Numerical Investigation of Oil–Water Two-Phase Flow Through Sudden Contraction Tube

Soham Mahindar, Mushtaque Momin, and Mukesh Sharma

1 Introduction

Multiphase flow has become a highlighted topic of research in recent era due to a large number of applications and its characteristics. Multiphase means the flow where combination of solid, liquid, and gas phases present in a single medium and characteristics of each of them remain same. Although the physics of multiphase flow is quite complicated, the high demand raised by industries led to a lot of research work in this field. Application areas include petroleum industries, chemical industries, food processing industries, transportation industries, and many more. Application of multiphase flow is quite common in nuclear power generation units. Because of the high rate of heat transfer of multiphase fluid, research work is going on to use it in the electronic industries as a cooling medium. Application of multiphase fluid in super computers, microchips, and CPUs is still a topic of research.

Many researchers have tried to understand the physics of multiphase flow, especially the characteristics of two-phase flow. A lot of studies are available for gas–liquid two-phase flow. The main emphasis was on finding out the pressure drop, flow distribution, void fraction, and flow regime. Pressure drop is directly related to the pumping power, hence the pumping cost which is a crucial factor for industrial application. Based on experimental and numerical work for gas–liquid two-phase flow, several researchers tried to develop correlation for pressure drop, void fraction, etc. Although many studies are available for gas–liquid two-phase flow through horizontal and vertical channels of uniform cross section, limited number of results is available for non-uniform cross section channels. Flow channels with non-uniform cross section are unavoidable in industrial applications. Sudden contraction

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K. M. Singh et al. (eds.), *Fluid Mechanics and Fluid Power, Volume 5*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-99-6074-3_46

and expansion are quite common in the flow passage and its effect in the flow field and pressure drop is a matter of research.

Gas–liquid two-phase flow through sudden contraction and expansion has been experimentally analyzed by few researchers among them [1–3], reported the variation of pressure. The effect of sudden contraction and expansion in pressure drop was also studied by them. Correlations for pressure drop due to the presence of singularity in flow field were developed by them that can be further used for calculation of pumping power requirement in industrial applications. A popular homogeneous model was developed for the calculation of pressure drop in sudden contraction in case of gas–liquid two-phase flow. In contrast, Abdelall et al. [4] reported that the homogeneous model was not applicable for their experimental results. According to them, the pressure drop was far less than the value calculated using homogeneous model. This shows a mismatch between mathematical and experimental calculation as the model adopted many approximations. Ahmed et al. [5] reported that the effect of sudden expansion was insignificant in fully developed regions.

Studies related to liquid–liquid two-phase flow through sudden contraction and expansion has been reported by a few researchers. Among them Hwang et al. [6] have done experimental analysis using oil–water two-phase flow and reported that loss coefficient is independent of density of fluids used and concentration of different fluids. Kerosene–water and lube oil–water were used by Balakhrisna et al. [7], for experimental analysis through conventional channels having singularity. Derived results from their experiment are flow transition due to the presence of singularity, less effect of density as compared to singularity in the pressure drop, difference in flow regime with the change in density of medium. Some new flow patterns were reported by them in this paper.

Numerical work on liquid–liquid two-phase flow has not been exploded in large scale yet. Roul et al. [8] investigated oil–water two-phase flow using experimental and numerical analysis and validate the numerical results with their experimental solution. Main motive of this analysis was to identify pressure drop in sudden contraction and expansion channels and develop the pressure profile.

Main concern of present work is to numerically find the pressure drop for sudden contraction in the flow field. Studying the effect of singularity in the flow field and phase distribution is another topic of this study. Present numerical model can be referred to as a practical model for industrial applications and will be useful for deriving pressure coefficients in different flow situations.

2 Methodology

2.1 Physical Problem Description

The physical problem consists of a 3-m-long tube having sudden contraction at a length of 2 m from entrance. Present analysis replicates oil–water two-phase flow through sudden contraction. 3-m-long tube is used in this model. A diameter of 0.0254 m is used for 2 m of total length and 0.012 m diameter is used for 1 m length. Figure 1a represents the horizontal alignment of the geometry for numerical analysis, and Fig. 1b shows the inlet of both the fluids and detailed geometry of each section. As shown in Fig. 1b that the oil entered through the inner section of the pipe and water is allowed to enter through outer periphery. ANSYS ICEM CFD 2020 R1 is used for the creation of mesh. The domain for the study was created by defining surfaces, curves, and solids describing shape and sizes. Details of mesh are depicted in Fig. 2. A uniform hex meshing is done close to the wall, and the mesh is comparatively coarser in the inner most section. Special modeling includes a greater number of equations to be solved for better result and capture all important characteristics.

