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Computational Fluid Dynamics based Flow Diagnostics in Hydraulic Capsule Pipeline Bends

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1. Abstract

Hydraulic Capsule Pipelines (HCPs) are the third generation of pipelines that are based on the transport of hollow spherical, or cylindrical, capsules by the force exerted on them from the carrier fluid, which is water. These hollow capsules can be filled with a variety of cargo goods, such as minerals, jewellery etc. The hydrodynamics of this transport phenomena is quite complex, and researchers around the globe have been trying to analyse the hydrodynamics of such systems. However, most of these studies are based on experimental investigations, which can provide reasonably accurate results for the pressure drop etc. across the pipeline. However, the flow structure within HCPs cannot be easily mapped using experimental facilities. Furthermore, in case of pipe bends, the difficulty level increases exponentially due to a constant curvature in the geometry of the pipeline, and hence mounting the flow measuring instruments can be very challenging. The present study makes use of the advanced Computational Fluid Dynamics (CFD) based solvers, with powerful computing services, in order to analyse the flow structure within HCP bends. It is expected that this information can provide valuable information to the HCP designers, not only to calculate pressure drop across HCP bends, but in order to select the correct size etc. bends for the pipeline.

2. Introduction

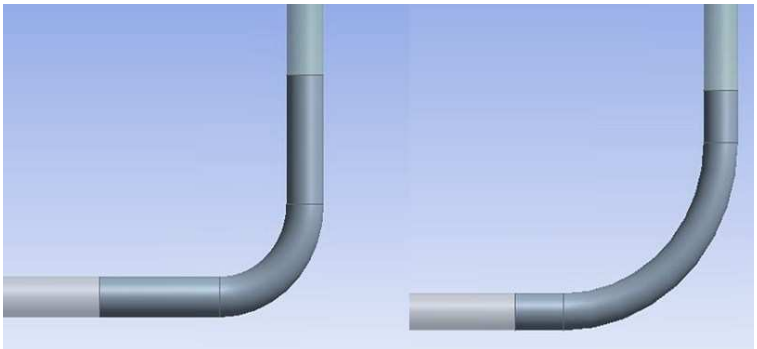
Bends are an integral part of any pipeline network. The bends contribute towards the minor losses in the pipelines. For practical designing of any pipeline, it is mandatory to accommodate the effects (commonly in terms of pressure drop or head loss) of the pipe bends for a realistic pipeline design. In order to achieve this for HCP bends, one must first understand the hydrodynamic behaviour of capsules in these. As the bends come in different sizes etc., a wide variety of investigations are required in order to fully understand the flow structure, and its dependency on the geometrical features of the bends.

Published literature regarding the flow of capsules in pipe bends is severely limited. Vlasak et al. [1] conducted experimental studies on the flow of heavy-density cylindrical capsules in both horizontal and vertical bends of various radii of curvature. The results presented for the velocity ratio and pressure gradient indicated that the pressure drop in vertical bends is significantly higher as compared to horizontal pipe bends. Furthermore, it has been reported that the radius of curvature of the bend has an insignificant effect on the velocity ratio of the capsules. Furthermore, Pavel et al. [2] conducted experimental studies on the flow of heavy-density cylindrical capsules in vertical bends of R/r=2 and Lc/D=5, where R is the radius of curvature of the bend, r is inner radius of the bend/pipeline, Lc is the length of the capsule/s and D=2r. The results indicate that as the average flow velocity increases within a pipe bend, the holdup also increases.

As can be seen that the published literature regarding the flow of capsules in HCP bends is based predominantly on experimental studies, determining the capsule/s velocity or pressure drop, the hydrodynamics of the capsule flow in HCP bends has not been investigated. The present study aims at numerically conducting a wide range of investigations, based on different geometrical parameters of the bends, on the static gauge pressure and flow velocity variations within horizontal HCP bends, transporting spherical capsules. It has been previously shown by researchers that CFD, along with experimental data, can be very useful in conducting flow diagnostics [3-12]

3. Numerical Modelling of HCP Bends

The geometry of the pipeline has been created in three separate steps. The first section is named as Inlet pipe, the second as Test section and the third as Outlet pipe. According to Munson et al. [13], it takes about 50D length of the pipe for the flow to become fully developed. As the pipe diameter considered in the present study is 0.1m (4"), therefore, the Inlet pipe of 5m length has been used for numerical investigations. Furthermore, an Outlet pipe of 1m length has been considered in the present study. Two different pipe bends of θ=90º configurations, having R/r equal to 4 and 8, have been used for the flow diagnostics of HCP bends, as shown in figure 1.



