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RESEARCH ARTICLE

Computational fluid dynamics-based study on the heavy crude oil-water emulsion flow through sudden expansion, contraction and 90° bend

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ABSTRACT - Oil-in-water emulsion (O/W) can be prepared to transport heavy crude oil (HCO) through a pipeline effectively with reduced viscosity and pumping power. Various pipe fittings such as bend, elbow, sudden contraction, sudden expansion of pipe etc., are sometimes essential in the design of such pipelines. Energy losses take place due to skin and form friction during pipe flow. The determination of friction loss, which results in pressure losses, in pipes and fittings is crucial for the proper estimation of pumping power required for pipeline transport of the emulsions. The present study represents a numerical simulation of the emulsion flow through sudden expansion, contraction and 90° bend in the pipeline using a mixture model considering the prepared emulsion as a pseudo-homogeneous liquid. O/W emulsion was prepared at the optimum conditions of viscosity and stability with 25 %v/v water, 75 %v/v HCO and 4.5 % w/vsurfactant PS-81. The effect of parameters like average mixture velocity on pressure drop and pressure loss coefficient for various pipe fittings has been studied as laminar flow. The estimated value of the loss coefficient for the expansion, Ke, is 0.2313, and the loss coefficient for the contraction, K_c, is 3. Higher values of loss coefficient for contraction are due to higher pressure drop. For a 90° bend, as the average mixture velocity, and hence Reynolds number, increases, the pressure loss coefficient decreases. Within the range of velocity considered in the present study, an increase in pressure drop has been observed for sudden contraction, whereas a slight rise in pressure drop was found for sudden expansion. A nearly linear increase in pressure drop has been observed for a 90° bend. Pressure loss data caused by such pipe fittings are helpful in predicting additional pressure drops caused by them and, hence, an increase in pumping cost.

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1. INTRODUCTION

The increasing crude oil demand in the 21st century is mainly due to growing demands from major emerging economies like India, China, Brazil etc. The increasing demands for transportation fuels lead to HCO exploration and processing. HCO accounts for about 70 % of total oil reserves. The midstream oil sector has been pushed to explore economical ways to reduce the viscosity of HCO to make it suitable for pipeline transportation. This is due to the depletion of light crude reserves and the decreased production of the same. Transporting through a pipeline is the most convenient means for the transportation of crude petroleum continuously and economically. Among the techniques proposed, the most favourable one is to transport such highly viscous crudes as concentrated O/W emulsion [1–4].Surfactants are used to improve their flowability [5]. It is required to prepare an O/W emulsion with water as a continuous phase, as the viscosity of the continuous phase is always lower than that of the prepared emulsion [6].

The flow of O/W emulsions occurs not only in the petroleum industry but also in other industries like pharmaceutical, chemical, food, agriculture, etc. In many applications, sometimes it is essential to pump O/W emulsions through various pipes and pipe fittings such as tee, bend, valves, sudden contraction, and expansion. Energy losses take place in straight pipes mainly due to skin friction. Form friction mainly happens in pipe fittings due to sudden velocity and direction changes, which in turn cause additional energy losses. Determination of friction loss, which results in pressure losses in pipes and fittings, is essential for the selection of the required size of the pump and accurate estimation of the pumping power required [7, 8]. The flow of O/W emulsion through sudden expansion and contraction were studied experimentally by Hwang and Pal [9] and numerically by Roul and Dash [7] using the Eulerian–Eulerian model. Their findings revealed that the loss coefficient was not affected by the type of emulsion or its concentration. The determination of pressure losses has been done by extrapolating the estimated pressure profiles downstream and upstream of the contraction/expansion section [7]. The author concluded that the expansion and contraction loss coefficients were independent of the velocity and Reynolds number. They found that when the flow is abruptly expanded or contracted, viscosity has a negligible effect on pressure drop.

Properties of emulsions, which are comprised of droplets, are expected to be similar to pseudo-homogeneous liquids and can be calculated based on average value [10]. Consequently, the pressure loss associated with sudden contraction and expansion for emulsion flow should be estimated as for the fluid flow in a single phase. However, the loss coefficient

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was evaluated for the power-law fluid flow through bends, valves, and unions [11] using the two-K method [12]. Using the two-K method, the authors found good agreement between experimental and predicted values after adjusting the method for the data. Roul and Dash [7] reported that in two-phase oil-water emulsions and single-phase water flow, vena-contracta always formed at a distance of about 0.5 D after the contraction section, and it was influenced slightly by the velocity and concentration. However, Schmidt and Friedel[13] reported that in a two-phase flow, the vena-contracta phenomenon did not occur in their system. For a given system, models based on the phenomenon of vena-contracta generally assumed that the vena-contracta occur at the same location in single as well as two-phase flow and lead to a similar contraction ratio.

Pressure loss coefficients for different pipe connections are needed to estimate the additional energy loss and to suggest the right pump size. The data on loss coefficients available in the literature are limited to single-phase flows of Newtonian fluids. Industrial flows are complex, non-Newtonian and involve multiphase flows. Pressure loss coefficients are not readily available in the standard literature for such flows. Therefore, researchers have made several attempts to determine these coefficients. In an early work Griskey and Green [14] determined pressure loss coefficients for dilatant fluids. Telis-Romero et al. [15] had presented the data for the laminar flow of pseudoplastic fluids. Parameters for calculating loss coefficients by using the two-K method for laminar and turbulent flow for various pipe fittings are summarised in [11,16]. Now estimation of the loss coefficient for flow through different pipe fittings can be carried out by experiment or numerical simulation. Both methods have their pros and cons. In the present study, a computational fluid dynamics-based simulation approach has been selected to predict the loss coefficient and flow dynamics. Kumar et al. [17] studied the effect of temperature, HCO velocity and pipe diameter on the flow characteristics of HCO in three horizontal pipelines using Ansys Fluent 6.2. Alade et al. [18] simulated a steady, isothermal and laminar flow of O/W emulsion, considering a pseudo-homogeneous dispersed laminar flow using Comsol Multiphysics 5.4. Gudala et al. [19] studied HCO and water-dispersed flows numerically, with and without additives, in horizontal pipelines with the volume of fluid (VOF) model using Ansys Fluent. Kumar et al. [20] recently prepared O/W emulsions using anionic surfactant, linear alkylbenzene sulfonic acid. The authors studied the flow characteristics through horizontal pipelines at different pipe diameters and velocities with the help of simulation. They concluded that the pressure drops across the pipeline decreased with an increase in the pipe diameter, whereas it increased with the increase in the inlet velocity. Thus, CFD-based modelling and simulation enable complex and difficult flow studies and provide insight into complex flow physics. However, little study has been reported on the simulation of heavy crude oil-water emulsion systems through pipe fittings in literature.

