American Journal of Mechanical and Industrial Engineering
2017; 2(1): 8-16
http://www.sciencepublishinggroup.com/j/ajmie
doi: 10.11648/j.ajmie.20170201.12

Hydrodynamic Study Using CFD Simulations in a Horizontal Two-Phase Flow Through Sudden Contraction

Ibtissem Belgacem[1, 2], Y. Salhi[1], E-K. Si-Ahmed[1, 3]

[1]LMFTA Faculty of Physique, University of Sciences and Technology Houari Boumediene, Algiers, Algeria

[2]Institute of Technology, University Akli Mhend Oulhadj, Bouira, Algeria

[3]GEPEA, CNRS UMR-6144 University of Nantes, Nantes, France

Email address:

ibtissem.belgacem@gmail.com (I. Belgacem)

To cite this article:

Ibtissem Belgacem, Y. Salhi, E-K. Si-Ahmed. Hydrodynamic Study Using CFD Simulations in a Horizontal Two-Phase Flow Through Sudden Contraction. *American Journal of Mechanical and Industrial Engineering.* Vol. 2, No. 1, 2017, pp. 8-16.
doi: 10.11648/j.ajmie.20170201.12

Received: October 31, 2016; **Accepted**: November 29, 2016; **Published**: December 26, 2016

Abstract: Two-phase flows are encountered in a wide range of industrial application. In the present work, two-phase computational fluid dynamics (CFD) calculations, using Eulerian–Eulerian model and commercial CFD package FLUENT 6.3, were employed to calculate pressure drops caused by abrupt flow area contraction in small circular pipes for two-phase flow of air and water mixtures at room temperature and near atmospheric pressure. The pressure drop is determined by extrapolating the computed pressure profiles upstream and downstream of the contraction. Variables studied include: gas and liquid velocities, and pipe contraction ratio. The numerical results were validated against experimental data from the literature and are found to be in good agreement. Our findings could be useful in designing pipeline.

Keywords: Two Phase Flow, Pressure Drop, CFD, VOF, Theoretical Models

1. Introduction

Liquid-gas two-phase flows are widely encountered in industrial applications including chemical processes, petroleum engineering and energy manufacturing units systems. To ensure the distribution of the fluids in the industrial hydraulic installations, these systems often exhibit complex geometry comprising singularities such as expansions, contractions, orifices, bends etc. Among these singularities, the abrupt contraction is relevant in many applications and has significant effects, on the two-phase flow behavior as well flow pattern, over manifolds the pipe diameter and subsequently the resulting pressure drop. This important subject has attracted several investigations particularly for applications involving design, safety and economical operations.

Although single flow through singularities has been largely studied, great uncertainties exist as far as the multiphase - flow is concerned. In subsequent years, some studies have been conducted in order to propose new experimental data and prediction correlations. It has been shown that current two phase pressure drop correlations are applicable to a limited range of experimental conditions, and large errors occur when these correlations are applied outside the intended range (Ferguson and Spedding [1], Colman [2]). Experimental pressure drops for steam water mixtures flowing through sudden contraction were reported by Geiger [3] for area ratios of 0.398, 0.253 and 0.144, as well as by McGee [4] for area ratios of (0.608 and 0.546). In both cases the homogeneous model gives the best predictions of the data. This was confirmed by Hewitt et al. [5] who recommended the homogeneous equation and stated that this model often provided reasonable agreement with experimental data. Based on the homogeneous model, Chisholm [6] introduced a constant B. On the other hand Abdelall et al. [7] pointed out that their recorded pressure drops, caused by abrupt flow area expansion and contraction, were lower than those predicted by the homogeneous flow model, a significant velocity slip ratio existed at the vicinity of the flow area change. One should note that their work concerned air-water two-phase flow in mini-channels, within the range of $1750<Rel<3920$, with inner diameters of 1.6 and 0.84 mm, and according to their recommendations the homogeneous flow model is not applicable in mini and micro-channels. Additional experimental work was reported by Chalfi et al. [8] for Rel <1020 who proposed a new pressure drop model.

Schmidt and Friedel [9] developed a model to calculate the two-phase pressure drop across a sudden contraction in a duct area. Their data were concerned with mixtures of air and water, aqueous glycerol, watery calcium nitrate and with Freon 12. The authors reported that a local pressure minimum was not detectable in their tests, thus the axial pressure profile and the shape of streamlines in two–phase flow are still unknown, and there is no evidence whether or not the profile is similar to single phase flow. Chen et al. [10] investigated the pressure change and flow pattern in small rectangular channels they reported that the pressure change increased with the rise of mass flux, and gas quality. To extend the applicable range of homogeneous model a modified correlation is proposed including the influences of gas quality, Bond number, Weber number and area contraction ratio in the homogeneous model. More recently Padilla et al. [11] investigated the pressure change and flow pattern subject to the influence of sudden contraction; they carried out experiments with R-410A, HFO-1234YF and R-410A refrigerants in a 10mm glass tube with an area ratio of 0.49. The experimental pressure drop data are compared against six prediction methods from the literature, the best prediction is given by the method of Abdelall et al. [7] with 54% of the data predicted within a ±30% error band. Based on the observations made in their study Padilla et al. [11] developed a new pressure drop model for sudden contraction; this new method will predict the effect of the friction resistance due to the singularity ΔP_{sin} and its perturbation effect up and downstream ΔP_{per}.

