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Pressure Drop in Capsule Transporting Pipeline Carrying Spherical Capsules

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ABSTRACT

Design parameters of hydraulic pipelines in which capsules flow can be developed if pressure drops $(\Delta P/L)_m$ *are known. Designers are in need of a general correlation to calculate pressure drop. Researchers, so far, have used rather simplified empirical and semi-empirical correlations for pressure drop calculations, the range and application of which is fairly limited. A mathematical correlation developed for pressure drops in equal density spherical capsule trains is presented here. Based on Computational Fluid Dynamics (CFD) analysis a numerical solution has been obtained 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* V_b= *0.2 to 1.6 m/sec. Obtained results of pressure gradient along the pipeline in presence of capsules were compared with the existing experimental data to validate the model used. The results predicted by the model agree well with the experimental data. The computationally obtained results having a wider range have then been used to develop a rigorous model for pressure drop.*

Keywords: Spherical Capsules, Bulk Velocity, Computational Fluid Dynamics (CFD), Pressure Drop, Turbulent Flow

NOMENCLATURE

D	Pipe Diameter (m)
d	Capsule Diameter (m)
ε	Pipe surface roughness (m)
f	friction factor
g	Acceleration due to gravity (m/s^2)
k	Diameter ratio of capsule to pipe (d/D)
L	Length of the test section (m)
N	Number of Capsules
ρ	Density (kg/m^3)
$\Delta P/L$	Pressure drop per unit length (Pa/m)

Re	Reynolds number
μ	Dynamic viscosity (Pa.s)
V	Velocity (m/s)

SUBSCRIPTS

p	Pipe
b	Bulk
w	Water
c	Capsule
m	Mixture

I. INTRODUCTION

In designing hydraulic capsule pipelines, a general mathematical model is required which can predict the pressure drop in the pipeline accurately. The mathematical model should be based on the variables of the flow, fluid and geometry of the capsules and the pipeline. Before developing such a correlation, the phenomena of water capsule flow must be established and understood completely in order to accurately predict the effect of the different variables on the pressure drop. Once a mathematical model is established, it should be compared with other experiments-based models for validating the model. Advantages of capsule pipelines listed by Agarwal and Mishra, 1998 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

6. There are no traffic jams or accidents involved

II. NUMERICAL MODELLING

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, 2005 has been numerically modelled for L= 1m and D = 0.1m. According to Munson and Young, 2002, 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. “Figure 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, 2010

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. $\rho_w = \rho_c = \rho$

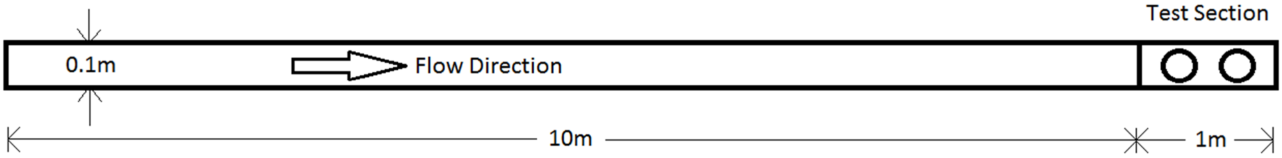

Fig. 1 Geometrical setup of the Capsules in the Pipeline

III. RESULTS

A. Pressure Drop in a hydraulic pipeline

"Figure 2" shows the comparison between the pressure drops calculated using Darcy-Weisbach equation and from CFD. It can be clearly seen that CFD predicts the pressure drop in a hydraulic pipeline with almost 100% accuracy.

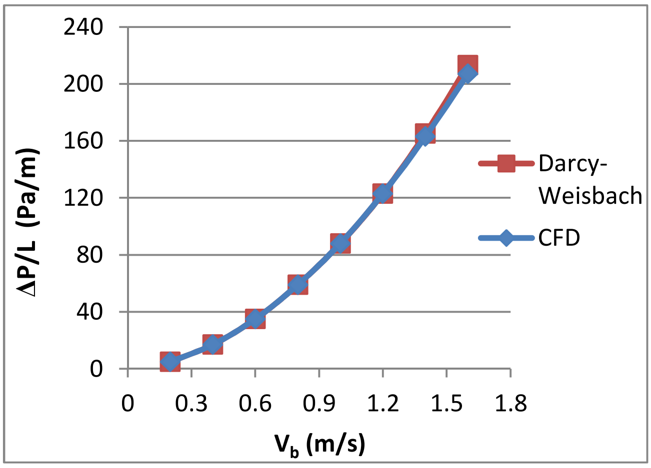

Fig. 2 Comparison of Pressure Drops in a Hydraulic Pipeline

Based on the results from CFD for the pressure drop in a hydraulic pipeline, the following correlation for pressure drop was developed:

$$\left(\frac{\Delta P}{L}\right)_w = \frac{\rho V^2}{2D} * f_w \tag{1}$$

Where f_w is the friction factor due to water. It can be expressed as:

$$f_w = \frac{0.177}{Re_w^{0.2}} \tag{2}$$

Where the Reynolds number of water is expressed as:

$$Re_w = \frac{\rho D V}{\mu} \tag{3}$$

B. Pressure Drop in Capsule transporting hydraulic pipeline

"Figures 3-6" shows the variation of pressure drops under different flow and geometric conditions in a capsule transporting hydraulic pipeline.

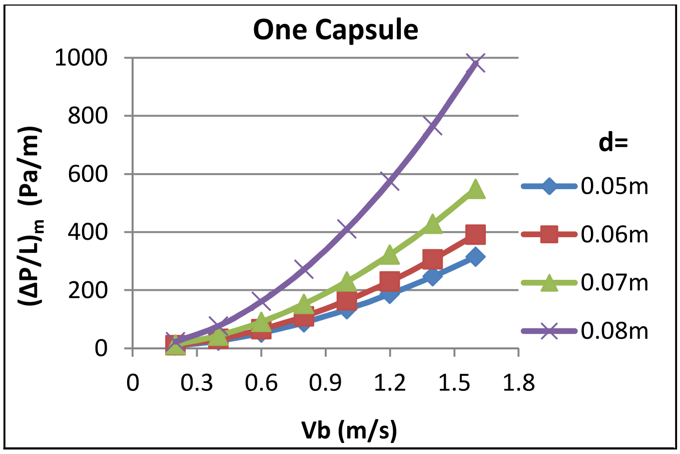

Fig. 3 Variations in Pressure Drop for a single Capsule with different diameters

The results shown in "Figures 3-6" have the same trend i.e. as the bulk velocity of the mixture increases, the pressure drop in the pipeline increases exponentially. Other than that, these figures predict that as the diameter of the capsule increases, the pressure drop in the pipeline also increases. The third information that these figures give is that as the number of capsules increases in a hydraulic pipeline, the pressure drop increases. These results can be summed up to develop the mathematical correlation for the pressure drop in the capsule transporting hydraulic pipeline.