The objective of the present study is the numerical simulation of O/W emulsion flow through sudden expansion, contraction and 90° bend in the pipeline using a two-phase flow mixture model. O/W emulsion has been prepared with 75 %v/v HCO, 25 %v/v water and 4.5 %w/v PS-81. Known data on the flow behaviour index and consistency index at different velocities have been used in a present simulation study. The laminar flow of prepared O/W emulsion was simulated, considering the emulsion to behave as a pseudo-homogeneous liquid to investigate the effect of parameters such as average mixing velocity on pressure drop and pressure loss coefficient for various pipe connections.

2. MATERIALS AND METHODS

2.1 Materials

In the present study, HCO and surfactant PS-81 were collected from ONGC Mehsana Asset, Gujarat and Matangi Industries, Ahmedabad, respectively. The surfactant is biodegradable and non-ionic, with an HLB value of 10. More details about the surfactant, the emulsion preparation method, and the characteristics are available in [21]. In the present study, emulsion with 75 %v/v HCO and 25 %v/v water with 4.5 %w/v surfactant was used for all simulations.

2.2 Preparation of Emulsion

The required quantity of the aqueous phase with a pH of 7 and the surfactant was mixed. Then, the required quantity of HCO was added to the aqueous surfactant mixture. After that, the mixture was heated to 45 ºC while stirring was continued. Stirring was done with a pitch blade agitator of Remi laboratory stirrer at 1400 RPM for 20 minutes. Details of the preparation method, its characteristics with droplet size distribution and functional group analysis are available [21].

2.3 Pipe Fittings and Dimensions

Figure 1 shows the pipe section for the investigation of the head loss coefficient and pressure loss. Figure 1(a) shows pipe geometry with a sudden expansion section. The diameter of pipe 1, D_1 is 0.01905 m, and pipe 2, D_2 is 0.0381 m. Figure 1(b) shows pipe geometry with a sudden contraction section. The diameter of pipe 3, D_3 is 0.0381 m, and pipe 4 D_4 is 0.01905 m. Figure 1(c) shows pipe geometry with a 90° elbow with a curvature ratio, R_c/D of 1.5. The length of upstream pipe 1 and downstream pipe 2 is 1 m, and the diameter is 0.0254 m.

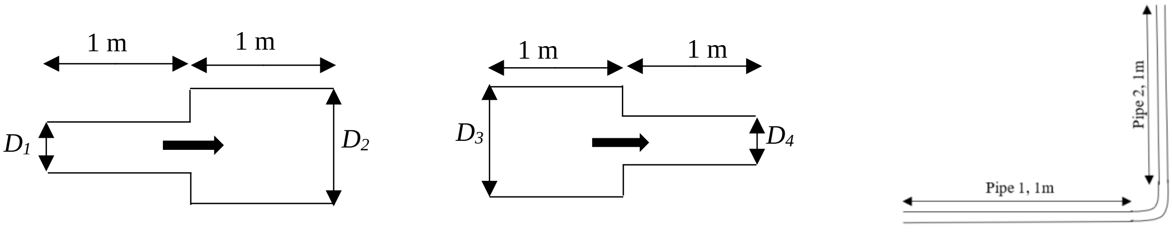


Figure 1. Pipe geometry: (a) sudden expansion, (b) sudden contraction and (c) 90° bend

2.4 Pipe Flow Equations

Considering the laminar flow of prepared emulsion as power-law fluid, wall shear stress, wall shear rate, shear viscosity friction factor, Reynolds number, and pumping power can be estimated using details available in[22]. Mechanical frictional energy loss, h_f due to sudden expansion or contraction of pipe cross-section can be estimated using the following equation.

$$h_f = \frac{P_1\text{-P}_2}{\rho} + \text{K}_1 \frac{U^2}{2} \tag{1}$$

where, h_f is frictional losses, pressure change at the expansion or contraction plane ($\Delta P = P_1 - P_2$), and U is the average velocity in the small diameter pipe. K_1 for the expansion and contraction plane can be defined as Eqs. (2) and (3) for expansion and contraction, respectively.

$$K_1 = \left[1 - \left(\frac{D_1}{D_2}\right)^4\right] \tag{2}$$

$$K_1 = \left[\left(\frac{D_3}{D_4}\right)^4 - 1\right] \tag{3}$$

where, K_2 is the slope of $\Delta P/\rho$ versus $U^2/2$ plot when $\Delta P/\rho$ versus $U^2/2$ plot exhibits a linear relationship for expansion ($\Delta P_e/\rho$) as well as for contraction ($\Delta P_c/\rho$).

$$\Delta P/\rho = K_2\, U^2/2 \tag{4}$$

From Eqs. (1) and (4),

$$h_f = (K_1 + \text{K}_2)\frac{U^2}{2} \tag{5}$$

Thus, loss coefficient K, for expansion, K_e and contraction K_c can be expressed by:

$$K = K_1 + \text{K}_2 \tag{6}$$

The friction coefficients in laminar flow for valves and fittings vary with the Reynolds number; K_f increases with a decrease in the Reynolds number. Another approach that is not very popular is the method developed by Hooper known as the two-K method, which is a correlation between Reynolds number, pressure drop coefficient, and the fitting diameter, D through Eq. (7) [8,11,16].

$$k_f = \frac{k_1}{R_e} + \text{k}_\infty \left(1 + \frac{1}{D}\right) \tag{7}$$

2.5 Mixture Model

The two-phase flow mixture model comprises of the continuity, momentum and energy balance equations. Details of the model are available in [23]. The continuity equation for oil-water emulsion can be written as Eq. (8).

