Optimal Design Methodology for On-shore Hydraulic Pipelines Transporting Spherical Capsules

Taimoor Asim*, Rakesh Mishra, Achilleos Paris, Karina Zala

School of Computing & Engineering, University of Huddersfield, UK (HD1 3DH)

* Corresponding author. Tel.: +0044-1484-472727. E-mail address: t.asim@hud.ac.uk

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Abstract

The third generation of pipelines comprises of the transportation of capsules that are hollow, water-borne containers, usually spherical or cylindrical in shape, filled with goods. These capsules are transported within pipelines along with the fluid, which is commonly water. Much of the research that has been carried out on HCPs deals with general designing of such pipelines for particular applications. The available literature dealing with the optimal designing of HCPs is based on assumptions and simplifications, such as neglecting minor losses within HCPs. Based on Least-Cost Principle, an optimisation methodology has been developed in the present study for single stage on-shore HCPs, transporting spherical capsules, that takes into account the minor losses encountered by water. The optimal design methodology is based on an iterative process in which the solid throughput required from the system is the input whereas the optimal diameter of the pipeline for that particular solid throughput is the output. Hence a design chart can be developed for optimal sizing of HCPs. The optimisation model presented in the present study is both robust and user-friendly.

Keywords: Hydraulic Capsule Pipelines, Spherical Capsules, Least-Cost Principle, Pressure Drop, Mixture Flow Rate

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1. Introduction

Scarcity of fossil fuels and rapid escalation in the energy prices around the world is affecting efficiency of established modes of cargo transport within transportation industry. Extensive research is being carried out on improving efficiency of existing modes of cargo transport, as well as to develop alternative means of transporting goods. One such alternative method can be through the use of energy contained within fluid flowing in pipelines in order to transfer goods from one place to another [1-5]. Although the concept of using fluid pipelines for transportation purposes has been in practice for more than a millennium now [6], but only a few optimal design methodologies for such pipelines are available [7,8]. This is due to the fact that most of the studies conducted on transporting goods in pipelines are based on experimental measurements of global pipeline and flow parameters, and only a very limited, and that too very rough, approximation of these parameters with that of the capsules has been reported [9,10].

For commercial viability of HCPs, it is quite evident that these pipelines need to be designed optimally for widespread acceptability. The designers are in need of a design methodology which accounts for the hydraulic and mechanical design of a pipeline transporting capsules. Hence, an optimization model needs to be developed, which should be robust and user-friendly. The optimization model should be based on the fact that the total cost involved in the design of a pipeline transporting capsules is kept to a minimum. The present study makes use of the design equations developed by Asim [11] explicitly for on-shore HCPs transporting spherical capsules, and developing an optimal design methodology for such pipelines.

Nomenclature

C_1	Cost of Power consumption per unit Watt (£/W)
C_2	Cost of Pipe per unit Weight of Pipe material (£/N)
C_3	Cost of Capsules per unit Weight of the Capsule Material (£/N)
C_c	Constant of Proportionality
D	Pipeline Diameter (m)
d	Capsule Diameter (m)
f	Friction factor (-)
k	Capsule to Pipe Diameter Ratio (-)

K_l	Loss Coefficient (-)
L	Length (m)
n	Number of Bends (-)
N	Number of Capsules (-)
P	Power of the Pumping Unit (W)
ΔP	Pressure Drop (Pa)
Q	Flow Rate (m^3/sec)
r	Radius of Curvature of Pipe Bend (m)
R	Radius of Pipe Bend (m)
Re	Reynolds Number (-)
Sc	Spacing between the Capsules (m)
t	Thickness (m)
V	Flow Velocity (m/sec)
ρ	Density (Kg/m^3)
ϒ	Specific Weight (N/m^3)
η	Efficiency of the Pumping Unit (%)

2. Optimal Design Methodology

The model presented here is based on the least-cost principle, i.e. the total cost of the pipeline remains minimum. The total cost of a pipeline transporting capsules consists of the manufacturing cost of the pipeline and the capsules plus the operating cost of the system.

$$C_{Total} = C_{Manufacturing} + C_{Operating}$$

The manufacturing cost can be further divided into the cost of the pipeline and the cost of the capsules. The operating cost refers to the cost of the power being consumed.

$$C_{Total} = C_{Pipe} + C_{Capsule} + C_{Power}$$

2.1. Cost of Pipes

The cost of pipe per unit weight of the pipe material is given by [12]:

$$C_{Pipe} = \pi D t \gamma_p C_2 L_p$$

where t is the thickness of the pipe wall. According to Davis and Sorenson [13] and Russel [14], the pipe wall thickness can be expressed as:

$$t = C_c D$$

where C_c is a constant of proportionality dependent on expected pressure and diameter ranges of the pipeline. Hence, the cost of the pipe becomes:

$$C_{Pipe} = \pi D^2 \gamma_p C_2 C_c L_p$$

2.2. Cost of Capsules

The cost of spherical capsules per unit weight of the capsule material can be calculated as:

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

where 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.