From the survey of the past literature, the majority of the numerical studies performed on two-phase flow involve the prediction of flow pattern, pressure drop in conduits of uniform cross-section (Vallée et al. [12], [13], Dhotre and Joshi [14], Ratkovich [15]; but very few little C. F. D models have been developed to study the effect of singularities on the phase redistribution and pressure drop. K. R Manmatha and Sukandak [16] compute the two-phase pressure drop of oil/water through sudden expansion and contraction, by using a two phase Eulerian model, the numerical results are validated against experimental data. Core annular flow of lubrificating oil and water through sudden contraction and expansion has been simulated by V. V. R Kaushik et al. [17] using a VOF technique, satisfactory match between simulated data and experimental data reported by Balakhrisna et al. [18] has been obtained, the study has been performed to generate the profile of velocity, pressure and volume fraction

The present work is devoted to investigate oil-water co-current two-phase flow behavior resulting from the existence of a sudden contraction in horizontal pipe. Computational fluid dynamic CFD calculation using VOF techniques are employed to generate the profile of pressure; the numerical results are validated against experimental data from the literature and are found to be in good agreement.

2. Numerical Procedure

2.1. Mathematical Model

For the mathematical model, Eulerian based volume of fluid VOF technique for two phase modeling were employed to investigate the two phase pattern in horizontal pipe. In this model, liquid is considered to be the continuous and primary phase, and gas considered to be the dispersed and secondary phase. The fluid in both phases is Newtonian, viscous and incompressible. The uniform pressure field is assumed to be shared by both phases, the flow is considered isothermal so the energy equations are not needed.

The VOF method has the advantages of high precision, and traces the volume of fluid in the grid, not the motion of fluid particles. In the VOF model, a single set of momentum equations is shared by the fluids, and the fluid volume fraction in each computational cell is tracked throughout the domain. This model has been found to be suitable for simulating interface among two or more fluids Ghorai et al. [19].

The VOF method utilizes the volume fraction, which means the fraction of the filled fluid volume in the grid to achieve the goal. The indicator function is defined as 0 for a cell with pure gas, 1 for a cell with pure liquid, and for a cell with a mixture of gas and liquid. An interface exists in those cells that give a volume of fluid value of neither 0 nor 1. Since the indicator function is not explicitly associated with a particular front grid, an algorithm is needed to reconstruct the interface (Hirt and Nichols. [20]):

$$\alpha = \begin{cases} 0 \text{ in pur gas} \\ 0 < \alpha < 1 \quad \text{gas} - \text{liquid interface} \\ 1 \text{ in pur liquid} \end{cases} \quad (1)$$

2.2. Governing Equations

Numerical simulation of any flow problem is based on solving the basic flow equations describing continuity, momentum and turbulence. The principal equations are solved for each phase and can be written as follow (2), (3) and (4):

Continuity equation

$$\frac{\partial(\alpha\rho)}{\partial t} + \nabla.(\alpha\rho\vec{v}) = 0 \quad (2)$$

Momentum equation

$$\frac{\partial(\alpha\rho\vec{v})}{\partial t} + \nabla.(\alpha\rho\vec{v}\vec{v}) = -\alpha\nabla p + \alpha\nabla.[\mu(\nabla\vec{v} + \nabla\vec{v}^T)] + \alpha\rho\vec{g} + \alpha\vec{F} \quad (3)$$

The void fraction α is the void fraction of water or liquid phase.

Turbulent model

The Reynolds Stress Model (RSM) is a higher level, elaborate turbulence model. It is usually called a Second Order Closure. This modeling approach originates from the work by Launder et al. [21], in RSM, the eddy viscosity approach has been discarded and the Reynolds stress is directly computed. The model can be used to predict the turbulent anisotropic level in the flow. Given that the two-phase flows are very unstable and highly anisotropic.

$$\frac{\partial(\rho\bar{\alpha}\tilde{R}_{ij})}{\partial t}+\frac{\partial}{\partial x_k}\left(\rho\bar{\alpha}\widetilde{\boldsymbol{U}}_k\tilde{R}_{ij}\right)=-\rho\bar{\alpha}[\tilde{R}_{ij}(\nabla\widetilde{\boldsymbol{U}}_k)^T+(\nabla\widetilde{\boldsymbol{U}}_k)\tilde{R}_{ij}]+\frac{\partial}{\partial x_k}[\bar{\alpha}\mu\frac{\partial\tilde{R}_{ij}}{\partial x_k}]-\frac{\partial}{\partial x_k}[\rho\bar{\alpha}\overline{u_i'u_j'u_k'}]+\bar{\alpha}p\overline{\left(\frac{\partial u_i'}{\partial x_j}+\frac{\partial u_j'}{\partial x_i}\right)}-\bar{\alpha}\rho\,\tilde{\varepsilon}_{ij}+\frac{2}{3}\delta_{ik}\Pi_k \quad (4)$$

2.3. Numerical Procedure

The experimental geometry with and without contraction has been modeled using an axi-symmetric 2D geometry. The simulation was performed using the commercial CFD code Fluent 6.3.26 at double precision solver mode, with an implicit scheme for all variables and a fixed time step t= 0.001 s for computation. To solve the momentum transport equation the Quick (quadratic upwind interpolation) scheme was used, for pressure the PRESTO (PREssure STaggering Option) scheme increases stability in the solution. The phase – coupled PISO (Issa. [22]) algorithm is used for the pressure –velocity coupling. RSM model has been used for turbulent two phase-flows. These schemes ensured, in general, satisfactory accuracy, stability and convergence. In addition, the steady-state solution strategy was employed. Meshing the geometry was achieved by using a software GAMBIT (2.4.6). We used the quadratic elements and the dimension of each cell is 0.004 making the number of cells equal to 842 205. The convergence criterion is decided based on the residual value of the calculated variables, namely mass, velocity components and pressure. In the present study, the numerical computation is considered converged when the residuals of the different variables are lowered by five orders of magnitude.