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0 \tag{8}$$

where, $\vec{v}_m$denotes the mass averaged velocity and is given by Eq. (9).

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k\, \vec{v}_k}{\rho_m} \tag{9}$$

the mixture density ρ_m is expressed as Eq. (10).

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \tag{10}$$

where, α_k is the volume fraction of phase k.

The momentum equation for the emulsions is obtained by summing the individual momentum equations for all phases. It can be expressed as Eq. (11):

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m(\nabla \vec{v}_m + \nabla \vec{v}_m^T)] + \rho_m \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \quad (11)$$

Here, n is the number of phases, $\vec{F}$ is the body force, and μ_m is the viscosity of the emulsion and given by Eq. (12):

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \quad (12)$$

where, $\vec{v}_{dr,k}$ is the drift velocity for the secondary phase k:

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \quad (13)$$

2.5 CFD-based Simulation Scheme

Simulation of O/W emulsion flow was performed using a mixture model and ANSYS Fluent 2019 R3, where the emulsion flow was considered to be a single-phase, incompressible and isothermal flow. A 2D computational domain was created using appropriate quadrilateral mesh elements to reduce the computational time. Grid independence test has also been carried out to find the optimum number of elements. At the inlet, the velocity boundary condition is applied. No-slip boundary conditions are used at the pipe wall. At the outlet, the outflow boundary condition is used, which means diffusion flux for all the variables in the exit direction is zero. The flow domain, as shown in Figure 1, has been used for the simulation study. The coupled first-order upwind scheme was used for the discretization of sudden expansion and contraction domains. However, for the 90° bend to resolve the coupling between pressure and velocity fields, the SIMPLE algorithm with a second-order upwind scheme was used. For all the variables, convergence criteria were set at 10^{-6} for all residuals. Velocity profiles and pressure drops across sudden expansion and contraction planes have been estimated. Calculated pressure profiles downstream/upstream of the contraction/expansion plane are extrapolated to determine pressure losses. The flow field is solved in two dimensions to reduce computation time.

3. RESULTS AND DISCUSSION

3.1 Model Validation and Grid Independency Test

Characterization of the heavy crude, PS-81 and viscosity data of the prepared emulsion is available in our previous work Vegad and Jana [21]. CFD simulation work of Alade et al. [18] has been reproduced using a mixture model in ANSYS Fluent to validate it. The estimated pressure drop using Ansys Fluent is 930 Pa as compared to 931 Pa reported in Alade et al. [18]. Pressure, velocity and viscosity profiles have been regenerated, which were similar to those reported by Alade et al. [18] with 70 %HCO content at 30 ºC. Less than 1 % error in pressure drop estimation shows good agreement, and the same model was selected in the present work. Grid independency test for three pipe geometries at an average mixture velocity of 2 m/s has been carried out, as shown in Figure 2, for 4.5 % w/v PS-81 O/W emulsion. Observed pressure drop remains almost constant at 1582 Pa, 8327 Pa and 10277 Pa beyond 2533460, 2250000 and 1035532 mesh elements for sudden expansion, sudden contraction and 90° bend geometries, respectively. Based on the grid independency test, as shown in Figure 2, pressure, velocity, and other profiles have been evaluated in the present study.

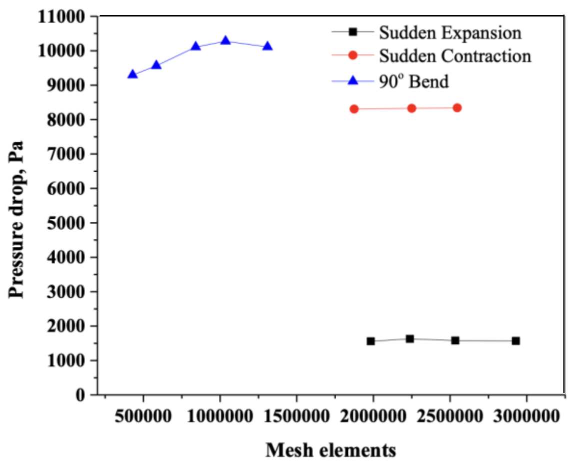
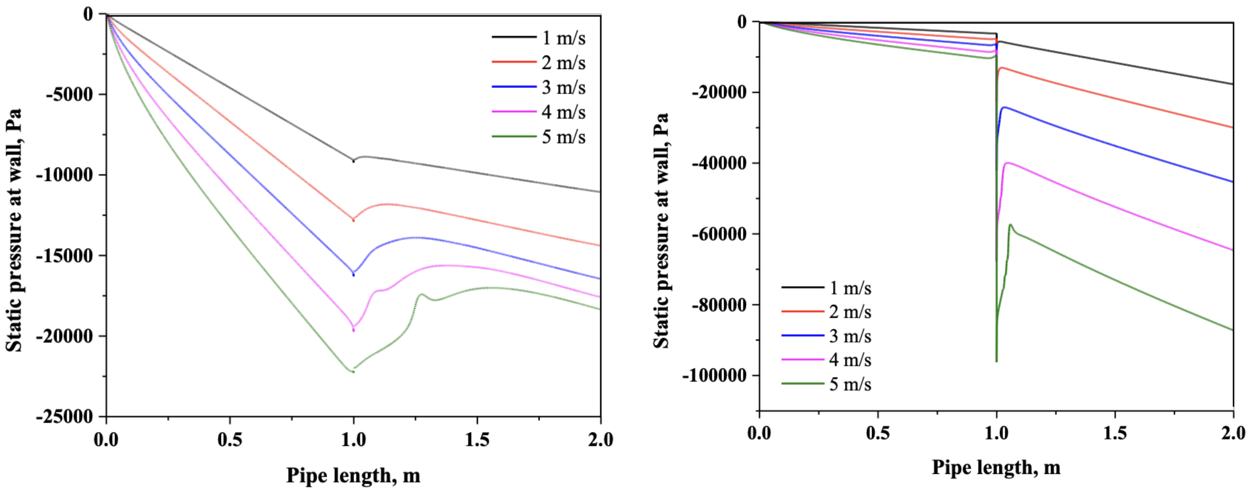