Grid independency test has been performed to make the solution independent of mesh. Figure 3 shows the result of grid independency test. This test has been performed for four different node counts 165440, 247232, 430016, and 730208, static pressure values are -1707.47 Pa, -1312.248, 1339.206, and -1369.87, respectively. After 430016 mesh count, the solution is getting stable as shown in Fig. 3, so the simulation s performed for mesh count 430016.

3 Mathematical Modeling

Numerical modeling consists of mathematical description of the physical problem and demands a set of equations to be solved to get the outcome. Common equations used in mathematical modeling of fluid flow are continuity equation, momentum equation, and energy equation. Initial and boundary conditions need to be defined prior to calculation.

Modeling of transient multiphase flow uses the following set of equations.

Continuity equation (simplified form)

$$\frac{\partial(\alpha_n U_n)}{\partial t} + \nabla.\alpha_n(\rho_n U_n) = 0.$$

Momentum equation (simplified form)

$$\frac{\partial(\alpha_n \rho_n U_n)}{\partial t} + \nabla.\alpha_n(\rho_n U_n U_n) = \alpha_n.\nabla P_n + \alpha_n \nabla.r + \alpha_n \rho_n g.$$

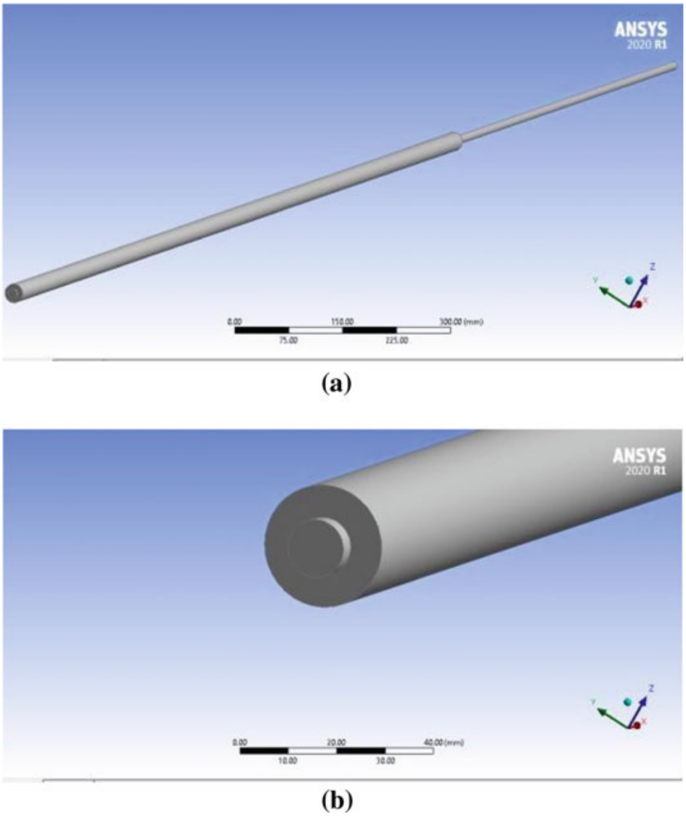


Fig. 1 **a** Geometry of the test section. **b** Inlet sections of oil and water

In the above equation, ρ represents density, α denotes volume fraction t stands for time, u means instantaneous velocity, *r* denotes viscous stress tensor, p is the pressure and gravitational acceleration g. Suffix n denotes the phase. The source and mass diffusivity terms are neglected in the above equations. Along with those 2, equation volume of fluid model in fluent uses phase equation.

k-ε model is used for the calculation because, this model is economic and have been used by different researchers for two-phase flow simulation Jiang et al. [9].

Calculation of Reynold’s number for two-phase combination is different from single phase flow. Mixture density, mixture viscosity, and mixture velocity need to be calculated in order to get the value of mixture Reynold’s number.