2.3. Cost of Power

The cost of power consumption per unit watt is given by:

$$C_{Power} = C_1 P$$

where P is the power requirement of the pipeline transporting capsules. It is the power that dictates the selection of the pumping unit to be installed. The power can be expressed as:

$$P = \frac{Q_m \ x \ \Delta P_{Total}}{\eta}$$

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 to 75%. The total pressure drop can be calculated from the friction factor relations developed in the previous chapters whereas the mixture flow rate has been computed from the cases that have been investigated in this study.

2.4. Mixture Flow Rate

Liu [15] reports the expression to find the mixture flow rate as:

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

for a circular pipe. V_{av} can be expressed in terms of the velocity of the capsule from the holdup data [11].

2.5. Total Pressure Drop

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.

$$\Delta P_{Total} = \Delta P_{Major} + \Delta P_{Minor}$$

The major pressure drop can be expressed as follows for horizontal pipes as:

$$\Delta P_{Major} = f_w \frac{L_p}{D} \frac{\rho_w {V_{av}}^2}{2} + f_c \frac{L_p}{D} \frac{\rho_w V_{av}^2}{2}$$

Similarly, the minor pressure drop can be expressed as follows for horizontal bends as:

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

where n is the number of bends in the pipeline. Here, f_w can be found by the Moody's approximation [16] as:

$$f_w = 0.0055 + \frac{0.55}{{Re_w}^{\frac{1}{3}}}$$

K_{lw} has been found out to be:

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

Expressions to calculate f_c and K_{lc} have been developed using multiple regression analysis and are listed in table 1.

2.6. Solid Throughput

The solid throughput in m^3/sec is the input to the model. One important point to note over here is that the pipeline designer has no information regarding the velocities in the pipeline, whether it is the average flow velocity or the velocity of the capsules. In order to replace the velocities mentioned in the above equations, the solid throughput has been used to as:

$$Solid\ Throughput = Amount\ of\ substance\ flowing\ per\ unit\ time$$

$$Q_c = Volume\ of\ a\ capsule\ x\ Time\ taken\ by\ the\ capsules\ to\ travel\ unit\ length$$

For spherical capsules:

$$Q_c = \frac{\pi d^3}{6}\ x\ \frac{Number\ of\ capsules\ in\ the\ train}{Time\ taken\ to\ travel\ unit\ length}$$

The number of capsules in the train can be calculated as follows:

$$L_p = NL_c + (N-1)S_c$$

Hence:

$$N = \frac{L_p + S_c}{L_c + S_c}$$

where $L_c = d$ for spherical capsules. Length of the capsules and the spacing between them should be chosen such that N is an integer. The time taken to travel unit distance will be:

$$Time\ taken\ to\ cover\ 1m\ distance\ = \frac{L_p}{V_c}$$

Hence:

$$Q_c = \frac{\pi d^3}{6}\ x\ \frac{L_p + S_c}{L_c + S_c}\ x\ \frac{V_c}{L_p}$$

$$Q_c = \frac{\pi d^3 V_c}{6L_p}\ x\ \frac{L_p + S_c}{L_c + S_c}$$

V_c can be represented in terms of Q_c. Furthermore, V_{av} can be expressed in terms of V_c using holdup expressions. Hence, there will be no velocity expression that will be explicitly required in the optimisation model.

Table 1. f_c and K_{lc} Expressions.