Figure 2. Grid independence test for all three pipe geometries

3.2 Pressure and Velocity Profiles

3.2.1 Sudden expansion and contraction of cross-section

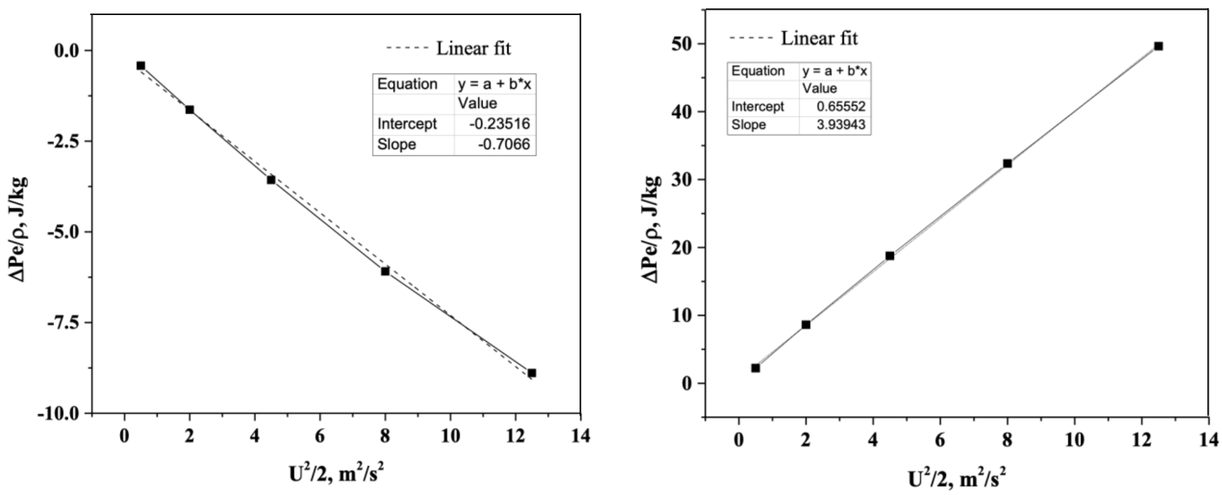
Figure 3(a) shows the variation of pressure along the length of the pipe at different velocities for a steady-state flow of O/W emulation through sudden expansion of pipe cross-section. A steady decline in pressure is observed due to frictional loss in the upstream section. The pressure drops value increases with the increase in average mixture velocity. As the fluid reaches the expansion plan, a rise in pressure is observed due to the slowing in the flow. At the expansion plane, sudden change in pressure is estimated by extrapolating the estimated pressure profiles downstream and upstream of the expansion plane to the expansion plane in the fully developed flow regime. Figure 3(b) shows the variation of the steady-state pressure along the pipe length at different velocities across the contraction plane. Pressure reduction in the inlet section of the pipe has been observed due to frictional losses. As the fluid reaches the transition section, the fluid accelerates in the contracted pipe area, and a pressure drop occurs. The pressure change at the contraction plane is determined by extrapolating the assessed pressure profiles downstream and upstream of the pipe contraction, as in the case of sudden expansion. The pressure drops increase with the increase in fluid velocity.



(a) (b)

Figure 3. Pressure profile for O/W emulsion flow: (a) sudden expansion and (b) sudden contraction

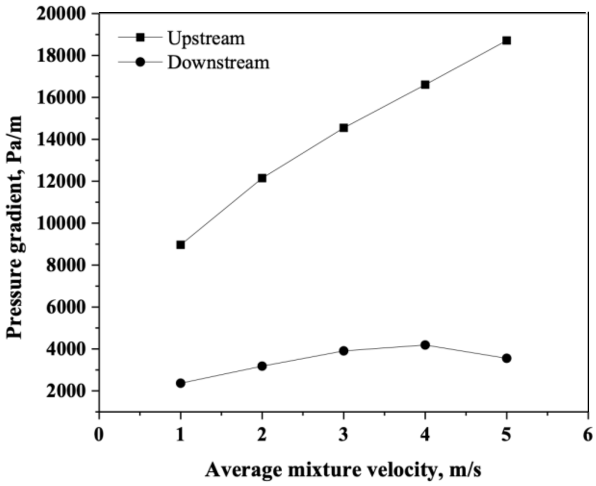
Figure 4(a) shows $\Delta P_e/\rho$ versus $U^2/2$ curve for emulsion flow through sudden expansion where ΔP_e is pressure changes at the expansion plane that can be determined by extrapolating the calculated profiles of pressure downstream and upstream of the pipe. The slope of this curve gives the value of K_2. From Figure 4(a), K_2 is -0.7066. Figure 4(b) shows $\Delta P_e/\rho$ versus $U^2/2$ curve for the emulsion flows through the sudden contraction. The slope of this curve gives the value of K_2 of 3.9394.