Mixture Reynolds number can be calculated by

$$Re_{mix} = \frac{\rho_m U_m D}{\mu_m},$$

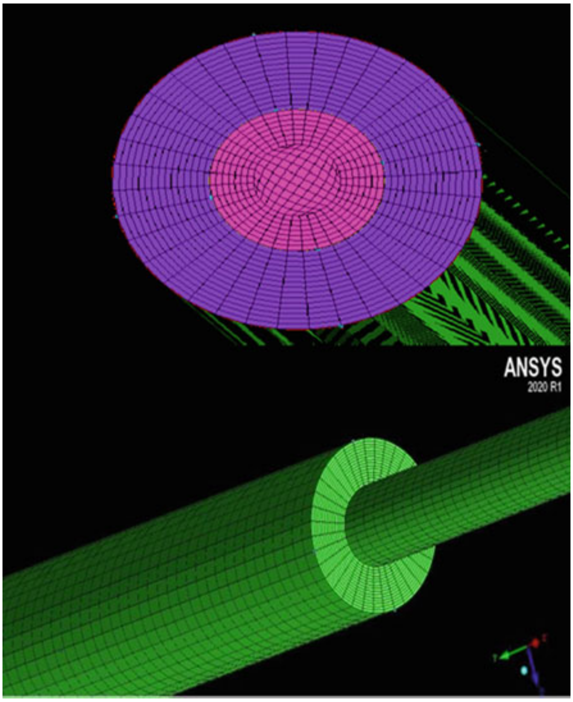


Fig. 2 Mesh of the test section

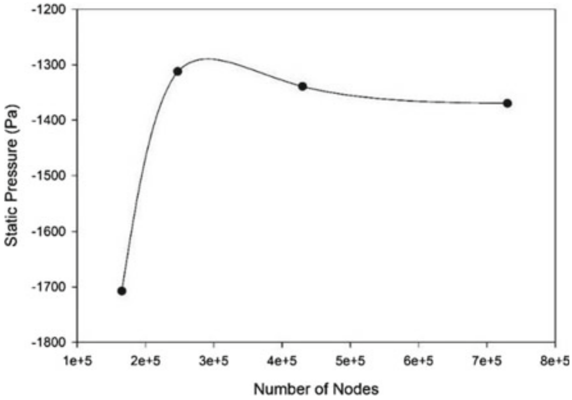


Fig. 3 Grid independency test

where ρ_m is the mixture density, U_m is mixture velocity, D is the diameter of the flow passage, and μ_m represents the mixture viscosity.

Mixture density ρ_m can be calculated by

$$\rho_m = \frac{\rho_o U_{sk}}{U_{sk} + U_{sw}} + \frac{\rho_w U_{sw}(1.35U_{sk} + U_{sw})}{(U_{sk} + U_{sw})^2},$$

where ρ_o is the density of kerosene and ρ_w is the density of water.

Mixture velocity U_m is the summation of superficial velocity of the phases that is

$$U_m = U_{sk} + U_{sw}.$$

Mixture viscosity can be given as

$$\mu_m = x\mu_o + (1 - x)\mu_w,$$

where μ_o and μ_w are viscosity of oil and water. ‘x’ represents mass quality of oil.

4 Boundary Conditions

Inlet boundary condition–velocity inlet condition is chosen for both water and kerosene inlet. The inner region is defined as kerosene inlet ($0 < r < 8.98$ mm), whereas annular portion is provided with water inlet condition ($8.98 < r < 12.7$ mm). r represents the radial distance from center. Water is considered as primary phase and kerosene as secondary phase.

Wall boundary condition—For the wall, no slip boundary condition is taken into consideration.

Outlet boundary condition—Outflow condition is chosen for outlet.

5 Result and Discussion

Pressure and velocity distribution are shown in Figs. 3 and 4, respectively. It is clearly seen from the figures that with an increase in length pressure decreases; hence, an increase in pressure drop is observed. In sudden contraction section, a drastic drop in pressure is observed. Rate of decrement in static pressure is more in downstream section as compared to upstream, and it is due to less flow area in the downstream section. That results in a steeper static pressure profile in downstream section as compared to upstream. Retardation of velocity is observed in both upstream and downstream sections due to wall friction. A sudden rise in velocity is observed in sudden contraction region. Similar kind of trend for velocity and pressure was reported by Balakhrisna et al. [7] in their experimental analysis of kerosene–water, two-phase flow (Fig. 5).

