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Pressure Drop in Capsule Transporting Bends Carrying Spherical Capsules

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Abstract. One of the most important parameters in designing a capsule transporting pipeline is the pressure drop in the pipes carrying capsules and associated pipe fittings such as bends etc. Capsules are hollow containers with typically cylindrical or spherical shapes flowing in the pipeline along with the carrier fluid. The dynamic behavior of a long train of capsules depends on the behavior of each capsule in the train and the hydrodynamic influence of one capsule on another. Researchers so far have used rather simplified empirical and semi-empirical correlations for pressure drop calculations, the range and application of which are fairly limited. Computational Fluid Dynamics (CFD) based techniques have been used to analyze the effect of the presence of solid phase in hydraulic bends. A steady state numerical solution has been obtained from the equations governing turbulent flow in pipe bends carrying spherical capsule train consisting of one to four capsules. The bends under consideration are of 45^0 and 90^0 with an inner diameter of 0.1m. The investigation was carried out in the practical range of $0.2 \leq Vb \geq 1.6$ m/sec. The computationally obtained data set over a wide range of flow conditions has been used to develop a rigorous model for pressure drop calculations. The pressure drop along the pipe bends, in combination with the pressure drop along the pipes, can be used to calculate the pumping requirements and hence design of the system.

1. Introduction

Bends are an integral part of any pipeline network. The total pressure or power requirement for a piping network depends on pressure drop due to the bends along with the pipes. This is especially true for HCPs (Hydraulic Capsule Pipelines) which carry spherical or cylindrical capsules. Research on straight HCP pipelines is extensively available. However, limited research is available on pressure drop in bends carrying spherical capsules. Ulusarslan and Teke [1-4] have recently carried out experimental work to calculate the pressure drop in hydraulic pipe bends. They have shown that due to the presence of the solid medium in the flow, the pressure drop increases. This increase in the pressure drop is reflected in the increase in friction factor to be used in the equations. In order to completely understand the dynamic behavior of the capsules in the bends, and to analyze the effects of flow and geometry of the capsules on the pressure drop, CFD based analysis has been carried out for spherical capsules in pipe bends.

Nomenclature

k	Capsule to Bend Diameter ratio (-)	L	Length of the test section (m)
d	Capsule Diameter (m)	N	Number of Capsules (-)
D	Bend Diameter (m)	ΔP	Pressure drop (Pa)
ε	Bend's surface roughness (m)	ρ	Density (Kg/m^3)
f	Friction Factor (-)	Re	Reynolds Number (-)
g	Acceleration due to gravity (m/sec^2)	μ	Dynamic Viscosity (Pa-sec)
V	Flow Velocity (m/sec)	θ	Bend Angle (°)
n	Number of bends (-)		

Subscripts

p	Pipe	c	Capsule
b	Bulk	m	Mixture
w	Water		

2. Numerical Modelling

Three dimensional steady Navier-Stoke's equations have been numerically solved using commercially available CFD package FLUENT 6.3.26. Second order spatial discretization scheme with SIMPLE pressure-velocity coupling has been employed. The mesh incorporated is fine enough to capture all the important flow features. 'Figure 1' shows the geometrical setup for the case θ = 90°, N = 1 and d = 0.08m. The following assumptions have been made to solve the equations governing the turbulent flow in the capsule carrying bends:

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

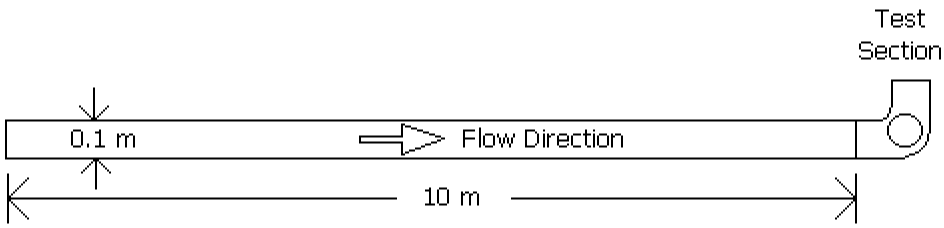


Figure 1. Geometrical setup of the Capsules in the Bend.

3. Results

The important non-dimensional parameters, as suggested by Ulusarslan [4], in order to develop a semi-empirical model for the calculation of pressure drop in the cylindrical capsule carrying hydraulic pipeline, are Reynolds number (for both water and capsules), capsule to pipe diameter ratio (k = d/D) and number of capsules (N).