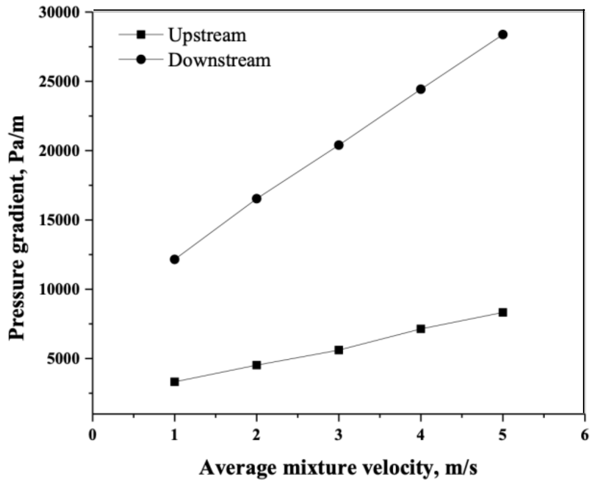
(a) (b)

Figure 4. Plot of $\Delta P_e/\rho$ versus $U^2/2$ for O/W emulsion flow: (a) sudden expansion and (b) sudden contraction

From Figure 5(a), pressure gradients are measured at the upstream and downstream with fully developed flow regimes. It can be observed that pressure gradient values are lower in the downstream section than in the upstream section. As average fluid velocity increases, pressure gradient values increase in both sections of the pipe. The rise in pressure gradient values with velocity is more in the upstream section as compared to the downstream section. With the rise in velocity pressure gradient is expected to increase, but it is showing a reduction in pressure as the velocity increases from 4 m/s to 5 m/s. From Figure 5(a), as average emulsion velocities increase, for flow to become fully developed, the required length of the pipe in the downstream section also increases. At a velocity of 5 m/s, we can still observe a reduction in average velocity even at a 2 m pipe length. This results in a lower pressure gradient measurement, as shown in Figure 5(a). From Figure 5(b), pressure gradients are measured in the upstream and downstream with fully developed flow regions. It can be observed that pressure gradient values are higher in the downstream section as compared to the upstream section. As average velocity increases, pressure gradient values increase in both sections of the pipe. The rise in pressure gradient values with velocity is more in the downstream area as compared to the upstream section. The difference in pressure gradient between upstream and downstream increases with an increase in velocity, as can be observed from Figure 5(b). Thus, measured pressure gradient values are higher in the upstream section for the sudden expansion section as compared to the downstream section within the range of average velocity considered, while pressure gradient values are higher in the downstream section for the sudden contraction section as compared to the upstream section.

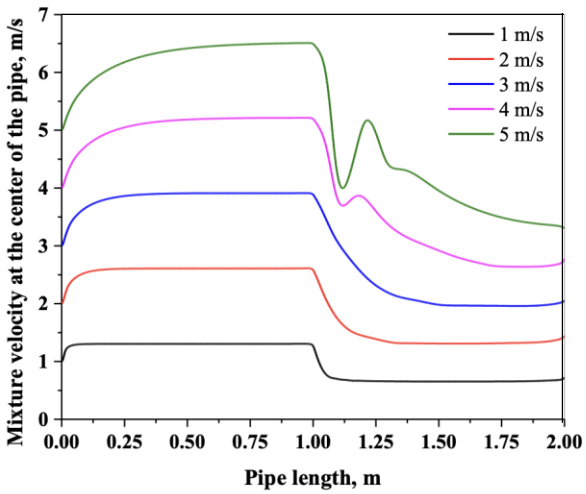


(a)

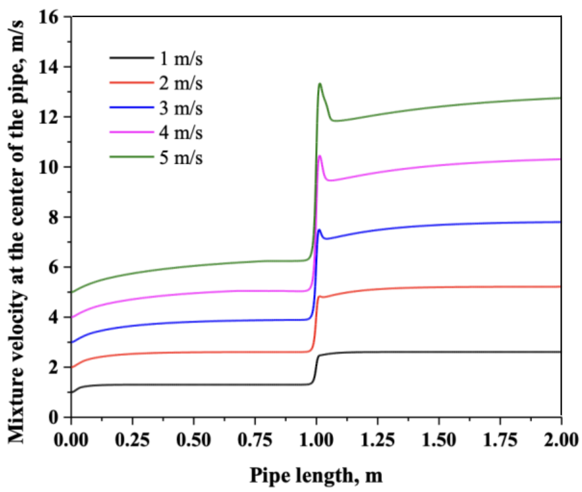


(b)

Figure 5. Pressure gradients at different average mixture velocities: (a) sudden expansion and (b) sudden contraction



(a)



(b)

Figure 6. Velocity profile at the centre of the pipe: (a) sudden expansion and (b) sudden contraction

From Figure 6(a) and (b), it can be observed that after the expansion and contraction plane, transition length (pipe length required for flow to become fully developed) increases with an increase in average mixture velocity. From Figure 6(b), the approximate location of vena contracta at 3, 4 and 5 m/s velocities can be observed at the maximum velocity point nearer to the centre of the pipe towards the downstream pipe section. At velocities of 1 and 2 m/s, the vena contract is not observed in Figure 6(b). Figure 7 shows velocity profiles for sudden expansion as well as contraction of cross-section pipe geometry in a fully developed flow region for 3 m/s inlet velocity. From Figure 7, the velocity profile at 0.8 m distance from the pipe entrance is similar for both geometries. The same can be observed in Figures 6(a) and (b). Then, based on the sudden expansion/contraction of the pipe, we can observe a decrease/increase in maximum velocity at the centre of the pipe. On the other hand, from Figure 3(a) and (b) at a constant average velocity of the mixture in the upstream section of both the pipe geometries, we can observe more increase in pressure drop for sudden expansion geometry as compared to sudden contraction geometry mainly due to smaller diameter of the pipe in sudden expansion geometry. The same can be observed for the upstream pipe section from Figure 5(a) and (b). From Figure 6(a), it can be observed that after the expansion plane, transition length (pipe length required for flow to become fully developed) increases with an increase in average mixture velocity.