Pressure drop per unit length at the singularity region has been plotted against Reynold’s number in Fig. 6. Two points at a distance of 0.03 m in both the sides from singularity are taken into consideration to obtain pressure the drop. Reynold’s number is calculated for the mixture by using mixture density, mixture velocity, and mixture viscosity. It is clearly seen from the Fig. 6 that pressure drop increases in proportional with Reynold’s number at the singularity region. Velocity of the

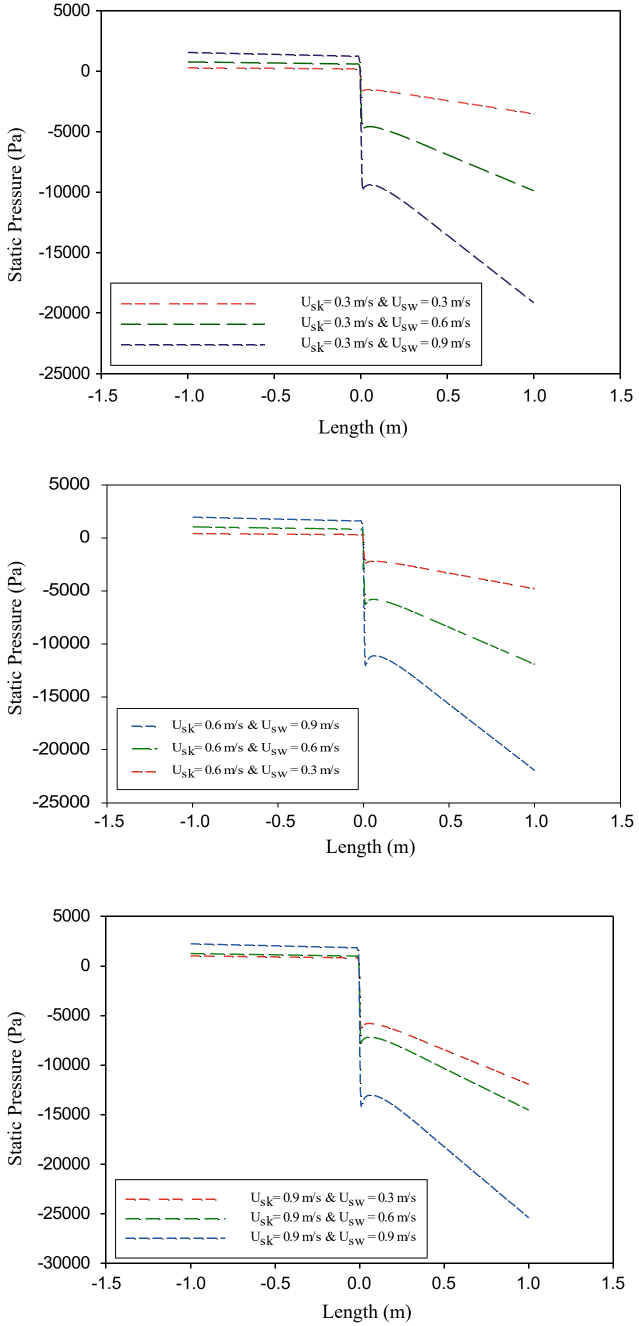


Fig. 4 **a** Variation in static pressure with length of the tube for constant U_{sk}. **b** Variation in static pressure with length of the tube for constant U_{sk}. **c** Variation in static pressure with length of the tube for constant U_{sk}