Inlet boundary: For both geometries the velocity of the fluids is specified at the inlet.

Outlet boundary condition: At the outlet, pressure outlet boundary is used.

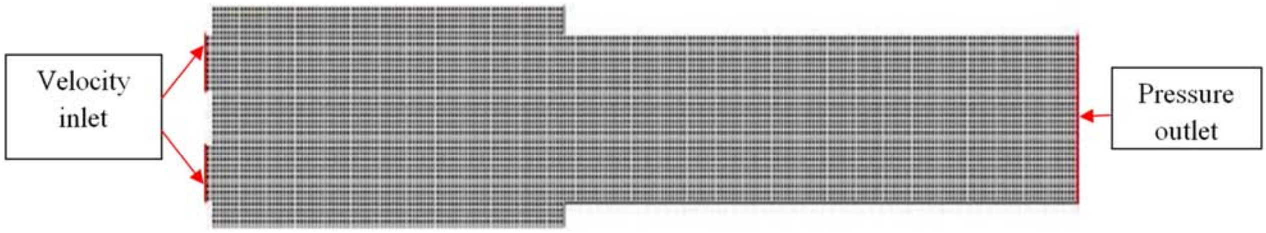


Figure 1. *Computational domain and boundary conditions for contraction section.*

3. Results and Discussions

3.1. Two-Phase Pressure Drop

The pressure profile and the idealized course of the boundary streamlines for a two phase flow through a sudden contraction are depicted respectively in figures 2a and 2b. When flow approaches the contraction, due to the acceleration of the flow in the transitional region, the static pressure initially decreases to the contraction area, after the pressure reaches the minimum, the pressure increases to a downstream point and then merges with the downstream fully developed pressure gradient line.

According to Kays [23] the pressure drop due to a sudden area change is not a directly measurable quantity but must be determined from static pressure drop measurements taken along the sections upstream and downstream of the area changes.

In single phase flow through sudden contraction, the fluid acceleration is approximately isentropic, and mechanical energy loss takes place predominantly during the deceleration following the vena-contracta point. Many authors report that the two phase flow has the same characteristics as those in single phase-flow, Assuming incompressible gas and liquid phases, and assuming x and α remained constant across the sudden contraction, following these assumptions, the total pressure drop across a sudden contraction can be estimated from Abdelall et al. [7] (Zivi model [24]). The slip flow expression was derived as:

$$\Delta P_c=G_l^2\left[\frac{\rho_h}{2\rho''^2}\left(\frac{1}{C_c^2}-\sigma^2\right)+\frac{1}{\rho'}(1-C_C)\right] \quad (5)$$

$$\rho_h=\left(\frac{x}{\rho_G}+\frac{1-x}{\rho_l}\right)^{-1} \quad (6)$$

Where ρ_h is homogeneous density, and

$$\rho''=\left[\frac{(1-x)^3}{\rho_L^2(1-\alpha)^2}+\frac{x^3}{\rho_G^2\alpha^2}\right]^{-1/2} \quad (7)$$

is fictitious mixture density;

$$\rho'=\left[\frac{(1-x)^2}{\rho_l(1-\alpha)}+\frac{x^2}{\rho_G\alpha}\right]^{-1} \quad (8)$$

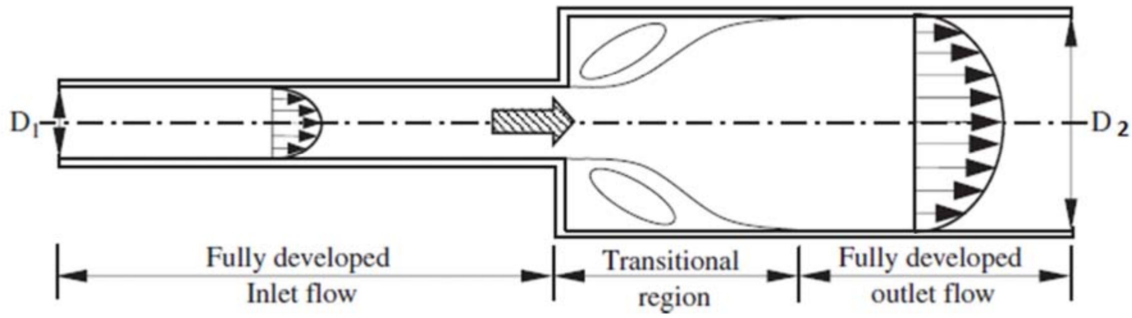
is momentum density.