3.1. Pressure Drop in Hydraulic Bends without Capsules

Figure 2 shows the variations in pressure drop per unit length for 45º and 90º pipe bends in the absence of capsules. The results depict that as the bulk velocity of the flow increases, the pressure drop in the bends increases. The difference between the pressure drops between both the bends is 8.38% on average with a standard deviation of 0.19%.

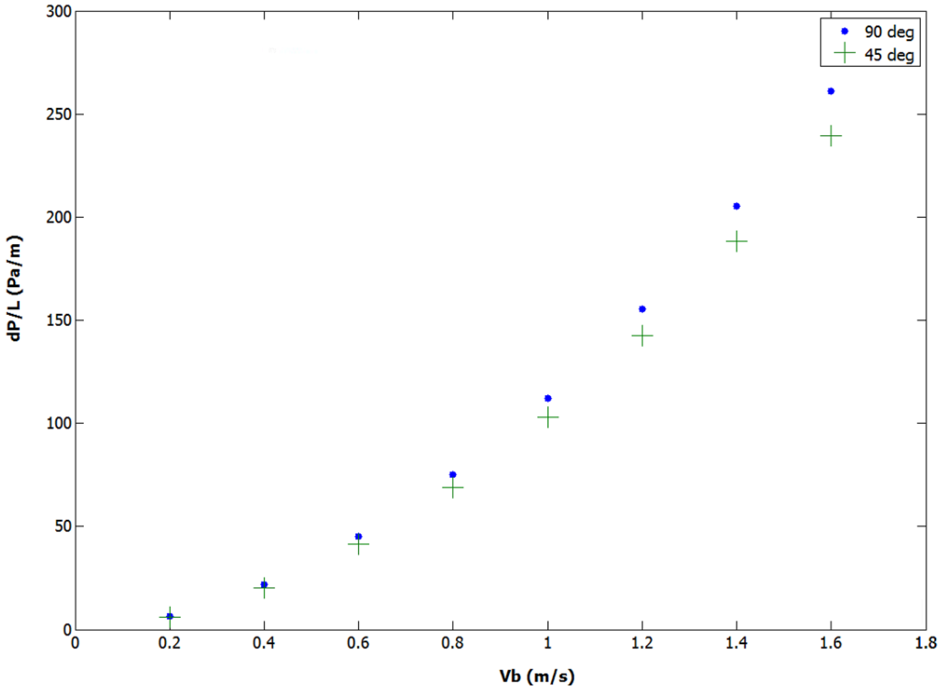


Figure 2. Variations in Pressure Drop in Hydraulic Bends.

The result, compared with that of Asim et al. [5] for a horizontal pipe, indicates that the pressure drop depends on the angle given to the flow i.e. angle of the pipe bend. For a flow velocity of 1.6 m/s, the pressure drop in a horizontal pipe and in the aforementioned bends is shown in table 1.

Table 1. Comparison of Pressure Drop in different pipe geometries.

Geometry	Pressure Drop
	(Pa/m)
Horizontal Pipe	210
45^0 Bend	240
90^0 Bend	260

The results in table 1 show that in 45^0 and 90^0 bends, the pressure drop is 12.5% and 19.2% more than that in a horizontal pipe respectively. Using curve fitting technique, it can be shown (figure 3) that the pressure drop in the hydraulic bends, without the presence of the solid phase, can be expressed as:

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

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

$$f_w = \frac{(0.06 * \mathrm{Sin}\theta)+0.177}{{Re_w}^{0.2}} \tag{2}$$

Where the Reynolds number of water can be computed from:

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

Equation (2) predicts the friction factor due to water in the bends with an average error of less than 5% and hence can be considered reasonably accurate. For the case when θ = 0°, which represents a straight pipe, equation (2) reduces to the form obtained by Asim et al. [5] for a horizontal pipe.