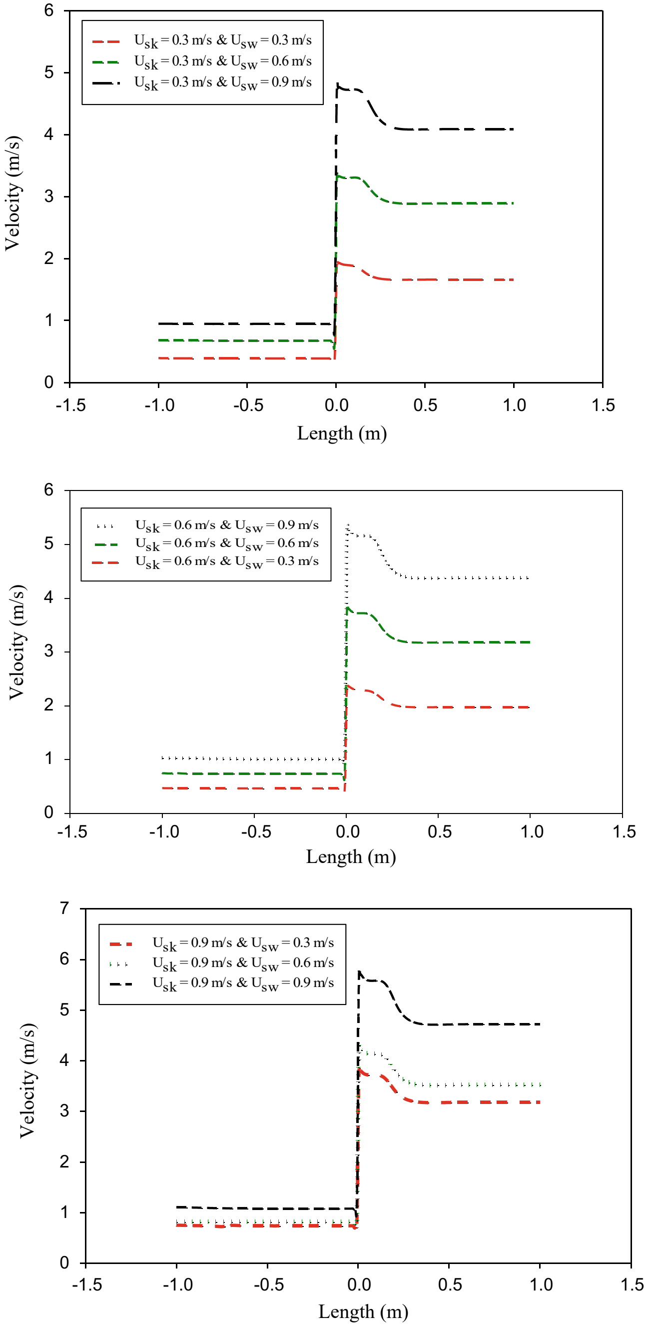


Fig. 5 **a** Variation in velocity with length of the tube for constant U_{sk}. **b** Variation in velocity with length of the tube for constant U_{sk}. **c** Variation in velocity with length of the tube for constant U_{sk}

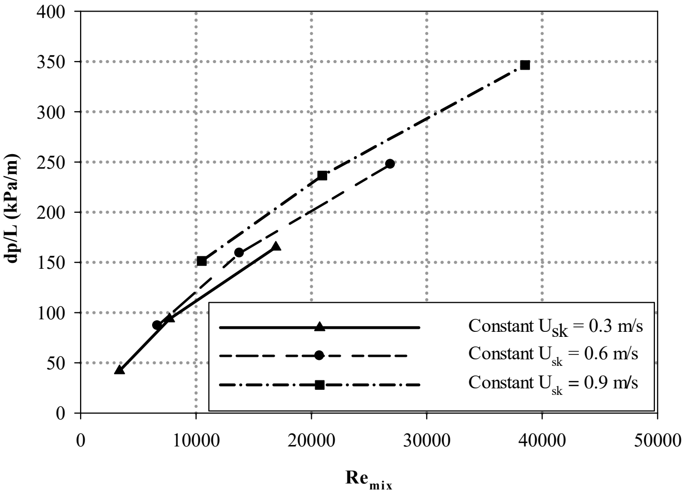


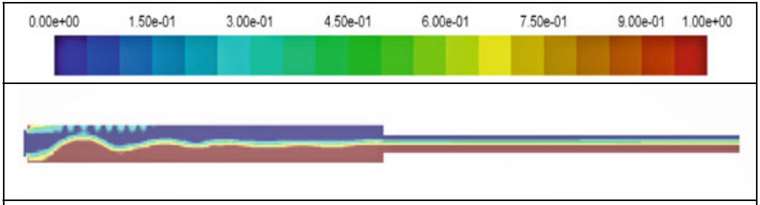
Fig. 6 Pressure drop variation with Reynold's number

mixture increases with the increase in superficial velocity of the mediums results in an increase in Reynold's number. As the mixture velocity increases losses in sudden contraction region also increase which results in more pressure drop at the singularity region. Increased in pressure drop at the singularity region leads to the change in flow patterns as depicted in Fig. 7.

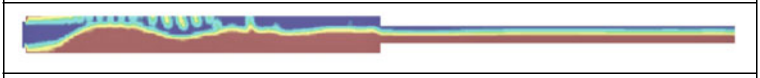
Flow patterns for different combinations of kerosene and water superficial velocities are depicted in the Fig. 7.