(a) (b)

Figure 1 Geometry of HCP bends (a) R/r=4 (b) R/r=8

The concept of hybrid meshing has been incorporated for the meshing of the flow domain. Two different meshes with 1 million and 2 million mesh elements were created for mesh independence testing. The results obtained depict that the difference in the pressure drop is less than 1% between the two meshes under consideration. Hence, mesh with a size of 1 million elements has been chosen for numerical investigations here, which is capable of accurately predicting the flow features within HCP bends.

The flow of capsules in an HCP bend is quite complicated to model as the trajectory of the capsules keeps on changing while passing through the bend. A novel modelling technique, called Discrete Phase Modelling (DPM), has been used in the present study to accommodate these effects. DPM is used for tracking the trajectory of particles in the flow domain. A particle having the same diameter and density as that of the capsule is injected at the inlet boundary of the pipeline. The history of the particle's trajectory and velocity in space has been monitored and recorded.

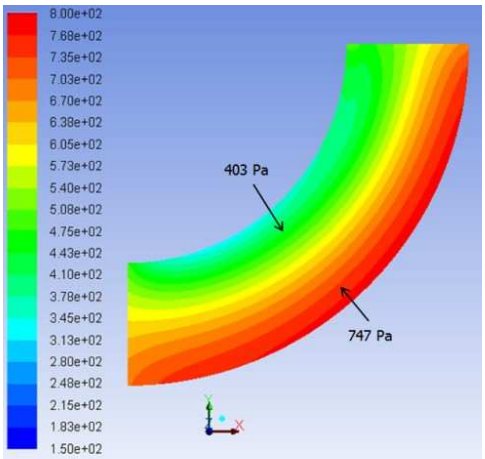
Three dimensional time averaged Navier Stokes equations, alongwith the continuity equation, have been iteratively solved for the steady turbulent flow of water and capsule/s in HCP bends. As the investigations carried out in the present study focuses on the turbulent flow in HCP bends, due to the formation of a wake region downstream of the capsule because of flow separation, SST k-ω model has been chosen for the modelling of turbulence. The primary reason behind choosing SST k-ω model is its superiority in accurately modelling the wake regions and extreme pressure gradients, which are expected to occur between the capsule/s and the pipe wall.

4. Results and Discussions

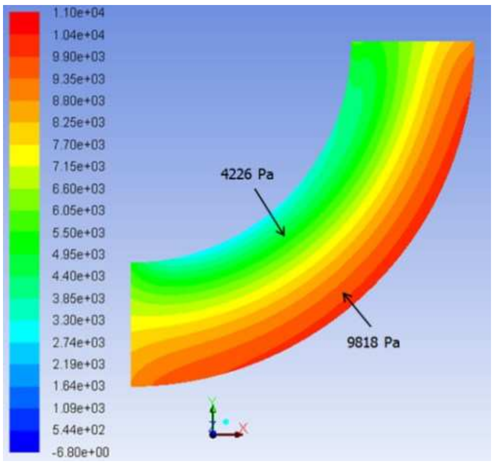
Before moving on to the flow of capsules in pipe bends, the flow structure of a single phase in within bends needs to be understood and validated. The static gauge pressure distributions within a pipe bend of R/r=4 at Vav=1m/sec is shown in figure 2. It is observed in figure 2(a) that the pressure on the outer wall of the bend is higher as compared to the inner wall due to the centrifugal force acting on water as it passes through the bend. Munson et al. [13] has provided with the loss coefficient values for various pipe fittings, including bends. For a hydrodynamically smooth pipe bend, the loss coefficient for R/r=4 is 0.26. This corresponds to a pressure drop of 130Pa across the bend. The pressure drop predicted by CFD is 132Pa. It can be thus concluded that CFD predict the pressure drop in a single phase flow within horizontal pipe bends with reasonable accuracy.