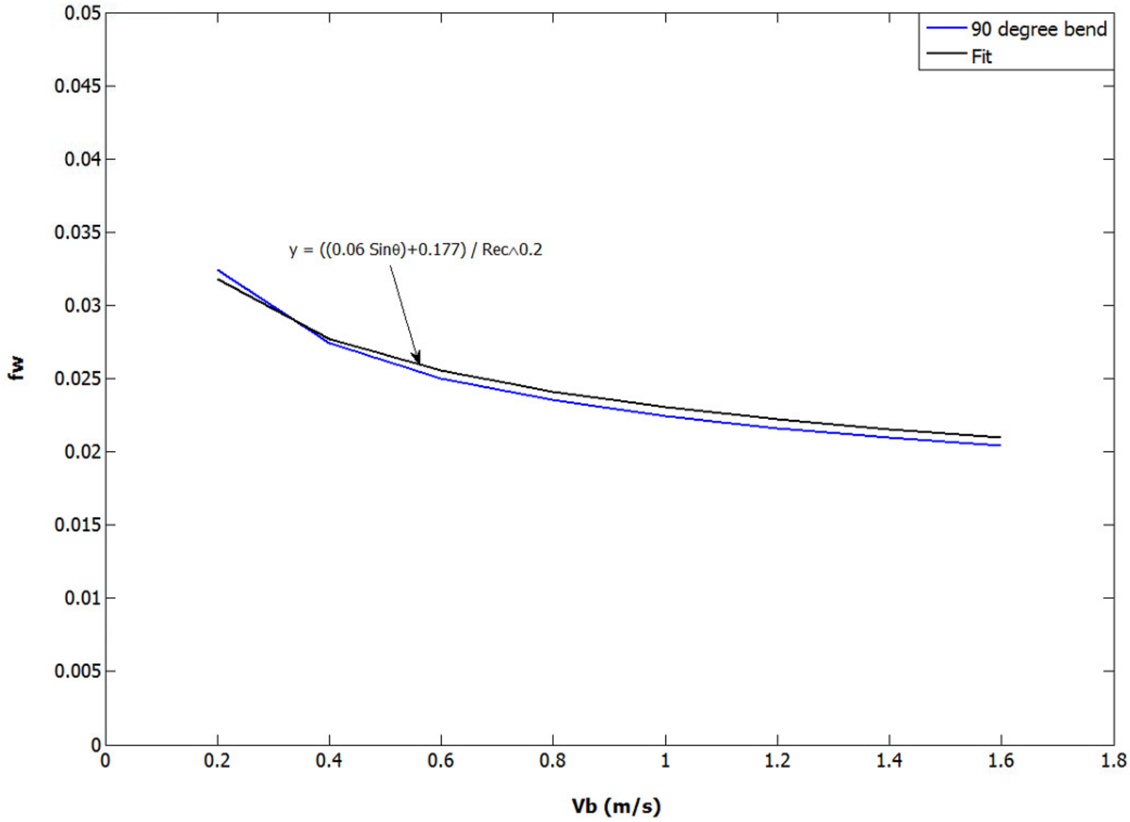
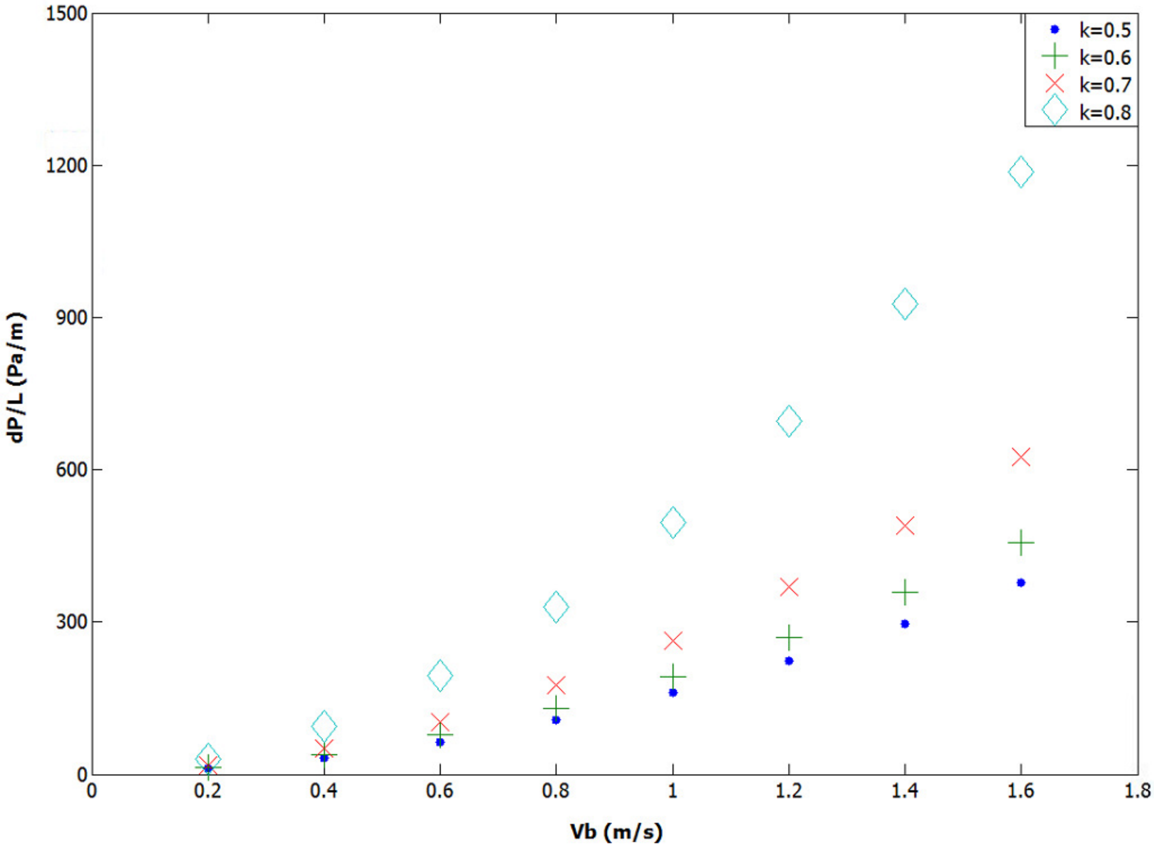


