Simulation of Stratified Two-phase Flow Regime using Air-Water Model in ANSYS Fluent®

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Abstract. Two-phase flow has widely grown in importance in various fields of science and engineering system such as nuclear reactors, heat exchangers, transport system, chemical processing plants etc. One of the major issues faced by these sectors is the development of an accurate and reliable multiphase flow measurement system. At present there is no single system which could measure the two phase flow parameters irrespective of its incoming conditions. Characterization of the single phase flow parameter is easier when compared with two phase flow as the velocity distribution, mass flow rate and void fraction of each component phases are not easily measurable. The other factors that add to these difficulties are the prediction of flow regimes and the effect of pipe or channel orientation on the flow properties in the two phase flow. The hold-up of the individual phases and their relative velocity along with pressure drop needs to be taken care while dealing with these flows. Various researches have clearly shown that no correlation can be used for predicting the flow regimes in a two phase flow satisfactorily. By using volume of fluid multiphase flow model air-water two phase flow was simulated for inlet velocities of water and air as 0.121 m/s and 6.56 m/s respectively. Stratified laminar flow was obtained from the CFD simulation. Variation in volume fraction of both air and water, mass flow rate and pressure drop with respect to change in time are investigated using the simulation.

1. Introduction
Liquid-gas or gas-liquid two-phase flows are common phenomena in various engineering fields like chemical, nuclear and petroleum industries. These two phase flow are most common in all applications wherever cryogens are being used as coolants which include aerospace, superconductivity applications etc. The characteristic study of these two phase flow is complex mainly because of the different flow patterns encountered during the flow. On comparing with the single phase fluid flow, its concept is well understood but its complex behaviour limits its application. As a result of this many experimental, simulation and modelling studies are being carried out to characterize the two phase flow behaviour with the aim of simplifying the complex concept behind it.

Many different flow regimes are possible for two phase flow whereas in single phase flow there exists only laminar or turbulent flow along with a transition region in between the two. In two phase flow it may be turbulent in liquid phase and laminar in vapour phase or any of the four different combinations possible. Some sources vary on the descriptions of the flow and the exact number of variations. This is because certain flow patterns are either very similar or are transitional regimes, so they are grouped together as single pattern. While the flow regime cannot be determined from the void fraction or flow quality alone, the flow does typically change with respect to the increase or decrease of either of these
values [1]. A brief description of the flow patterns is given, arranged with respect to increasing flow quality:

- **Bubbly flow**: Gas bubbles of various sizes flow at approximately the same velocity as the liquid. At lower liquid flow rate, the bubbles tend to travel at the top of the channel. At higher liquid flow rates, the bubbles are seen more evenly dispersed in the channel.
- **Plug flow**: As the gas flow rate increases, the small bubbles begin to combine to form ‘plugs’ of gas in the channel.
- **Stratified flow**: Gravitational forces separate the liquid and gas phases. The liquid-gas interface is smooth. This is the rarest type of two-phase flow because it occurs most often in larger diameter pipes and laminar flow.
- **Wavy flow**: Increasing mass flow rates creates disturbances at the phase boundary. The amplitude of these waves increases as the mass flow rates continue to increase. At the higher gas flow rates, semi-slug flow begins to appear and is sometimes considered a separate flow regime.
- **Slug flow**: Wave amplitude is high enough that the liquid touches the top of the channel. The vapour is completely separated by ‘slugs’ of liquid traveling in the channel.
- **Annular flow**: At very high vapour flow rates, the liquid is forced to the walls of the channel and the gas travels in the center. At higher gas flow rates, liquid droplets are found in the vapour flow.
- **Dispersed flow**: The vapour flow rate is so much higher than the liquid flow rate that the liquid is broken into small droplets and carried in the vapour stream. As the vapour flow rate continues to increase, the droplets continue to get smaller and eventually become froth flow. Figure 1 shows common flow patterns seen in horizontal two-phase flow.

These flows were mostly been investigated only experimentally due to their complex nature and all the empirical relations derived on the basis of these experimental results were valid only in a limited range of operating condition [1]. The growth in computer technology provided flexibility for using and constructing large-scale computational models for analysis of these complex two-phase flow types [2]. Determination of the geometry of the flow patterns or flow regimes is considered as one of the major difficulties in the modeling of two-phase gas/vapor-liquid flow [3].

![Figure 1: Basic flow regimes for horizontal two-phase flow [1]](image-url)
2. Two-Phase Flow Theory

The mathematical model for two-phase flow can vary significantly depending on the flow regime that is in question. There are, however, some common terms that should be recognized when dealing with two-phase flows. The key factors and common terms that determine and describe two-phase flow are void fraction ($\alpha$), flow quality ($\chi$), and slip ($S$). In all the equations given below suffix v and l denote the vapor and liquid phase in two phase flow. Void fraction is the ratio of the vapor cross sectional area to the total area. This is one of the most basic commonly mentioned terms in two-phase flow and can be written as

$$\alpha = \frac{A_v}{(A_v + A_l)}$$ (1)

The flow quality is the ratio of vapor mass flow rate to the total mass flow rate and is given as

$$\chi = \frac{m_v}{(m_v + m_l)}$$ (2)