As compared to figure 2(a), it can be seen in figure 2(b) that the static gauge pressure on the outer wall has increased by 12 times, and on the inner wall by 9 times, when the average flow velocity of water increases by 4 times. The total pressure drop is 1644Pa, which is 11 times higher than for Vav=1m/sec, indicating that an increase in the average flow velocity increases the pressure drop in a horizontal bend. Moreover, as compared to figure 2(a), in figure 2(c) the static gauge pressure on the outer wall has decreased by 11%, and has increased by 20% on the inner wall of the bend, when a bend of R/4=8 is considered. The total pressure drop is 117Pa which is 11% lower than for R/r=4. Hence, an increase in the radius of curvature of the bend decreases the pressure drop due to reduced secondary flows. An important point to note in figure 2 is that the changes in the geometrical or flow parameters do not change the flow structure within bends.

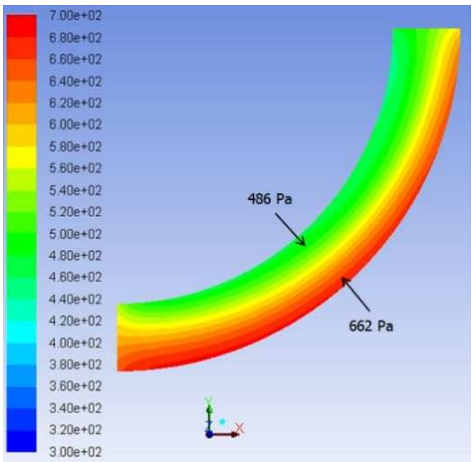
Figure 3 depicts the static gauge pressure distributions in horizontal HCP bends. Figure 3(a) corresponds to R/r=4 carrying a single spherical capsule of k=0.5 and having density equal to water, being transported at Vav=1m/sec. It can be seen that the pressure is higher at the upstream locations of the capsule, whereas it is considerably lower in the annulus region due to the area reduction for the flow. The pressure recovers to some extent downstream the capsule. The total pressure drop in this case is 169Pa, which is 28% higher as compared to the flow of water only in the same bend at the same average flow velocity. Hence, the presence of a capsule in a pipe bend increases the pressure drop across the bend.



(a)



(b)