Figure 3. Variations of friction factor in hydraulic bends.

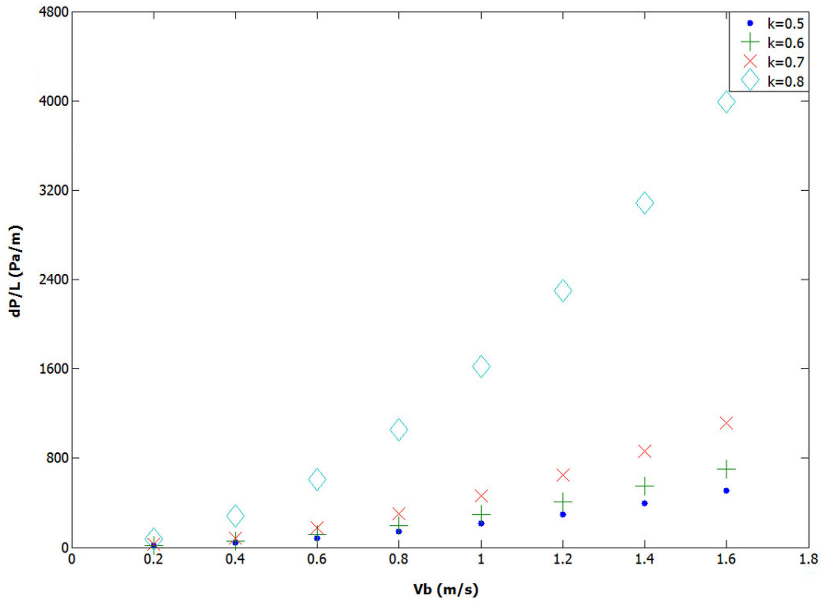
3.2. Pressure Drop in Capsule transporting Hydraulic Bends

Kroonenberg [6] states that the pressure drop in a capsule transporting hydraulic pipeline is more than the pressure drop in a hydraulic pipeline in the absence of capsule/s. This increase in the pressure drop due to the presence of solid phase is reflected in the friction factor. The same is true for pipe bends. The effect of the number of capsules, the diameter of the capsules and the flow velocity has been analyzed. Figures 4a and 4b show the variations in pressure drop per unit length at different bulk velocities in capsule transporting hydraulic bend with an angle of 90º.



(a) Pressure drop for one capsule.

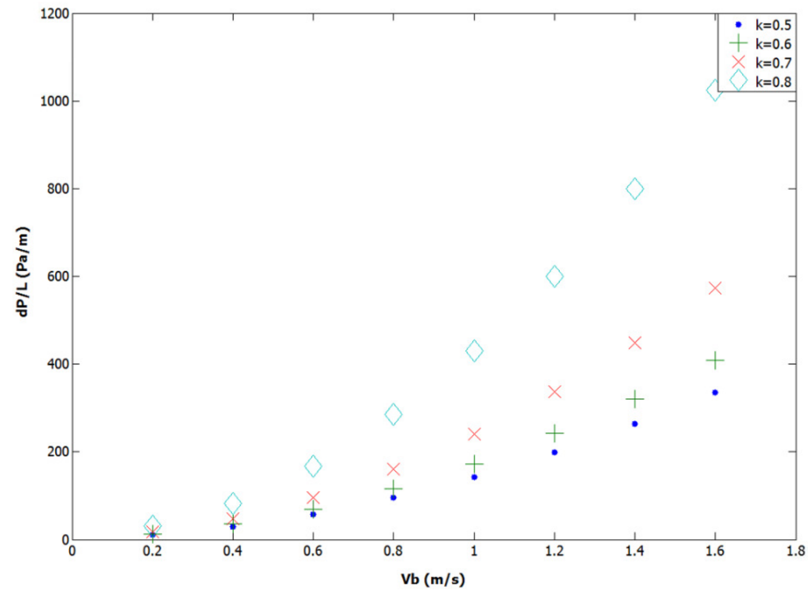
The results depict that the pressure drop increases as the bulk velocity increases. Furthermore, as the volumetric concentration of the solid phase in the bend increases, the pressure drop increases. Increasing the number of capsules in the bend and increasing the capsule to bend diameter ratio *k* increases the volumetric concentration of the solid phase in the bend.