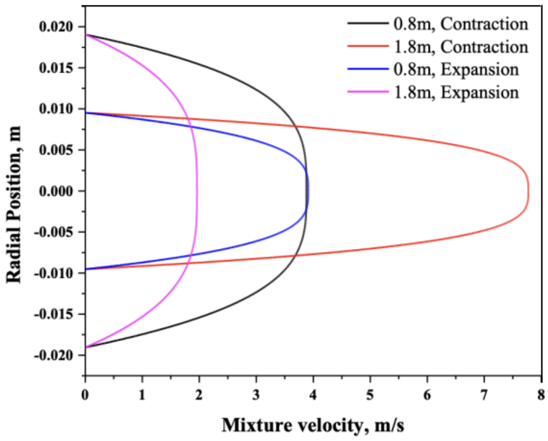
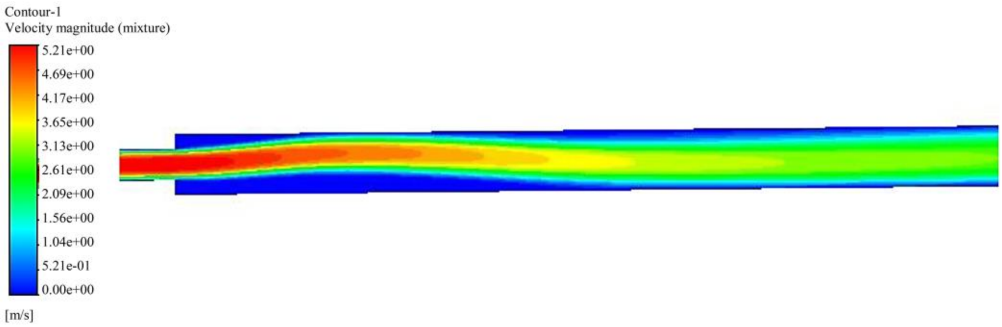
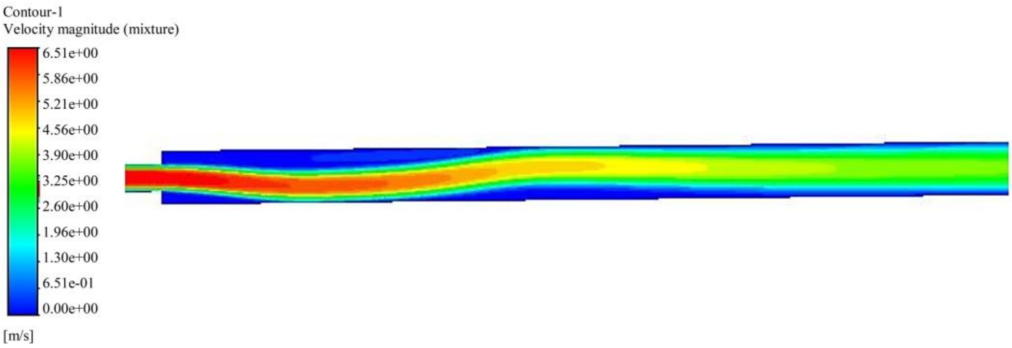


Figure 7. Velocity profiles for sudden expansion as well as contraction of cross-section pipe geometry, in a fully developed flow region for 3 m/s inlet velocity

From Figure 8-(a) and (b) at velocities 4 and 5 m/s, respectively, it can be observed that as velocity increases, the jet of emulsion enters from upstream into downstream via the expansion section, causing a sudden reduction in velocity. These jets of emulsion enter into a downstream section for some distance and get mixed with surrounding low-velocity fluid. This causes fluctuations in the average velocity of emulsion, as can be observed in Figure 8, in the downstream section, at 4 and 5 m/s velocities. Figure 9 shows the velocity contour for sudden contraction geometry in the contraction section region. Due to the sudden reduction in the cross-section, we have observed a sudden rise in velocity in the contraction pipe section. The similar velocity behaviour can be observed from Figure 6(b). Figure 10 shows a static pressure contour plot at 5 m/s velocities for sudden expansion and sudden contraction geometries, respectively. A gradual reduction in static pressure has been observed from inlet to outlet in sudden expansion geometry, while a sudden rise in pressure in the downstream pipe at the contraction pipe section has been observed. A similar static pressure behaviour can be observed in Figure 3.



(a)



(b)

Figure 8. Velocity contour for the sudden expansion of cross-section pipe geometry at velocity: (a) 4 m/s and (b) 5 m/s

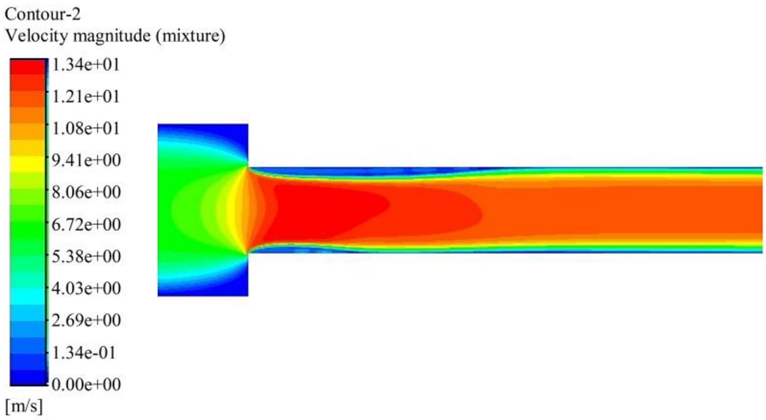
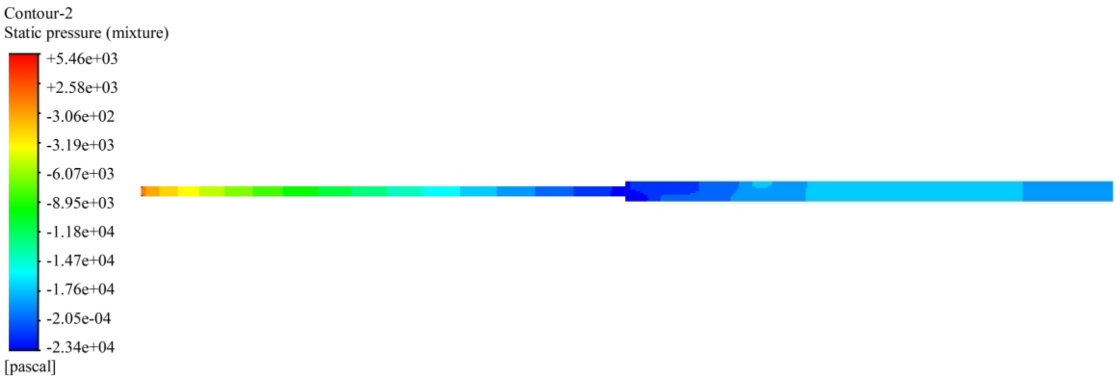
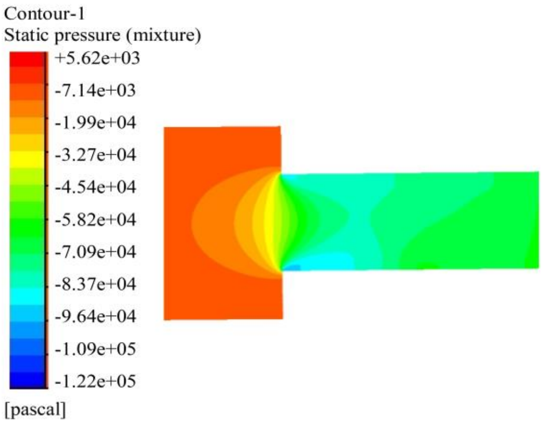