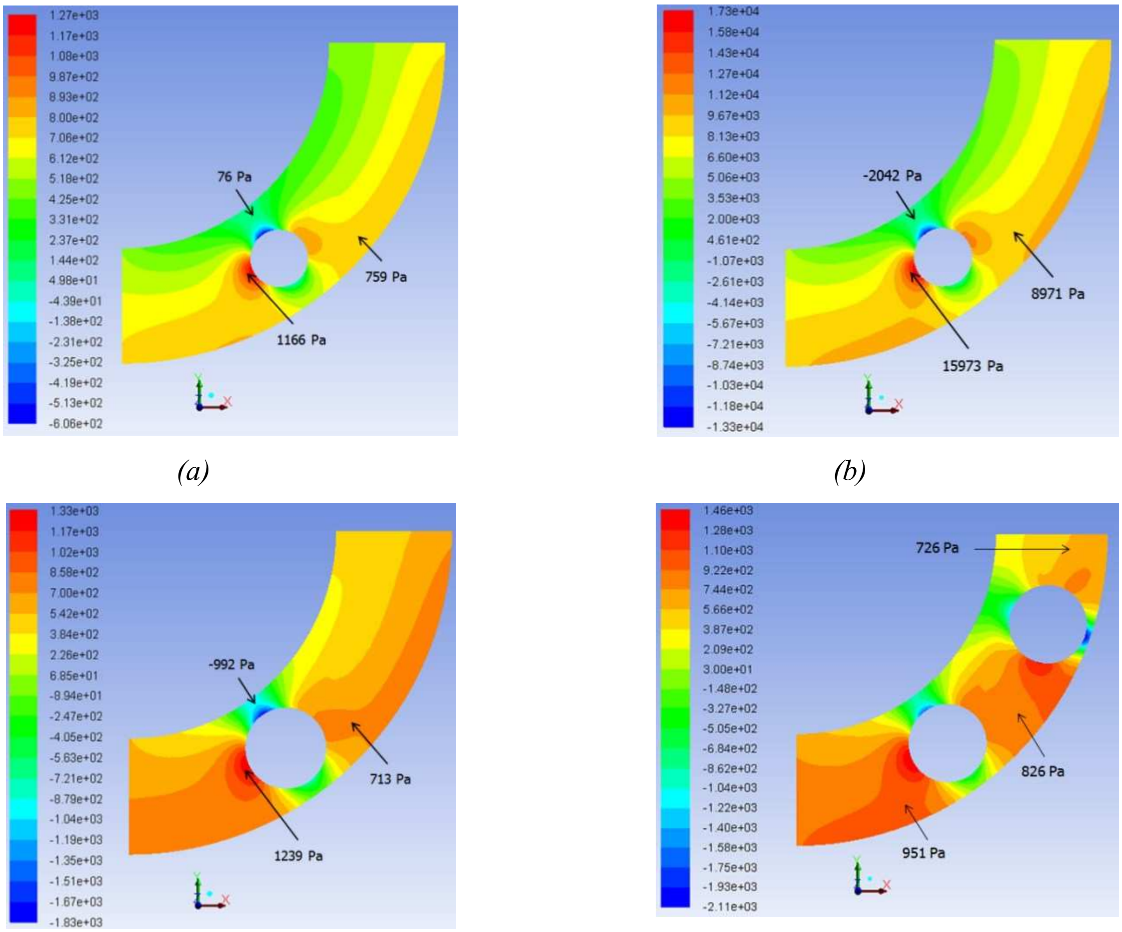


(c)

Figure 2 Variations in static gauge pressure in horizontal pipe bends for the flow of water (a) R/r=4 at Vav=1m/sec (b) R/r=4 at Vav=4m/sec (c) R/r=8 at Vav=1m/sec

Figure 3(b) depicts the static gauge pressure distribution for the case considered in figure 3(a), except that Vav=4m/sec in this case. The results depict that the trends are similar to the one observed in case of Vav=1m/sec. The static gauge pressure upstream the capsule has increased 12 times, while the pressure has decreased 27 times in the annulus region. The total pressure drop in this case is 2010Pa, which is 10 times higher as compared to the flow of an equi-density spherical capsule of k=0.5 at Vav=1m/sec in a horizontal pipe bend of R/r=4. Hence, increase in the average flow velocity within an HCP bend increases the pressure drop.

Figure 3(c) depicts the static gauge pressure distribution for the case considered in figure 3(a), except that k=0.7 in the present case. The results depict that the trends are similar to the one observed in case of k=0.5. The static gauge pressure upstream the capsule has increased by 6%, while it has decreased by 14 times in the annulus region. The total pressure drop in this case is 244Pa, which is 44% higher as compared to the flow of an equi-density spherical capsule of k=0.5 at Vav=1m/sec in a horizontal pipe bend of R/r=4. Hence, increase in the capsule diameter within an HCP bend increases the pressure drop.

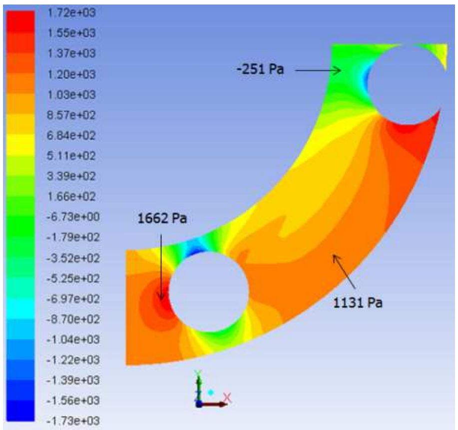


(a) *(b)*

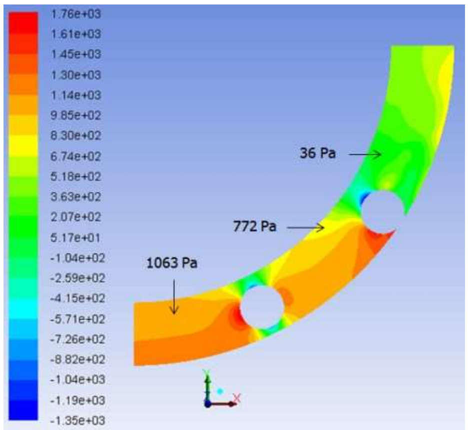
(c) *(d)*

Figure 3(d) depicts the static gauge pressure distribution for the case considered in figure 3(c), except that the number of capsules (N) in the bend has doubled. Furthermore, the spacing between the capsules (Sc) has been maintained to be equal to 1d. The total pressure drop in this case is 378Pa, which is 55% higher as compared to the flow of a single equi-density spherical capsule of k=0.7 at Vav=1m/sec in a horizontal pipe bend of R/r=4. Hence, increase in the concentration of the capsules within an HCP bend increases the pressure drop.