Density of Capsules	f_c and K_{lc} Expressions
Equi-Density	$f_c = \frac{\left(2.63\ \left(\frac{N}{Lp} * d\right)^{1.069} k^{2.56}\ \frac{Sc+Lp}{Lp}^{0.218}\right)}{Re_c^{0.116}}$ $K_{lc} = \frac{\left(22387\ \left(\frac{N}{Lp} * d\right)^{2.26} k^{3.5}\ \frac{Sc+Lp}{Lp}^{1.5}\right)}{Re_c^{0.38}\ \frac{r}{R}^{0.2}}$
Heavy-Density	$f_c = \frac{\left(5.5\ \left(\frac{N}{Lp} * d\right)^{0.87} k^{4.12}\right)}{Re_c^{0.004}\ \frac{Sc+Lp}{Lp}^{0.089}}$ $K_{lc} = \frac{\left(138\ \left(\frac{N}{Lp} * d\right)^{0.66} k^{3.5}\right)}{Re_c^{0.077}\ \frac{r}{R}^{0.2}\ \frac{Sc+Lp}{Lp}^{1.17}}$

3. Working of Optimization Model

The following steps should be followed to run the optimisation model. The input to the model is the solid throughput.

1. Assume a value of D
2. The length of the pipeline is already known from the information of the capsules injection and evacuations sites
3. Calculate the cost of pipes and capsules based on the information regarding the materials of the pipe and the capsules, and the market price of these materials
4. Fix the value of k (this study suggests a value of 0.7 as optimum)
5. Assume the value of the efficiency of the pumping unit (0.6 – 0.75) and then keep it fixed
6. Calculate V_{av}, V_c, R_{ew} and R_{ec}
7. Calculate friction factors and pressure drop (both major and minor)
8. Calculate Q_m
9. Find out the power requirement for the system
10. Calculate the total cost of the pipeline based on the cost of per unit of electricity
11. Repeat steps 1 to 10 for various values of D until that value is reached at which the total cost of the pipeline is minimum

Figure 1 shows a flow chart for the optimisation methodology presented here.

4. Design Example

Polypropylene needs to be transferred from the processing plant to the storage area of the factory half kilometer away in the form of spherical capsules of k=0.7. The spacing between the capsules should be 3*d. The required throughput of polypropylene is $0.001m^3$/sec. Find the optimal size of the pipeline and the pumping power required for this purpose.

Solution: According to the current market, the values of different constants involved in the optimization process are:

$C_1 = 1.4$ $C_3 = 1.1$ $C_2 = 0.95$

Polypropylene has a density equal to that of water. Assuming the efficiency of the pumping unit η=60% and following the steps described in the working of the optimization model, the following results (table 2) are obtained.

The results presented in table 2 depict that a pipeline of diameter=110cm is optimum for the problem under consideration because the total cost for the pipeline is minimum at D=0.11m. The power of the pumping unit required, corresponding to the optimal diameter of the pipeline, is 4.44kW. Further analyzing the results presented in table 2, figure 2 depicts the variations in the manufacturing and operating costs for various pipeline diameters. It can be seen that as the