Figure 9. Velocity contour for sudden contraction of cross-section pipe geometry for 5 m/s



(a)



(b)

Figure 10. Pressure contour at 5 m/s velocity for: (a) sudden expansion of cross-section pipe geometry and (b) sudden contraction of cross-section pipe geometry

3.2.2 90° bend geometry

Figures 11(a) and (b) show the centreline pressure profile for pipe with a 90° bend for 2 m/s average velocity at optimum mesh elements of 1035532. Figures 11(c) and (d) show the pressure profile at various cross sections in pipe 1 and pipe 2. From both of these figures, it is clear that pressure reduces from the inlet to the outlet.

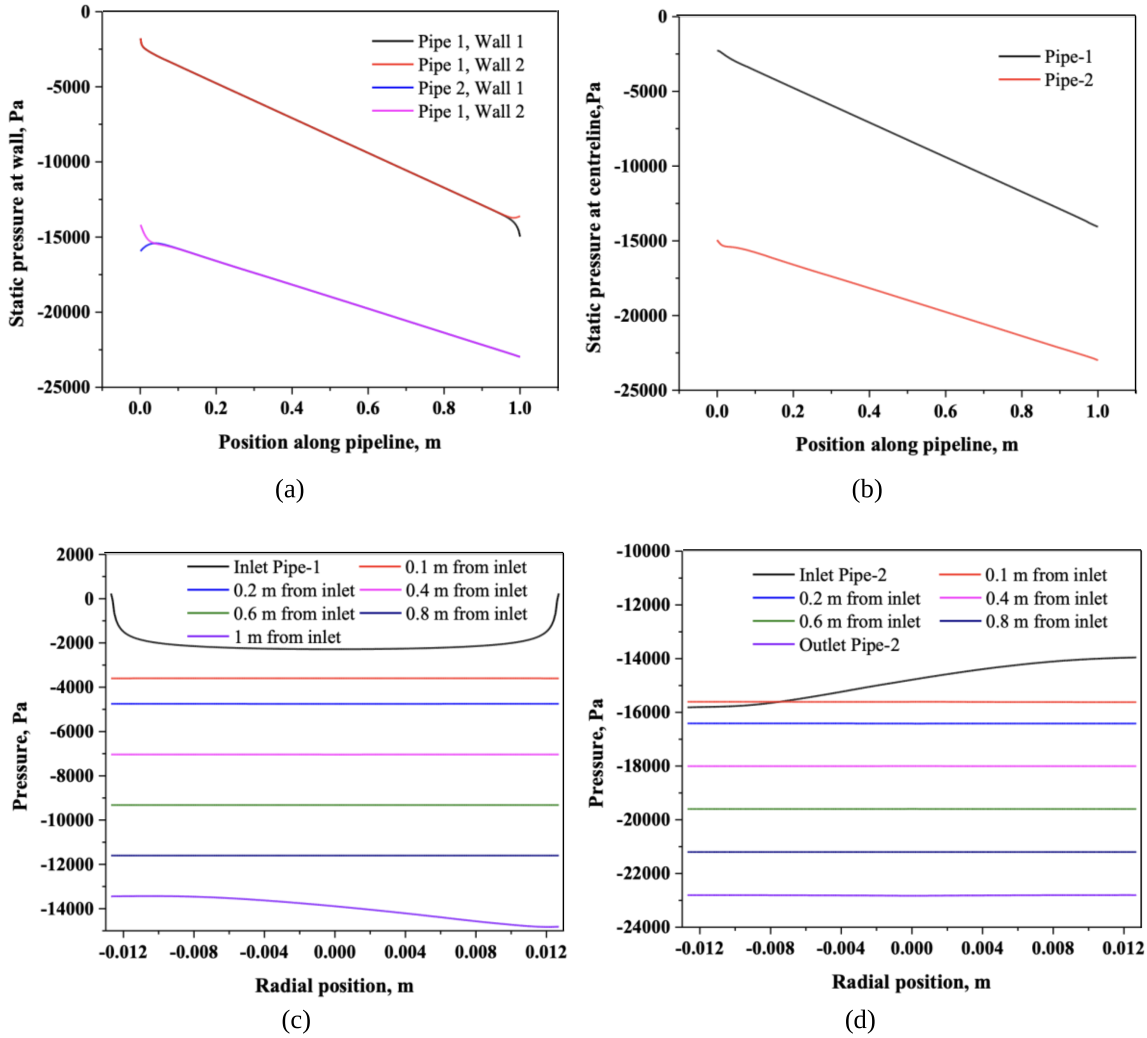


Figure 11. Pressure profile at 2 m/s velocity in both the pipes: (a) at the wall, (b) at the centerline, (c) in pipe-1 and (d) in pipe-2