It can be inferred from the figure that, for all the combination of superficial velocities of kerosene and water, wavy stratified flow with droplet flow was observed (three layered) at upstream section. Similar observation was reported by Balakhrisna et al. [7]. Further, as U_{sw} increases from 0.3 to 0.9 m/s with U_{sk} 0.3 m/s the frequency of water droplet increases at upstream (Fig. 7a, b, and c). Similar flow pattern was observed experimentally by Balakhrisna et al. [7]. The propagation of the droplets is seen for more length in the upstream section as the superficial velocity of water increases from 0.3 to 0.9 m/s for constant U_{sk}.

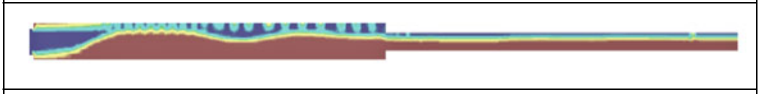
Mostly, stratified slow was observed in the downstream section for lower superficial velocity of kerosene ($U_{sk} = 0.3$ m/s) and water superficial velocity of 0.3 and 0.6 m/s as shown in Fig. 7a, b. With further increase in the superficial velocity of water from 0.6 to 0.9 m/s, stratified flow converts into large plug flow as shown from Fig. 7c. Further increase in the superficial velocity of kerosene from 0.3 to 0.6 m/s similar patterns with a higher frequency of water droplet was observed in the upstream section as displayed in Fig. 7d, e, and f. In the downstream section stratified flow transformed into small plug and large plug as the superficial velocity of water increases from 0.3 to 0.9 m/s. From Fig. 7g, h, and i, wavy stratified flow with water droplet was observed. In the downstream region smooth stratified flow with few water droplets were observed for kerosene superficial velocity 0.9 m/s and



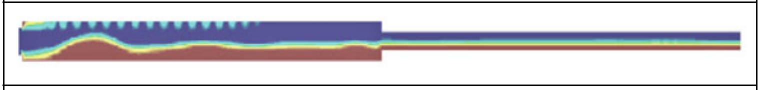
(a) Flow pattern for U_{sk}=0.3m/s & U_{sw}=0.3m/s



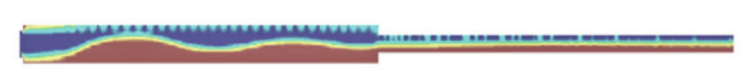
(b) Flow pattern for U_{sk}=0.3m/s & U_{sw}=0.6m/s



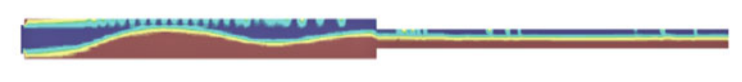
(c) Flow pattern for U_{sk}=0.3m/s & U_{sw}=0.9m/s



(d) Flow pattern for U_{sk}=0.6m/s & U_{sw}=0.3m/s

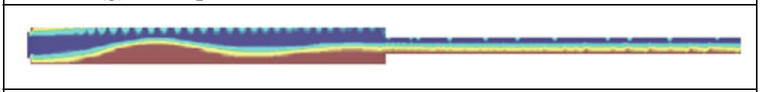


(e) Flow pattern for U_{sk}=0.6m/s & U_{sw}=0.6m/s

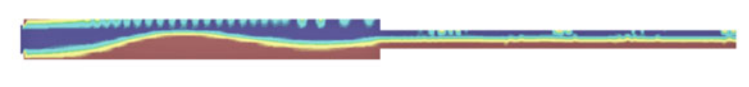


(f) Flow pattern for U_{sk}=0.6m/s & U_{sw}=0.9m/s

(g) Flow pattern for U_{sk}=0.9m/s & U_{sw}=0.3m/s



(h) Flow pattern for U_{sk}=0.9m/s & U_{sw}=0.6m/s



(i) Flow pattern for U_{sk}=0.9m/s & U_{sw}=0.9m/s

Fig. 7 Flow patterns for different combinations of U_{sw} with U_{sk}

water superficial velocity equals to 0.3 and 0.6 m/s. With further increase in water velocity, plug flow is observed as shown in Fig. 7i.

It is clearly seen from the velocity and pressure characteristics that, with an increase in superficial velocity, pressure drop increases. For a particular superficial velocity of kerosene, as the velocity of water increases, pressure drop increases rapidly at the singularity region and same is true for other sets of kerosene superficial velocities. Static pressure profiles in the downstream region are diverging in nature. As the superficial velocity of water increases for a constant kerosene superficial velocity the slope of the static pressure profile in the downstream section increases. Keeping U_{sw} constant, the pressure drop at the singularity region increases with the increase in kerosene superficial velocity. Pressure drop at the upstream section is very less as compared to singularity and downstream section. Static pressure profile at downstream section becomes steeper. Similar observation was reported in the result of Balakhrisna et al. [7]. Formation of vena contracta just after the singularity region is the reason behind the pressure rise just after the singularity region. Vena contracta is formed because of sudden contraction both in single phase and two-phase flow and can be confirmed by the pressure characteristics as shown in Fig. 5.