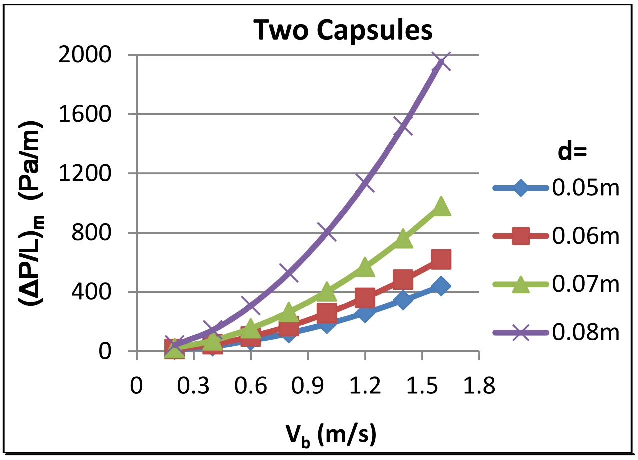

Fig. 4 Variations in Pressure Drop for two Capsules with different diameters

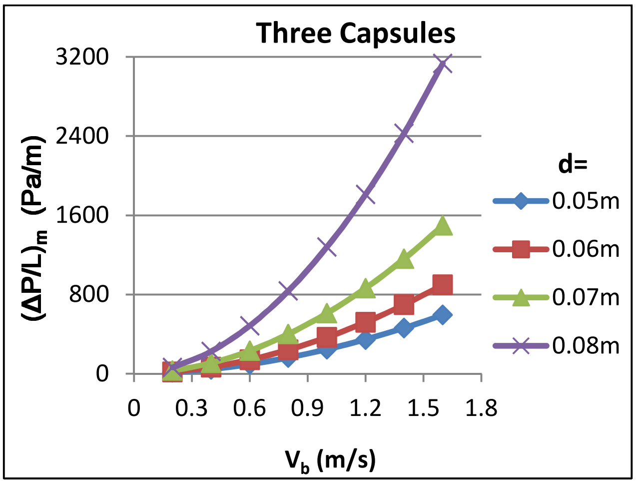

Fig. 5 Variations in Pressure Drop for three Capsules with different diameters

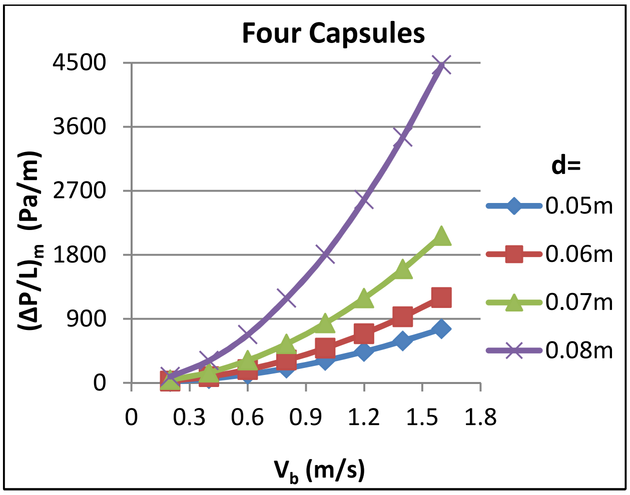

Fig. 6 Variations in Pressure Drop for four Capsules with different diameters

Pressure drop in a capsule transporting hydraulic pipeline can be expressed as:

$$\left(\frac{\Delta P}{L}\right)_m = \frac{\rho V^2}{2D} * f_m \tag{4}$$

Where f_m is the friction factor for the mixture of capsule and water in the pipeline. It can be expressed as:

$$f_m = f_w + f_c \tag{5}$$

Where f_c is the friction factor for the solid phase in the mixture only i.e. for capsules. To calculate f_c, the following procedure is adopted:

1. Calculate the pressure drop i.e. $\left(\frac{\Delta P}{L}\right)_m$ from CFD
2. Divide this pressure drop by $\frac{\rho V^2}{2D}$. This will give the value of f_m
3. Subtract f_w from f_m to get the value of f_c

Hence, the correlation for the pressure drop in the capsule transporting pipeline can be expressed as:

$$\left(\frac{\Delta P}{L}\right)_m = \frac{\rho V^2}{2D} * (f_w + f_c) \qquad (6)$$

Where f_c can be expressed in terms of the variables of flow and geometry as follows:

$$f_c = (0.0032N - 0.0011) * \frac{e^{7k}}{Re_c^{0.2}} \qquad (7)$$

Where the Reynolds number of capsules is calculated by:

$$Re_c = \frac{\rho d V}{\mu} \qquad (8)$$

"Figures 7-10" shows the variations in the value of f_c at different bulk velocities and for different number of capsules. The results indicate that the flow regime can be divided into two sections as suggested by Ulusarslan and Teke, 2010:

1. Transitional Flow
2. Fully Turbulent Flow

For V_b= 0.2 to 0.4m/s, the decrease in the value of f_c is more than the decrease for the range V_b= 0.4 to 1.6m/s. In both the regimes, although the value of f_c decreases linearly, but the slopes of the two curves are very different. From "Fig. 11", which shows the variation of f_c with Re_c, another result can be deduced that for capsule transporting hydraulic pipelines, fully turbulent flow occurs at Re_c = 25000. The correlation presented here is for the fully turbulent regime.

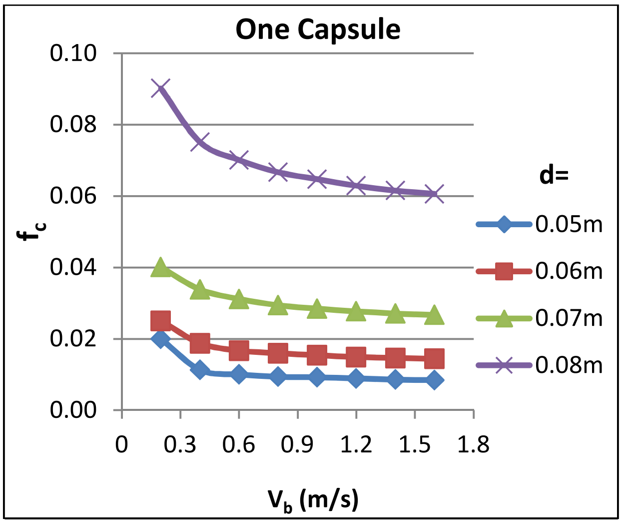

Fig. 7 Variations in Capsule Friction Factor for a single Capsules with different diameters