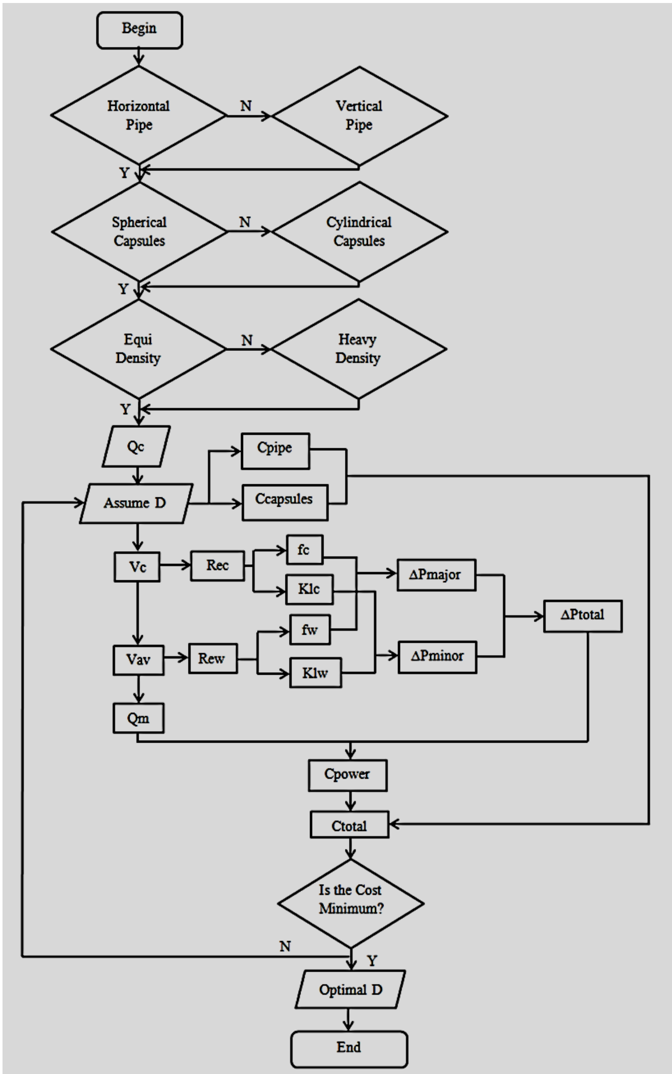

Fig. 1. Flow chart of Optimization Model.

pipeline diameter increases, the manufacturing cost increases. This is due to the fact that pipes of larger diameters are more expensive than pipes of relatively smaller diameters. Furthermore, as the pipeline diameter increases, the operating cost decreases. This is due to the fact that, for the same solid throughput, increasing the pipeline diameter decreases the velocity of the flow within the pipeline.

The operating cost has a proportional relationship with the velocity of the flow; hence, increase in the pipeline diameter decreases the operating cost of the pipeline.

Table 2. Variations in Pumping Power and Various Costs w.r.t. Pipeline Diameter.

D (m)	P (kW)	$C_{Manufacturing}$ (£)	C_{Power} (£)	C_{Total} (£)
0.08	20.87	9129	29218	38347
0.09	11.77	11468	16487	27955
0.10	7.06	14073	9883	23956
0.11	4.44	16944	6222	23166
0.12	2.91	20081	4079	24160
0.13	1.97	23485	2766	26251
0.14	1.38	27154	1930	29084

Figure 3 depicts the variations in the total cost and the pumping power required at various pipeline diameters. It can be seen that as the pipeline diameter increases, the required pumping power decreases. Furthermore, as the pipeline diameter increases, the total cost of the pipeline first decreases and then increases. As the total cost of the pipeline is a sum of the manufacturing and operating costs, which have opposite trends with respect to the pipeline diameter, hence, the combination of these costs give rise to the total cost curve. The pipeline diameter, which corresponds to the minimum total cost of the pipeline, is the optimal pipeline diameter.

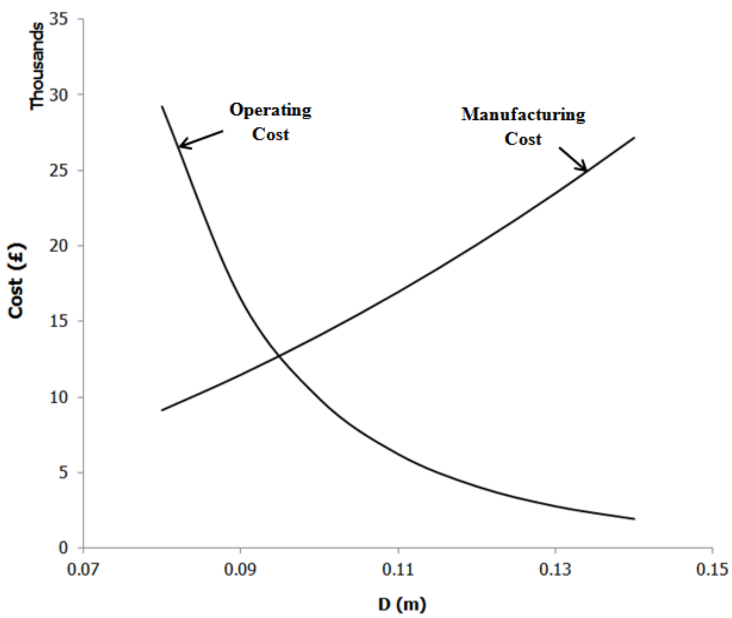

Fig. 2. Variations in Operating and Operating Costs w.r.t. Pipeline Diameter.

Table 3 summarizes the variations in the capsule velocity and the various pressure drops in the pipeline for different pipeline diameters. It can be seen that the capsule velocity and the total pressure drop that corresponds to the optimal pipeline diameter are 1.28m/sec and 242.93kPa respectively.