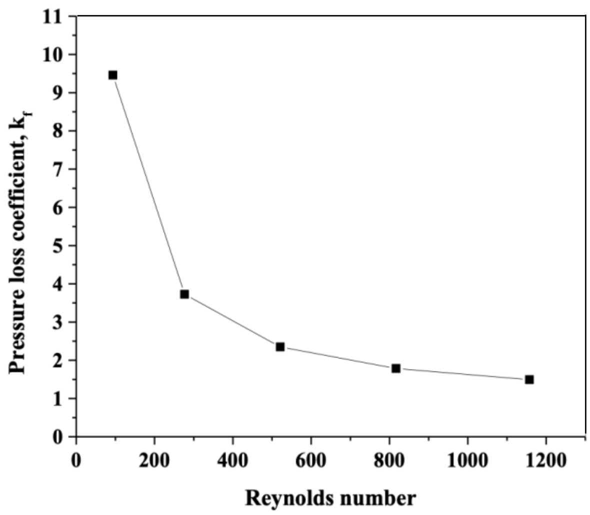


Figure 12. Pressure loss coefficient for 90° bend

3.3 Effect of Velocity on Pressure Loss Coefficient

In the present work, the estimated value of the loss coefficient for the expansion, $K_{e,}$ is 0.2313, and the loss coefficient for the contraction, $K_{c,}$ is 3. Hwang and Pal [9] prepared O/W or W/O emulsions with viscosity values below 13 mPa.s and estimated the average value of loss coefficient to be 0.47, all in the turbulent flow regime. In the present work for sudden contraction, higher values of loss coefficient, all in laminar flow regime which are due to higher viscosity of the emulsion (> 500 mPa.s at 30 °C) and hence frictional losses resulting in higher pressure drops. Similarly, for sudden expansion geometry, a small value of pressure loss coefficients is due to better pressure recovery in the expansion section. This can be observed in Figure 12. For 90° pipe bend, K_1 and K_∞ values are 812.2 and 0.3955, respectively [11,16]. The diameter of pipe fitting, (D) is 1 inch. Applying these values in Eq. (7) at different average mixture velocities results in values of pressure loss coefficient, K_f as shown in Figure 12. As the average mixture velocity, and hence Reynolds number, increases pressure loss coefficient decreases. From Eq. (7), it is clear that the pressure loss coefficient is inversely proportional to the Reynolds number.

3.4 Pressure Drop Analysis

From Figure 13, the pressure drop for the entire pipe length increases with the increase in average mixture velocity. The exponential growth in pressure drop was observed for sudden contraction as compared to a nearly small rise in pressure drop for sudden expansion geometry. An almost linear increase in pressure drop for the 90° bend has been observed. This information helps us in predicting additional pressure drops caused by pipe fittings and hence an increase in pumping cost. From Figure 13, sudden contraction results in higher pressure drop and therefore pumping power among all geometries considered in the present study.

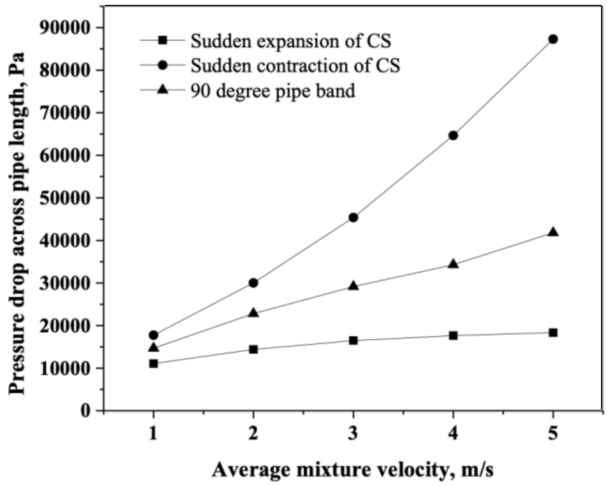


Figure 13. Pressure drop over three different pipe geometries for the entire length of 2 m

4. CONCLUSIONS

Pressure drops through sudden contractions, expansions, and 90° bend for flow of O/W emulsion with 25 %v/v water, 75 % v/v HCO, and 4.5 % w/v surfactant PS-81 have been studied numerically using Ansys Fluent. In the present work for sudden contraction, higher loss coefficient values were observed in the laminar flow regime. The laminar flow is mainly due to the higher viscosity (>500 mPa.s at 30 °C) of oil-water emulsion. Again, frictional losses result in higher pressure drops. Similarly, for sudden expansion geometry, a small value of pressure loss coefficients was observed, which is mainly due to better pressure recovery in the expansion section. For the 90° bend, with an increase in the average mixture velocity, and hence the Reynolds number, the pressure loss coefficient was observed to decrease. Within the range of velocity considered in the present study, an exponential increase in pressure drop has been observed for sudden contraction compared to a slight rise in pressure drop for sudden expansion. A nearly linear increase in pressure drop for a 90° bend has been observed. Pumping costs increase as pressure drops increase in the pipeline. Pressure loss data caused by such pipe fittings are useful in predicting additional pressure drops caused and, hence, an increase in the pumping cost.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS CONTRIBUTION

G. D. Vegad (Conceptualization; Methodology; Formal analysis; Visualisation; Writing - original draft)
A. K. Jana (Supervision; Conceptualization; Methodology; Formal analysis; Visualisation)

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NOMENCLATURE

Symbol

D	Pipe diameter (m)
h_f	Frictional energy loss
K	Loss coefficient
k	Consistency index (Pa.s^n)
k_f	Pressure drop coefficient for fittings
L	Length (m)
n	Flow behaviour index
P	Static pressure (Pa)
R_e	Reynolds number
U	Linear velocity (m s^{-1})
ΔP	Pressure drop (Pa)
μ	Dynamic viscosity (Pa.s)
ρ	Density (kgm^{-3})

Subscript and Superscript

∞	Infinite
c	Contraction
e	Expansion
f	Fittings