The contraction coefficient C_c is calculated by using the Geiger [3] correlation; that is:

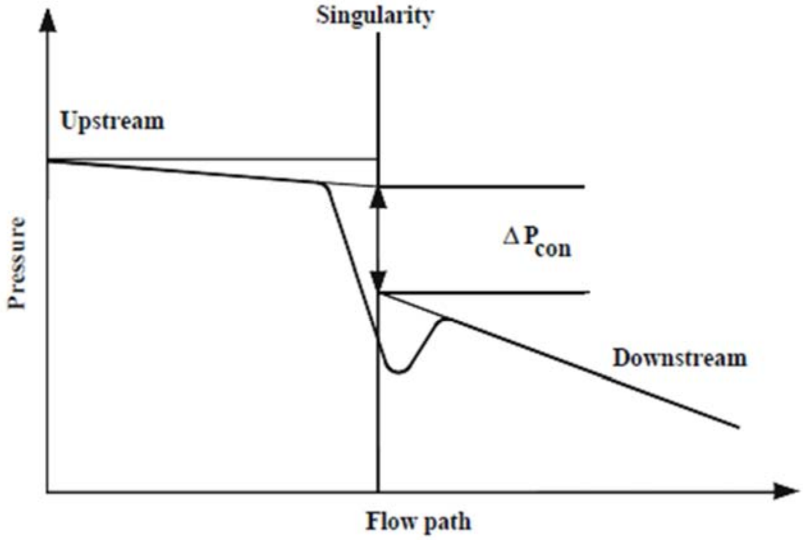
$$C_c=1-\frac{1-\sigma_A}{2.08(1-\sigma_A)+0.5371} \quad (9)$$

The data were also compared to the following homogeneous model prediction given by Hewitt et al.[5] equation:

$$\Delta P_{cHom}=\left(\frac{G^2}{2\rho_l}\right)[(C_c^{-1}-1)^2+(1-\sigma_A^2)]\left[1+x\left(\frac{\rho_l}{\rho_g}-1\right)\right] \quad (10)$$



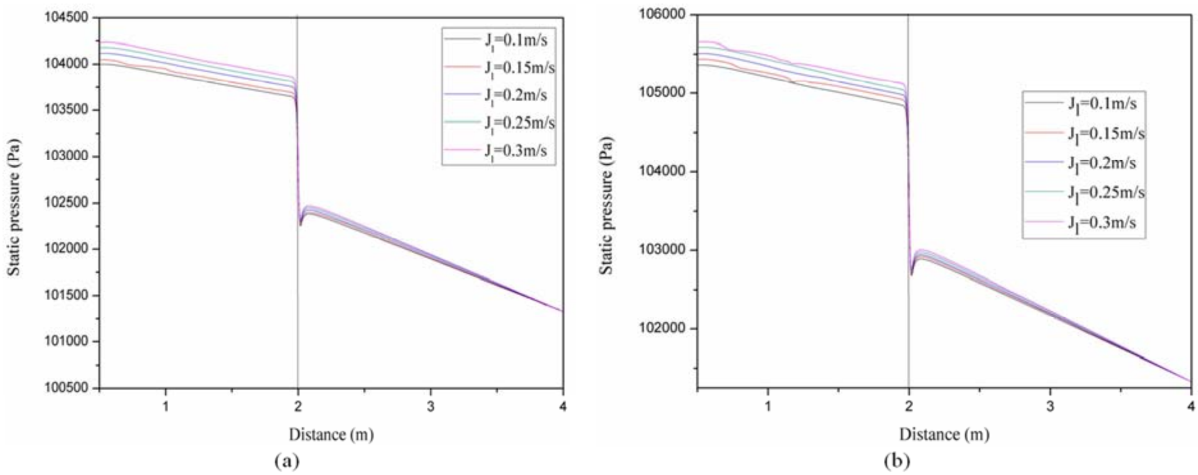
(a)



(b)

Figure 2. *a/ Idealized course of boundary stream lines and b/pressure profile for a sudden contraction.*

Figures 3a and 3b depict the predicted two-phase pressure profiles subjected to a sudden contraction for different liquid velocities keeping the gas velocity gas. Similarly to the experimental results it is observed that the pressure drop through sudden contractions increases with increasing the liquid velocities. The figure show the pressure change upstream and downstream the contraction, the static pressure decreases more rapidly than in the region of fully developed flow, It attains the (locally) smallest value at a distance of about L/D = 3.33 after the contraction section., the results agree well with the experimental data Schmidt et Friedel [9] and Belgacem [25].



(a) Jg=3m/s, (b) Jg=4m/s

Figure 3. *Numerical pressure profiles for two-phase air –water flow through sudden contraction.*

Figure 4 compares the computed values of the two-phase pressure drop with the experimental data of Friedel et Schmidt [9]. The agreement is found to be quite good. The proposed numerical model shows acceptable accuracy against the experimental prediction. The prediction of pressure drops lies within ±25%.