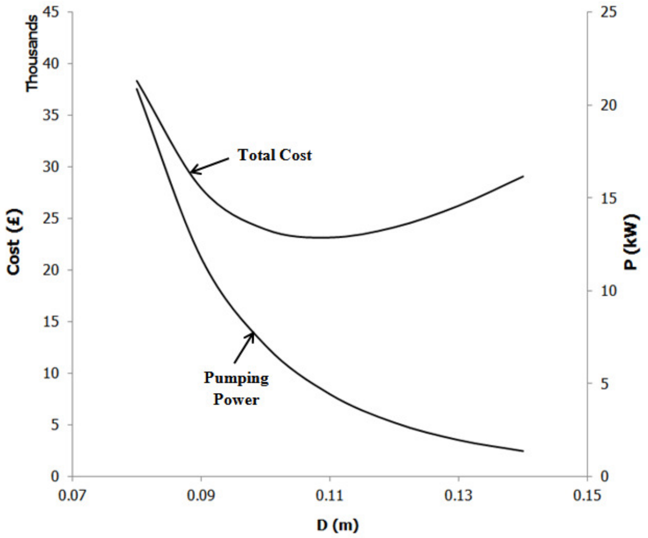

Fig. 3. Variations in Total Cost and Pumping Power Required at Various Pipeline Diameters.

Table 3. Variations in Capsule Velocity and Pressure Drops.

D (m)	V_c (m/sec)	ΔP_{Minor} (kPa)	ΔP_{Major} (kPa)	ΔP_{Total} (kPa)
0.08	2.43	5.43	1135.2	1140.6
0.09	1.92	3.54	640.1	643.6
0.10	1.55	2.41	383.4	385.8
0.11	1.28	1.70	241.2	242.9
0.12	1.08	1.24	158.0	159.2
0.13	0.92	0.93	107.0	108.0
0.14	0.79	0.71	74.6	75.3

Figure 4 depicts the variations in the capsule velocity and the total pressure drop in the pipeline for various pipeline diameters. It is evident from the figure that as the pipeline diameter increases, the velocity of the capsules decreases. This supports the aforementioned statement regarding the variations in the flow velocity for increasing pipeline diameters. Furthermore, as the pipeline diameter increases, the total pressure drop decreases. This statement is again supporting the results presented above for the variations in pumping power required for the pipeline. Hence, all the results presented here are in agreement with the design methodology presented in this chapter for the flow of capsules in a pipeline.

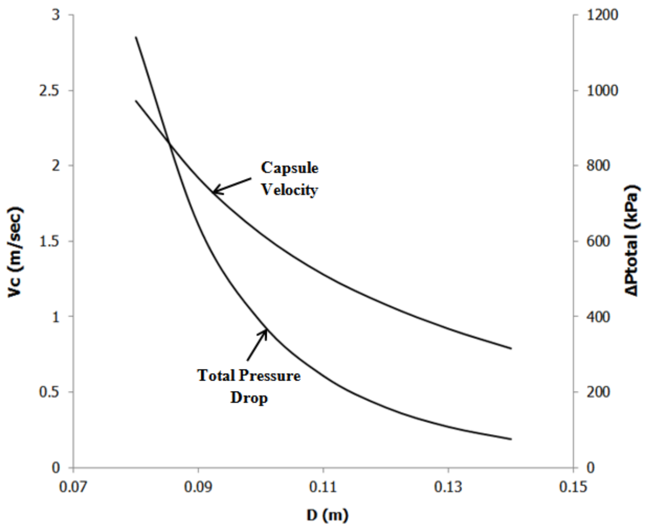

Fig. 4. Variations in Capsule Velocity and Total Pressure Drop w.r.t. Pipeline Diameter.

Table 4 presents the variations in the capsule velocity, pumping power and the optimal diameter of the pipeline for various solid throughputs. Hence, table 4 can be used as a design table for the capsule pipeline designs.

Table 4. Variations in Optimal Diameter, Capsule Velocity and Pumping Power for Various Solid Throughputs.

Q_c (m^3/sec)	V_c (m/sec)	P (kW)	D (m)
0.001	1.28	4.44	0.11
0.002	1.38	7.16	0.15
0.005	1.76	19.30	0.21
0.008	1.84	26.31	0.26
0.010	1.98	34.81	0.28

Figure 5 depicts the variations in the optimal diameter of the pipeline and the required pumping power at various solid throughputs. It can be seen that as the solid throughput increases, the optimal pipeline diameter increases. Furthermore, as the solid throughput increases, the required pumping power also increases.

