available commercially is 0.508 m and is less than existing.

The pipeline cost can be significantly higher than 20 % of total plants investment cost. Hence, the economic pipe size selection is very important. Nowadays piping designs are normally based on quick estimation of capital piping cost, without accounting its operating cost.

6. Conclusion

It is the purpose of this article to present a clear picture of the way of analysis from which the economic pipe diameter can be derived by graphical method is employed for analysis.
Since the economic pipe diameter is a function of different parameters such as flow rate, cost of electricity, pump efficiency, and as was developed in this article, pipe density and thickness of a pipe, it would be helpful to find out the trend of the changes in economic pipe diameter as these parameters are altered. The analysis can be performed by using regression equation which were obtained by curve fitting for minimum cost curves in graphical method.
In accordance to this article, it can be concluded that the developed model made it possible to calculate the economic diameter but the following discussion and further work is required.

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