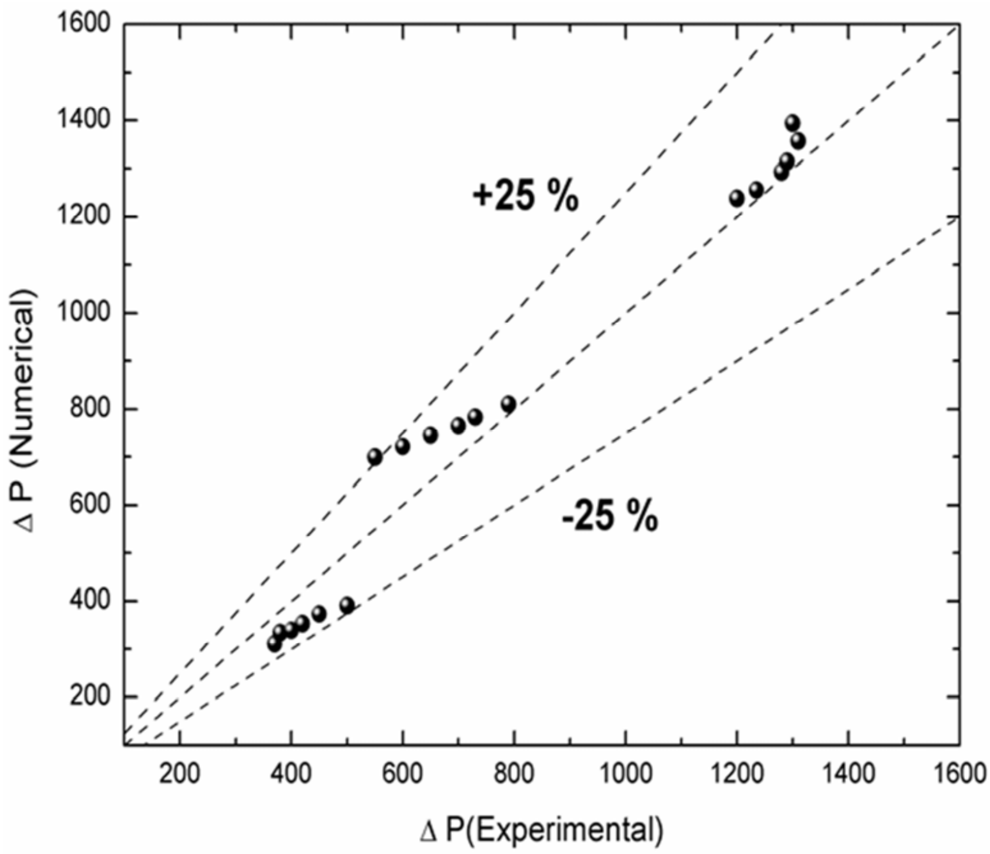


Figure 4. *Comparison between numerical prediction and experimental data of Schmidt et Friedel [9].*

After validation with experiments, the models are used to generate useful information on the hydrodynamics of two-phase flow through sudden contraction. Simulated pressure contour are illustrated in Fig. 5, which clearly shows the pressure change upstream and downstream the contraction, the static pressure decreases more rapidly than in the region of fully developed flow, On the other hand, the pressure contours as depicted in this figure, clearly shows that the two-phase flow does not contract behind the edge of transition, the zone of recirculation is not observed, and the vena contracta phenomena is not detectable, the results agree well with the experimental data.