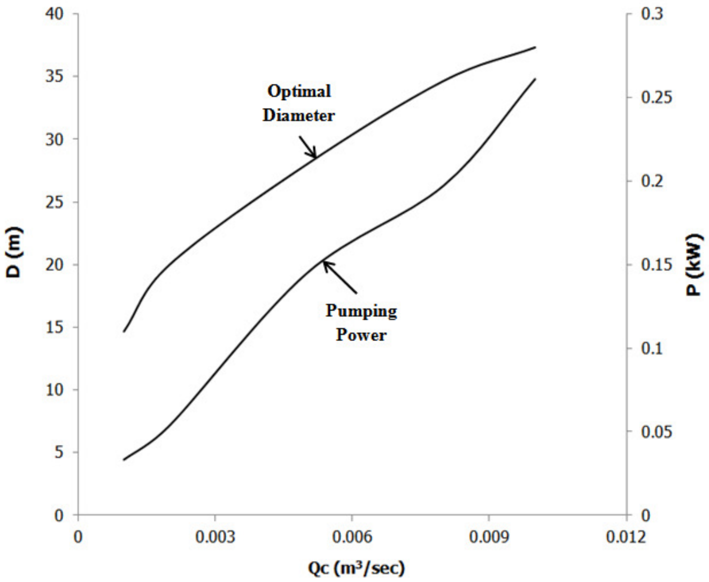

Fig. 5. Variations in Optimal Diameter and Pumping Power w.r.t. the Solid Throughput.

5. Conclusions

A detailed investigation of the various costs involved in a pipeline transporting capsules has revealed that increase in the pipeline diameter increases the manufacturing cost and the operating cost. Furthermore, increase in the pipeline diameter first decreases and then increases the total cost of the pipeline. Moreover, increase in the pipeline diameter decreases the pressure drop, capsule velocity and the pumping power required for the pipeline.

References

[1] Liu, H. Hydraulic Behaviours of Coal Log Flow in Pipe, In the Proceedings of the 4th International Conference on Bulk Materials Handling and Transportation (1992); Symposium on Fright Pipelines, Wollongong, Australia.

[2] Subramanya, K. Pipeline transportation technology: An overview, Current Science (1998); 75: 824.

[3] Govier, G. W. Aziz, K. Flow of Complex Mixtures in Pipes, Society of Petroleum Engineers (2008); 2nd Ed.

[4] Mole Solutions Ltd. Aggregate Strategic Research Programme Project 05: Assess the feasibility of using pipelines to transport aggregates in England (2010); Final Report.

[5] Round, G. F. Pneumatic Capsule Pipeline Systems: A Short History and State-of-the-Art, Bulk Solids Handling (1992); 12: 67 – 72.

[6] Needham, J. Science and Civilization in China, Physics and Physical Technology: Part 1, Physics (1986); 4.

[7] Polderman, H. G. Design Rules for Hydraulic Capsule Transport Systems, Journal of Pipelines (1982); 3: 123 – 136.

[8] Swamee, P. K. Design of Sediment Transporting Pipeline, Journal of Hydraulic Engineering (1995), 121.

[9] Assadollahbaik, M. Liu, H. Optimum Design of Electromagnetic Pump for Capsule Pipelines, Journal of Pipelines (1986); 5: 157 – 169.

[10] Agarwal, V. C. Mishra, R. Optimal Design of a Multi-Stage Capsule Handling Multi-Phase Pipeline, International Journal of Pressure Vessels and Piping (1986); 75: 27 – 35.

[11] Asim, T. Computational Fluid Dynamics based Diagnostics and Optimal Design of Hydraulic Capsule Pipelines, Ph.D. Thesis (2013); University of Huddersfield, UK.

[12] Cheremisinoff, P. N. Cheng, S. I. Civil Engineering Practice, Technomies Publishing Co. (1988); Lancaster, P. A., U.S.A.

[13] Davis, C. Sorensen, K. Handbook of Applied Hydraulics, McGraw-Hill Book Co. (1969); New York, 3rd Ed., U.S.A.

[14] Russel, G. Hydraulics, Holt, Rinehart and Winston (1963); New York, 5th Ed., U.S.A.

[15] Liu, H. Pipeline Engineering, Lewis Publishers (2003); U.S.A.

[16] Moody, L. F. Friction factors for pipe flow, Transactions of the ASME (1944); 66: 671– 684.