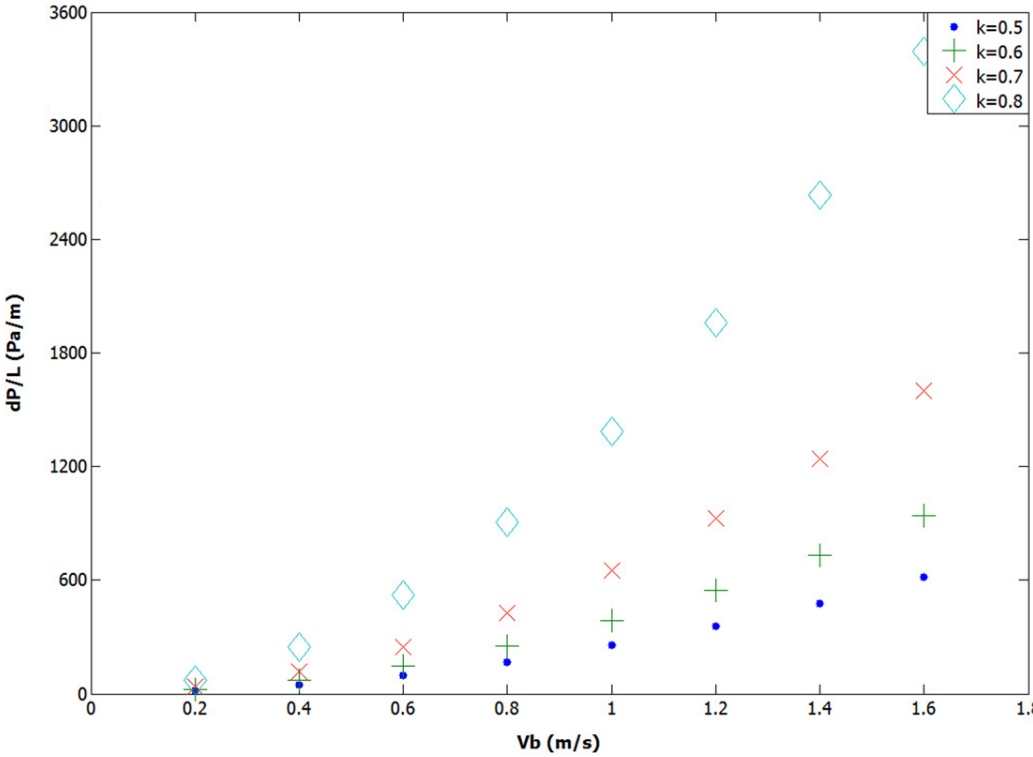
(b) Pressure drop for three capsules.

Figure 4. Variations in Pressure Drop for Spherical Capsules in 90° Hydraulic Bend, (a) N=1, (b) N=3

Figures 5a and 5b shows the same trends as figures 4a and 4b i.e. as the bulk velocity increases, the pressure drop increases. Furthermore, as the volumetric concentration of the solid phase in the bend increases, the pressure drop increases. By comparing figures 3 and 4, it can be seen that the pressure drop, at the same bulk velocity and for the same number of capsules in the bends, is more in the 90º as compared to the 45º bend. On average, the pressure drop in a 90º bend is 13% higher than the pressure drop in a 45º bend with a standard deviation of 3%.



(a) Pressure drop for one capsule.



(b) Pressure drop for three capsules.

Figure 5. Variations in Pressure Drop for Spherical Capsules in 45° Hydraulic Bend, (a) N=1, (b) N=3.