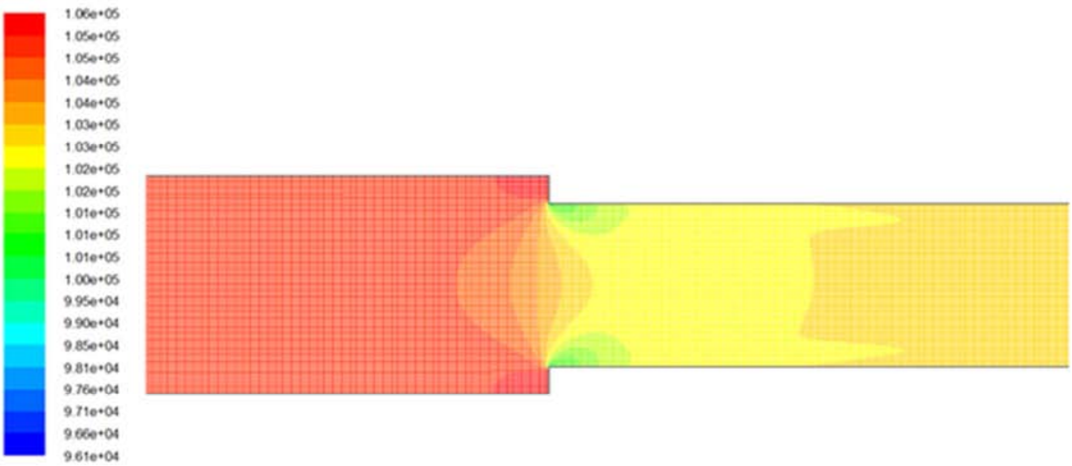
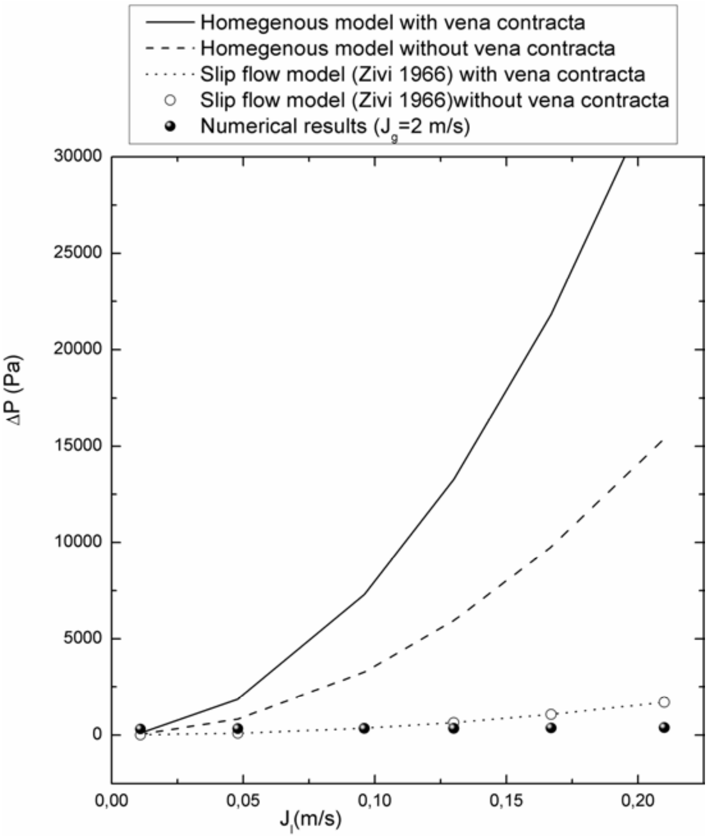
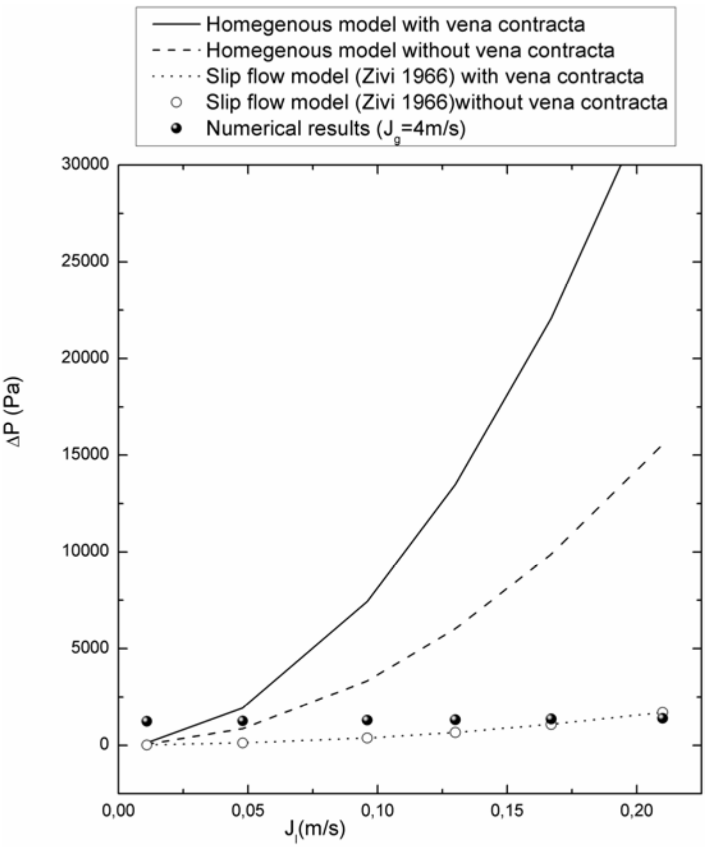


Figure 5. *Snapshots of pressure contours* J_g*=5 m/s* J_l*=0.3 m/s T= 20s 48* $d_1 < x_{amont} < 50 d_1$ $0 < x_{aval} < 3 d_2$.