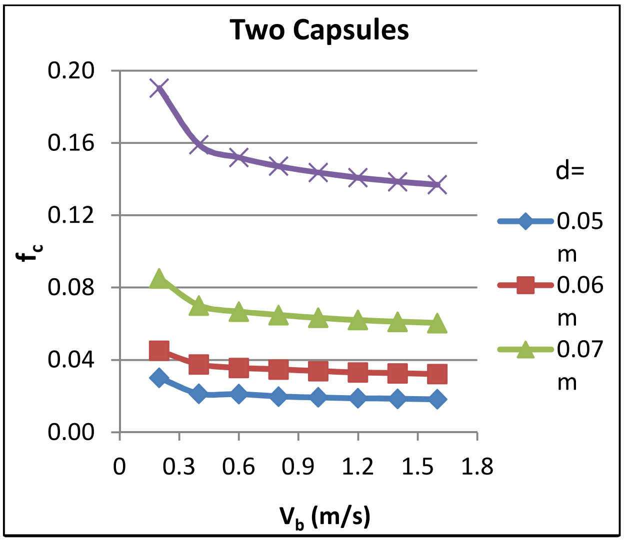

Fig. 8 Variations in Capsule Friction Factor for two Capsules with different diameters

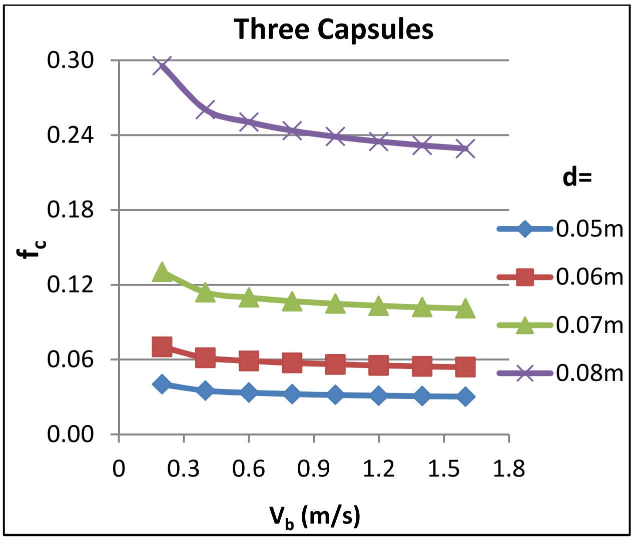

Fig. 9 Variations in Capsule Friction Factor for three Capsules with different diameters

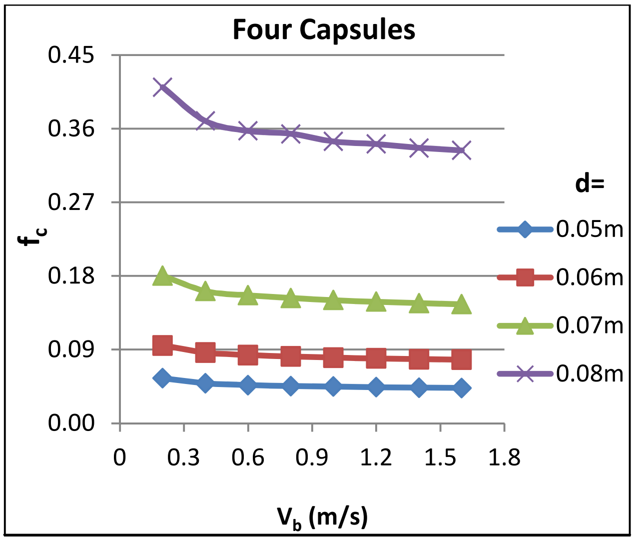

Fig. 10 Variations in Capsule Friction Factor for three Capsules with different diameters

C. Comparison of Pressure Drop correlations in Capsule transporting hydraulic pipeline

"Figure 12" shows the comparison of two experiments based correlations with CFD based correlation for pressure drop in spherical capsules transporting horizontal hydraulic pipelines where the number of capsules in the pipeline is one and the diameter of the capsule is 80% of the pipeline diameter. The results indicate that the correlation which has been presented here, agrees quite well with the experimental data with an average difference of less than 20% with Govier and Aziz curves, 1972. The correlation given by Agarwal and Mishra, 1998 is basically for slurry flows. The results show that CFD based correlation can be used for pressure drop calculations in capsule transporting hydraulic pipelines.