6 Conclusion

Numerical analysis of liquid–liquid two-phase flow through sudden contraction has been done in the present study. The analysis based on the adiabatic flow situation of liquid–liquid two-phase flow, as many industrial applications, does not consider the effect of heat transfer in similar flow situation. Main emphasis is given on determining the pressure drop due to the presence of sudden contraction region. From the analysis the following observations can be drown:

- Flow pattern and pressure drop of the flow is straight way related to superficial velocities of participating mediums.
- Increase in velocity of any of the phases leads to the increase in pressure drop at the singularity region. Pressure drop at the downstream section increases in much higher rate as compared to the pressure drop at the upstream section. Presence of singularity in the flow region results in drastic pressure drop and huge losses at the junction.
- Flow losses are more significant at the downstream section as competed to upstream section due to lesser flow diameter. Maximum losses are observed at the singularity region.
- It is better to select low velocity combinations if there is any singularity present in the flow passage because drop in pressure in much higher at the singularity region as compared to upstream and downstream section due to contraction losses.

- Pressure drop per unit length against mixture Reynold's number has been plotted to understand the actual pressure drop scenario in practical applications. The comparison can be made as because non-dimensional Reynold's number is taken into consideration.
- Pressure drop increases at the singularity region with the increase in Reynold's number.
- Vena contracta phenomena was observed just after the sudden contraction region which results in smaller pressure rise just after the singularity section for very short length.
- It can be seen from the flow regime map that presence of singularity in the flow passage results in a change of the flow pattern from upstream to downstream. Frequency of water droplet formation increases with the increase in superficial velocities at the upstream section. On the other hand, stratified flow changes into large plug flow as the superficial velocity increases in the downstream section.

Nomenclature

Us	Superficial velocity (m/s)Subscript
D	Internal diameter of tube (m)1Larger diameter
L	Length of the tube (m)2Smaller diameter
ρ	Density (kg/m^3)kkerosene
σ	Surface tension (N/m)wwater
P	Static pressure (Pa)ooil
g	Gravitational constant (m/s)mmixture
μ	Dynamic viscosity (Pa.s)

References

1. John W (1967) Two-phase flow through abrupt expansion and contraction
2. Lottes PA (1961) Expansion losses in two-phase flow. Nucl Sci Eng 9(1):26–31. https://doi.org/10.13182/nse61-a25860
3. Janssen E, Kervinen JA (1964) Geap-422 AEC research and development report two-phase pressure drop across i contractions. Am San Ibse, California
4. Abdelall FF et al (2005) Pressure drop caused by abrupt flow area changes in small channels. Exp Therm Fluid Sci 29(4):425–434. https://doi.org/10.1016/j.expthermflusci.2004.05.001
5. Ahmed WH, Ching CY, Shoukri M (2008) Development of two-phase flow downstream of a horizontal sudden expansion. Int J Heat Fluid Flow 29(1):194–206. https://doi.org/10.1016/j.ijheatfluidflow.2007.06.003
6. Hwang CYJ, Pal R (1997) Flow of two-phase oil/water mixtures through sudden expansions and contractions. Chem Eng J 68(2–3):157–163. https://doi.org/10.1016/S1385-8947(97)00094-6
7. Balakhrisna T, Ghosh S, Das G, Das PK (2010) Oil-water flows through sudden contraction and expansion in a horizontal pipe—phase distribution and pressure drop. Int J Multiph Flow 36(1):13–24. https://doi.org/10.1016/j.ijmultiphaseflow.2009.08.007

8. Roul MK, Dash SK (2009) Pressure drop caused by two-phase flow of oil/water emulsions through sudden expansions and contractions: a computational approach. Int J Num Methods Heat Fluid Flow 19(5):665–688. https://doi.org/10.1108/09615530910963580
9. Jiang F, Wang K, Skote M, Wong TN, Duan F (2018) The effects of oil property and inclination angle on oil–water core annular flow through U-Bends. Heat Transfer Eng 39(6):536–48