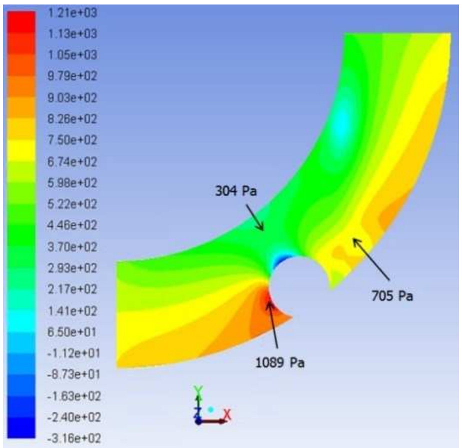
Figure 3(e) depicts the static gauge pressure distribution for the case considered in figure 3(d), except that Sc=3d in the present case. The total pressure drop in this case is 375Pa which is about the same as compared to the case where Sc is equal to 1d. Hence, increase in the spacing between the capsules negligibly changes the pressure drop within an HCP bend.



(e)



(f)



(g)

Figure 3 Variations in static gauge pressure in horizontal HCP bends (a) R/r=4, k=0.5, N=1 and Vav=1m/sec (b) R/r=4, k=0.5, N=1 and Vav=4m/sec (c) R/r=4, k=0.7, N=1 and Vav=1m/sec (d) R/r=4, k=0.5, N=2, Sc=1d and Vav=1m/sec (e) R/r=4, k=0.5, N=2, Sc=5d and Vav=1m/sec (f) R/r=8, k=0.5, N=2, Sc=5d and Vav=1m/sec (g) R/r=4, k=0.5, N=1 (heavy-density) and Vav=1m/sec

Figure 3(f) depicts the static gauge pressure distribution for the case considered in figure 3(e) except that R/r=8 in the present case. The total pressure drop in this case is 345Pa, which is 8% lower as compared to R/r=4. Hence, increase in the radius of curvature of the bend decreases the pressure drop due to reduced secondary flows within the bend

Figure 3(g) is of particular importance as it considers the flow of heavy-density spherical capsules in an HCP bend. The case considered in this figure is the same as in figure 3(a), except that the capsule is made of aluminium, having a specific gravity of 2.7. The first major difference is the trajectory of the capsule. It can be seen that the heavy-density capsule propagates along the outer wall of the bend, under the action of centrifugal force being acting on it. Furthermore, the flow structure downstream the capsule is considerably different to the flow of an equi-density capsule. The complex static pressure distribution downstream the capsule indicates the formation of secondary flows, which are expected to increase the losses in the bend, resulting in increased pressure drop across the bend. The total pressure drop in this case is 246Pa, which is 45% higher as compared to the flow of equi-density spherical capsule of the same diameter and at same average flow velocity. Hence, it can be concluded that heaver capsule in an HCP bend offer more resistance to the flow, increasing the pressure drop across the bends.

5. Conclusions

From the detailed numerical investigations presented in the present study, it can be concluded that the presence of a spherical capsule in an HCP bend can significantly alters the flow structure within the bend, resulting in increased pressure drop across it. Furthermore, increase in the average flow velocity, capsules diameter, number of capsules and the density of the capsules increases the pressure drop in an HCP bend. Increasing the radius of curvature of an HCP bend decreases the pressure drop across it. Moreover, there is negligible effect on the pressure drop across an HCP bend when the spacing between the capsule changes, within the range specified in the present study, and by keeping the capsule concentration the same in the bend. It has also been observed that heavy-density spherical capsules propagate along the outer wall of the bend, generating complex flow structures that give rise to secondary flows in the bends.

6. References

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