From the results presented in figures 3 and 4, pressure drop in capsule transporting hydraulic bends can be expressed as:

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

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

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

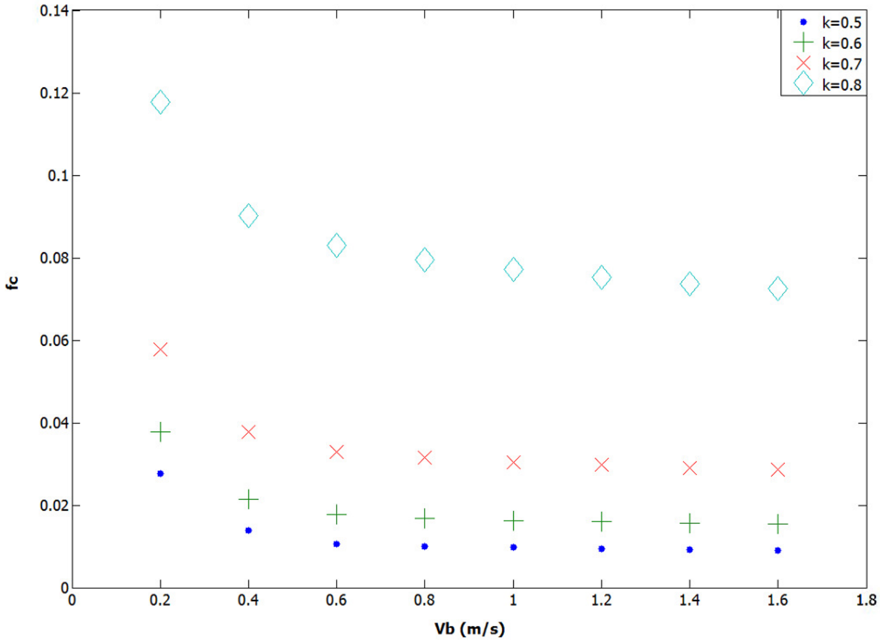
Where f_c is the friction factor for the solid phase in the mixture only i.e. for capsules. The steps involved in the determination of f_c from the results presented here are:

1. Calculate the pressure drop i.e. $\left(\frac{\Delta P}{L}\right)_m$ from CFD

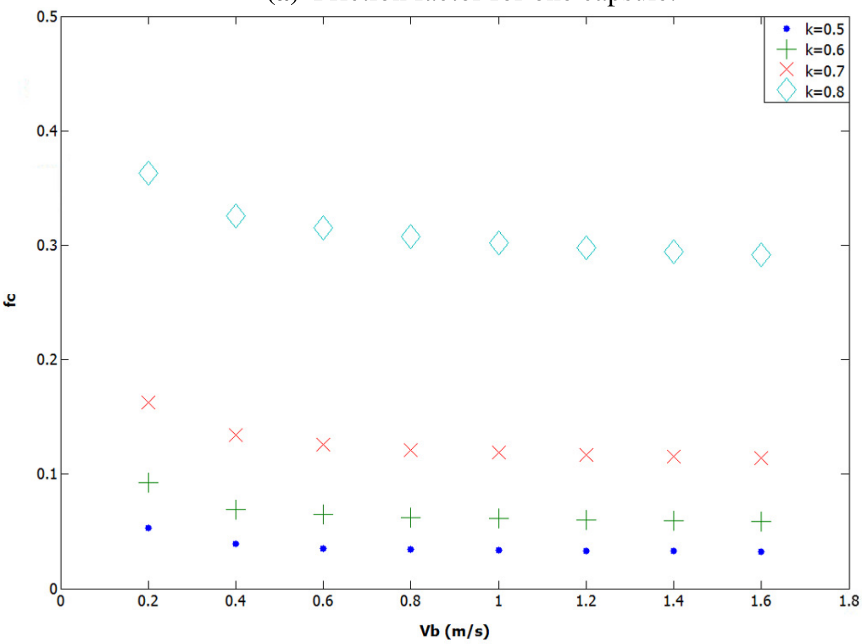
2. Divide this pressure drop by $\frac{\rho V^2}{2D}$. This will give the value of f_m

3. Subtract f_w from f_m to get the value of f_c

In order to develop a semi-empirical model for the calculation of pressure drop in spherical capsule transporting hydraulic bends, the curve fitting technique, as discussed earlier, has been applied for f_c data calculated using the above steps. Figures 6a and 6b show the variations in f_c at different Reynolds number of the capsule in a 90º pipe bend whereas figures 7a and 7b show the variations in f_c in a 45º pipe bend.