(a) Jg=2m/s



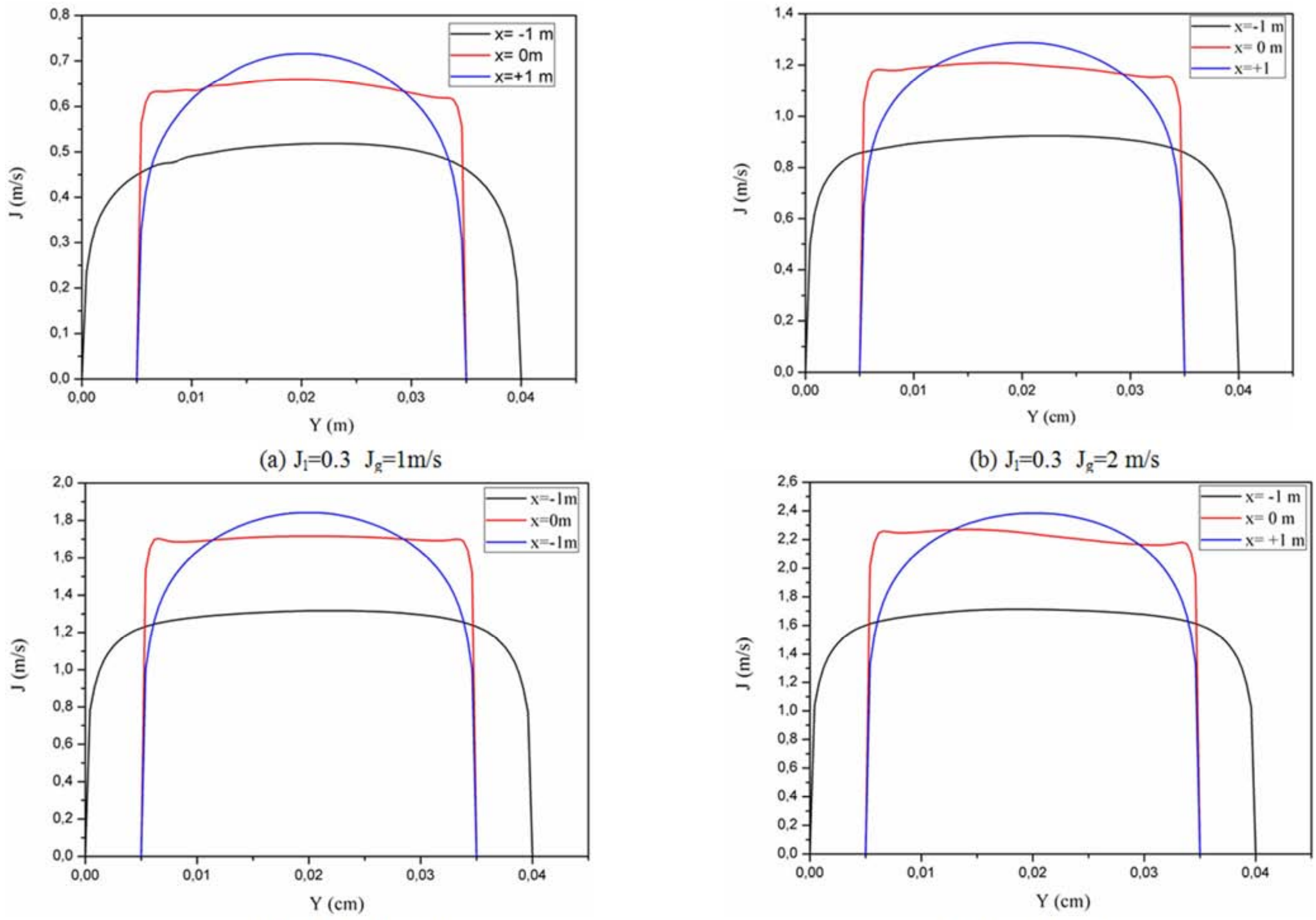
(b) Jg=4m/s

Figure 6. *Numerical pressure drop as function of* J_l.

The numerical two-phase pressure changes ΔP_c caused by flow area contraction are displayed in figure 6 a-b and. The computed data are compared with analytical model calculations assuming homogeneous flow and slip flow. For the homogeneous flow model ΔP_c was calculated using Eq 10, Whereas for the slip flow model Eq 5 was used, both models are considered assuming a vena-contracta, and no vena contracta (i.e. Cc=1). It is observed that calculations with the homogeneous flow over predict the data monotonically and significantly, the main reason for this may be attributed to the following. In this approach, the gas-liquid mixture is assumed to behave as a single –phase fluid having average properties, on the other hand, the homogeneous model is not applicable since it assumes the slip ratio of unity. The deviation could also be attributed to the test conditions in the present work were such that a stratified, wavy and intermittent (slug / elongated bubbles) flow occurred in all the tests, as well as the low flow quality coved in this study (0.008≤*x*≤0.22). In the literature the agreement between the predictions given from the homogeneous model and the experimental data remains poor (Belgacem [25]). The computational and experimental data are found to agree fairly well with the prediction of the slip flow model. The results are analogous to those reported by Belgacem [25] and Abdelall et al. [7], Chalfi et al. [8] in the case of micro channel.

3.2. Hydrodynamic Study

Subsequently, efforts have been made to understand the radial distribution of velocity at different axial locations. The velocity profiles depict a distinct change in slop at the interface. They are more peaked in the smaller pipe. The asymmetric nature of the profiles at the smaller cross-section is also prominent for both the cases.



(a) J_l=0.3 J_g=1m/s (b) J_l=0.3 J_g=2 m/s

(c) J_l=0.3m/s J_g=3m/s (d) J_l=0.3m/s J_g=4m/s

Figure 7. *Radial profile of velocity at different axial positions.*

4. Conclusion

Two-phase flows pressure drop and velocity are investigated in this work in a horizontal pipe with a sudden contraction. Simulation of two-phase flow in horizontal pipe are analyzed using the computational fluid dynamics software (Fluent) applying the volume of fluid VOF method and the RSM model.

The numerical simulations performed with the CFD code Fluent 6.3.26 revealed that the static pressure is predicted around 75%. The analysis was encouraging on showing that computational fluid dynamics model can be used for the prediction of pressure evolution and prediction of the hydrodynamic characteristics in horizontal two-phase flow through sudden contraction. The latter can be of practical importance in the design confidence.

Nomenclature

C	Vena- contracta coefficient.
d	pipe diameter (m).
$\vec{F}$	Body forces (N).
$\vec{g}$	Gravitation (m/s^2).
G	Total mass flux ($kg/m^{-2}s$).
G_j	Total mass flux of phase j ($kg/m^{-2}s$).
J_j	Superficial velocity of phase j (m/s).
P, p	Pressure (Pa).
ΔP	Pressure drop (Pa).
t	time
$\vec{v}$	Velocity (m/s)
x	Quality ($x=G_g/(G_{g+} G_l)$)
y	vertical position
z	axial position
Greeks:	
α_j	Volume fraction of phase j.
α	Void fraction.
μ	Dynamic viscosity (Pa.s)
ρ	Density ((kg/m^3)
σ_A	Passage cross section area ratio d_2^2/d_1^2 .
$\vec{v}$	Velocity(m/s)
λ	dimensionless parameter
ψ	dimensionless parameter
δ	Surface tension (N/m)
ε	dissipation rate
S	slip ratio
Sub and superscripts	
1	Inlet.
2	Outlet.
Hom	Homogeneous.
j=l	for liquid
j=g	for gas
per	Perturbation.
sing	Singular.
tot	Total.
c	contraction

References

[1] Ferguson, M. E. G., and Spedding, P. L., 1995. Measurement and prediction of pressure drop in two-phase flow, J. Chem. Tech. Biotechnol, 62, 262-278.