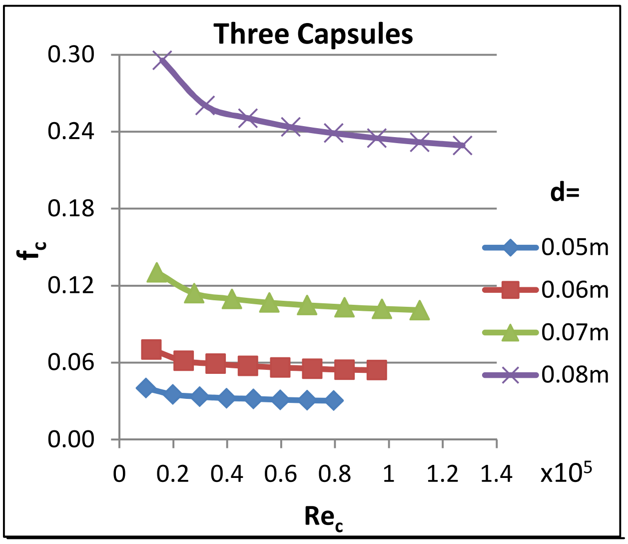

Fig. 11 Variations in Capsule Friction Factor for three Capsules with different diameters

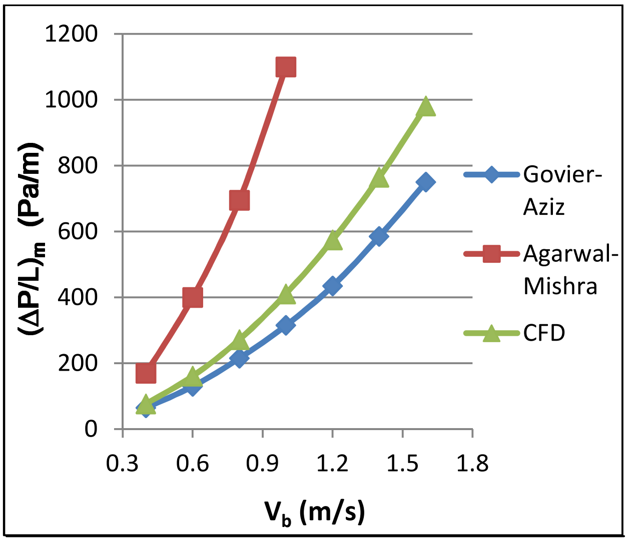

Fig. 12 Variations in Capsule Friction Factor for three Capsules with different diameters

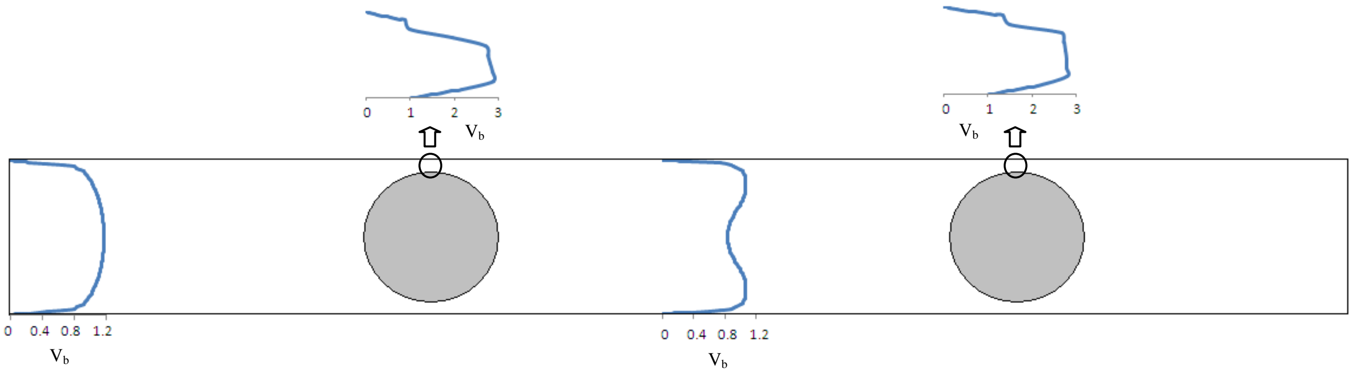

Fig. 13 Velocity profiles in the Test Section for two Capsules with 0.08m diameters

IV. CONCLUSIONS

A rigorous mathematical correlation for the pressure drop in capsule transporting hydraulic pipelines has been presented here. The correlation agrees well with the available experimental data. An effort has been carried out in order to understand the flow behavior in capsule pipelines. "Figure 13" shows the flow behavior at different locations in the test section of "Fig. 1".

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