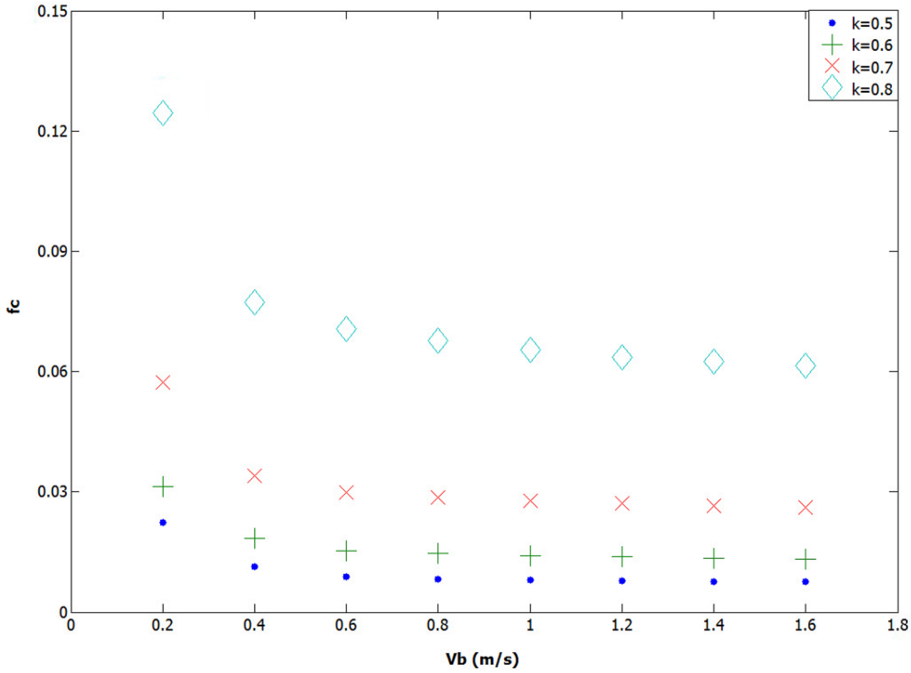
(a) Friction factor for one capsule.



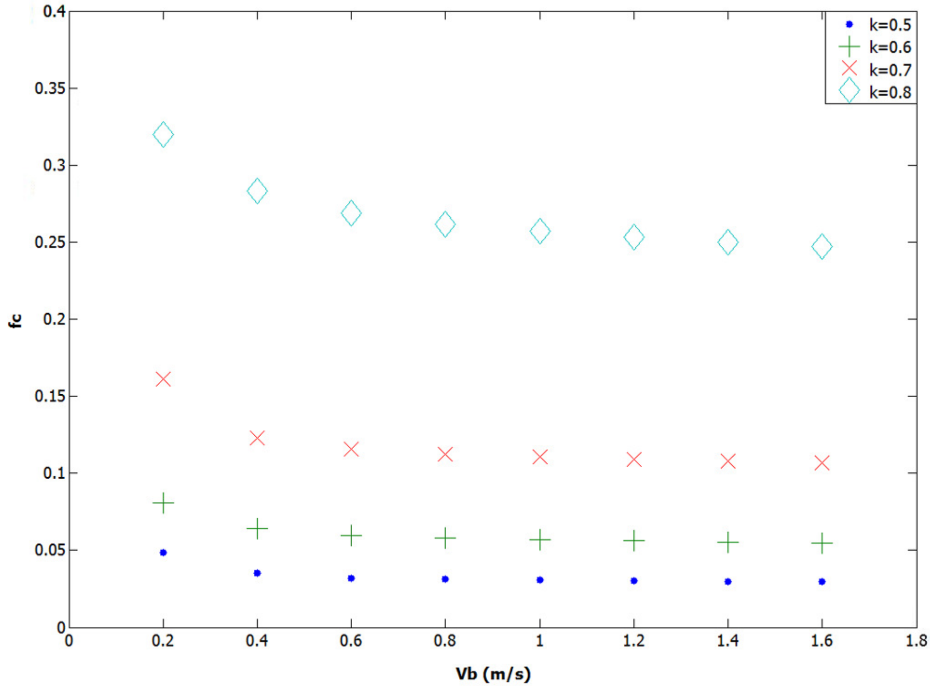
(b) Friction factor for three capsules.

Figure 6. Variations in fc for Spherical Capsules in 90° Hydraulic Bend, (a) N=1, (b) N=3.

The results show that as the bulk velocity increases, the friction factor due to the solid phase decreases. Furthermore, an increase in the volumetric concentration of the solid phase in the bend increases, the friction factor due to capsules increases.



(a) Friction factor for one capsule.



(b) Friction factor for three capsules.

Figure 7. Variations in fc for Spherical Capsules in 45° Hydraulic Bend, (a) N=1, (b) N=3.