[2] Coleman, J. W. 2010. An experimentally validated model for two-phase sudden contraction pressure drop in microchannel tube headers. Heat transfer engineering. 25 (3), 69-77.

[3] Geiger, G. E., 1964. Sudden contraction losses in single and two –phase flow. Ph.D Thesis, University of Pittsburgh, USA.

[4] McGee, J. W., 1966. Two–phase flow through abrupt expansions and contractions. Ph.D Thesis, University of North Carolina at Raleigh, UAS.

[5] Hewitt, G. F., Shires, G. L., and Bott, T. R., Process HeatTransfer, CRC Press, Boca Raton, 1994

[6] Chisholm, D. Two-phase flow in pipelines and heat exchangers. George Godwin. London. 1983. p, 304.

[7] Abdelall, E. F., Halim, G., Ghiaasiaan, S. M., Abdel-Khalik, S. I., Jeter, S. S., Yoda, M., Sadowski, D. L. 2005. Pressure drop caused by abrupt flow area changes in small channels. Exp. Thermal Fluid Sci. 29, 425-434.

[8] Chalfi, T. Y., Ghiaasiaan, S. M., 2008. Pressure drop caused by flow area changes in capillaries under low flow conditions. Int. J. Multiphase flow, 34, 2-12.

[9] Schmidt, J., Friedel, L., 1997. Two–phase flow pressure drop across sudden contractions in duct areas. Int. J. Multiphase flow 23.2, 283-299.

[10] Chen, I. Y., Tseng, C. Y., Lin, Y. T., Wang, C.2008. Two-phase flow pressure change subject to sudden contraction in small rectangular channels. Int. J. Multiphase flow, 35, 297-306.

[11] Padilla, M., Revellin, R., & Bonjour, J. 2013. Two-phase flow of HFO-1234yf, R-134a and R-410A in sudden contractions: Visualization, pressure drop measurements and new prediction method. Experimental Thermal and Fluid Science.

[12] Vallé, C., Lucas, D., Beyer, M., Pietruske, H., Schutz, P., Carl, H., 2010. Experimental CFD grade data for stratified two-phase flows. Nuclear Engineering and design 240, 2347-2356.

[13] Vallée, C., Hohne, T, Prasser, H. M., Suhnel, T., 2008. Experimental investigation and CFD simulation of horizontal stratified two-phase flow phenomena. Nuclear Engineering and design 238, 637-646.

[14] Dhotre, M. T and Joshi, J. B., 2004. Two –dimensional CFD model for the prediction of flow pattern, pressure drop and heat transfert coefficient in bubble column reactors. Chemical engineering research and design. 82 (A6), 689-707.

[15] Ratkovich, N., Chan, C. C. V., Berube, P. R., Nopens, I. 2009. Experimental study and CFD modeling of a two-phase slug flow for an airlift tubular membrane.

[16] Manmatha, K. R., Sukanta. K. D. 2011. Two-phase pressure drop caused by flow area contraction/expansion in small circular pipes. International journal for numerical methods in fluids. 66, 1420-1446.

[17] Kaushik, V. V. R, Ghosh, S, Gargi, D, Prasanta, K. D. 2012. CFD simulation of core annular flow through sudden contraction and expansion. Journal of petroleum science and engineering. 86-87, 153-164.

[18] Balakhisna, T, T., Ghosh, S., Das, P. K, 2010. Oil-water flows through sudden contraction and expansion in a horizontal pipe- phase distribution and pressure drop. Int. J. Multiphase flow. 36, 13-24.

[19] Ghorai, S., Nigam, K. D. P. (2006). CFD modeling of flow profiles and interfacial phenomena in two-phase flow in pipes, Chemical engineering and processing journal, 45 (1), 55-65.

[20] Hirt, C. W., and Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. Journal of computational physics, 39 (1), 201-225.

[21] Launder, B. E, Reece, G. J. and Rodi, W. 1975. Progress in the development of a Reynolds-Stress Turbulent closure. Journal of fluid Mechanics, 68 (3), 537-566.

[22] Issa, R. I., 1986. Solution of implicitly discretized fluid flow equations by operator splitting. J. Comput. Phys. 62, 40-65.

[23] Kays, W. M. 1950. Loss coefficients for abrupt drops in flow cross section with low Reynolds number flow in single and multiple-tube systems. Trans. ASME 73, 1063-1074.

[24] Zivi, S. M. Estimation of steady state steam void-fraction by means of principle of minimum entropy production. ASME Trans Series C, 1964, (86): 237-252.

[25] Belgacem, I. (2015). Contributions à l'étude de l'écoulement diphasique gaz-liquide co-courant en milieu confiné dans une conduite horizontale avec ou sans singularité. Thèse de Doctorat, U.S.T.H.B.