Using the curve fitting technique (figure 8), the following relationship for the prediction of friction factor due to the capsules in hydraulic bends has been developed with less than 5% variation:

$$f_c = \{(0.0025 * N) + (0.0014 * Sin\theta) - 0.0021\} * \frac{e(7.5 * k)}{{Re_c}^{0.2}} \tag{6}$$

Where the Reynolds number of capsules can be computed used the following equation:

$$Re_c = \frac{\rho d V}{\mu} \tag{7}$$

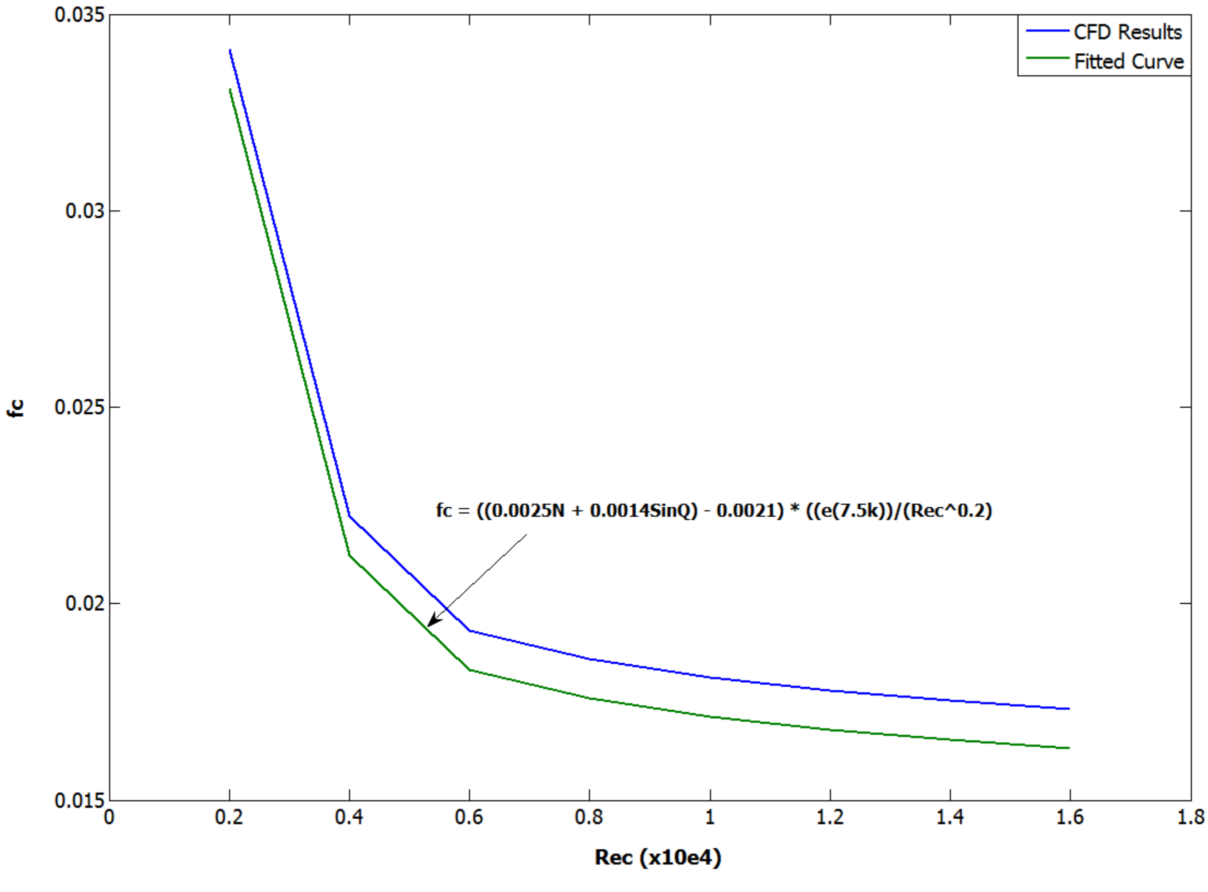


Figure 8. Variations in friction factor due to the capsule for $\boldsymbol{\theta}$=45^o, N=2 and k=0.5.

4. Conclusions

A methodology has been developed for the prediction of pressure drop in spherical capsules transporting hydraulic bends. Flow of equi-density spherical capsules of various diameters is simulated at different bulk velocities and pipe bends of different angles. The results indicate that the pressure drop, and hence head loss, in hydraulic capsule transporting bends increases as the bulk velocity, diameter of the capsules and the number of capsules increases. Furthermore, an increase in the bend angle increases the pressure drop. This increase in pressure drop is reflected in the friction factor due to the presence of solid medium in the flow. A rigorous semi-empirical model for the calculation of pressure drop has been developed which accounts for this increase in the friction factor with reasonably accuracy. The model developed here, along with the model developed by Asim et. al. [6], can be used to design a spherical capsule transporting pipeline.

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