Slip refers to the ratio of the vapor velocity to the liquid velocity which helps to determine how the liquid gas phase boundary behaves and is given by the relation

$$S = \frac{u_v}{u_l}$$ (3)

The slip can be related to the other parameters by the following relation

$$S = \frac{\chi (1-\alpha) \left(\frac{\rho_l}{\rho_v}\right)}{(1-\chi) \alpha}$$ (4)

When the slip ratio is unity, the void fraction and flow quality are related simply by the different liquid and vapor densities. When the slip ratio is not known, the void fraction cannot be easily determined from the flow quality and vice versa. Due to this, the flow regimes have been identified by numerous maps developed for different channel configurations. Baker map, later modified by Scott has been used by several authors for predicting flow characteristics in horizontal flow. Attempts have been made to simplify the problem of determining the flow regime in a quantitative way. There have been numerous maps developed for different channel orientations. Some of the maps are relatively simple and use only two axes to distinguish the flow patterns, while others involve different axes for different flow patterns.

3. Flow Pattern Maps

While liquid-gas two-phase flow is complicated, the flow patterns are distinct and can be consistently categorized. The primary factor which governs the flow behavior in a two phase flow is the vapor-liquid phase interaction that varies as the flow velocity of the phases change. Along with phase interaction, fluid characteristics like viscosity and surface tension plays a prominent role in determining the behaviour of the flow. The flow characteristics depends on the flow channel orientation whether it is horizontal, vertical or inclined at an angle and also depends on the gravitational force acting on it. Various researches have shown that no correlation or single theory can be used for predicting the pressure gradient or liquid hold-up over all flow regimes encountered in two phase flow in pipes satisfactorily [4]. Both empirical correlation methods and mechanistic models are still widely used to predict accurately what flow pattern will occur for given input flow rates, pipe size, and fluid properties [5]. Then only proper flow model can be selected for the two phase flow analysis. Various literatures have presented different methods for this purpose, usually in the form of two-dimensional maps in which the locations of the boundaries between flow pattern regions are based on empirical observations. Many of these maps covers a rather limited range of fluid properties and pipe diameters. Consequently, large discrepancies are often observed between a predicted flow regime and that actually observed in a subsequent test.

Different flow pattern maps developed by various researchers are briefly described below in chronological order. One of the first flow pattern maps was suggested by Bergelin and Gazley which...
was based on the air water system in a 1 inch pipe. It uses the liquid and gas mass flow rates $m_l$ and $m_g$ as the coordinates [5]. A similar flow pattern map based on air water data in 0.87 inch pipe was proposed by Johnson and Abou-Sabe [6]. Alves [7] suggested a flow pattern map based on data for air water and air--oil mixtures in a 1 inch pipe utilizing the superficial liquid and gas velocities, $v_{sl}$ and $v_{sg}$ as the coordinates. He represented both of the systems on a single map.

Figure 2 shows the Baker map, the most commonly used chart for predicting flow characteristics in horizontal flow. The Baker flow regime map shows the boundaries of the various flow pattern regions as functions of the superficial mass velocity of the gas phase and the ratio of superficial mass velocities of the liquid and gas phase. It has been used as a rough guide in prediction of the two phase flow regime in horizontal pipes. The dimensionless parameters $\lambda$ and $\psi$ were added so that the chart could be used for any gas/vapor--liquid combination rather than the standard combination, at which both the parameters $\lambda$ and $\psi$ will be equal to one. The standard combination is water and air flow under atmospheric pressure and at room temperature. Appropriate values for $\lambda$ and $\psi$ will help in proper prediction of the geometry of two-phase flows with any gas/vapor and any liquid at other pressures and temperatures. Although the transition from one flow pattern region to another is presented as a line, in reality these lines are rather broad transition zones. Each researcher probably observed the transition at slightly different superficial flow combinations during the experimental work [1]. Baker chart and was later modified by Scott and it does not have clearcut transition boundaries but instead shows relatively wide bands depicting regions of transition from one flow pattern to another [4].

In this map the vertical axes and horizontal axes denotes $G_G/\lambda$ and $(\lambda G_L \psi)/G_G$ respectively. $G_G$ and $G_L$ are the mass flux of the gas phase and liquid phase respectively. Expression for $\lambda$ and $\psi$ are given in the below equations.

$$\lambda = \left(\frac{\rho_G}{\rho_L}\frac{\rho_L}{\rho_\alpha}\right)^{\frac{1}{2}}$$

$$\psi = \left(\frac{\rho_\alpha}{\rho_L}\frac{\mu_L}{\mu_\alpha}\frac{\rho_\alpha}{\rho_L}\right)^{\frac{2}{3}}$$

There has also been a large amount of work done in predicting the pressure drop in a two-phase flow system. These mathematical models of the pressure drop vary significantly from one to the other and usually require at least the void fraction and flow quality to be known. These models also usually only work for very specific flow conditions and have strict sets of assumptions that must be met for them to apply.

4. Experimental Techniques for Flow regime identification

In consideration with the importance and complexity of two phase flow, various technique was developed for the identification of different flow regimes. The characteristics of two phase flow regime
depend on the length, diameter, orientation of the tube, superficial velocities of two phases and properties of the fluids. Since two phase flow patterns play a vital role in two phase flow pressure drop, void fraction, heat and mass transfer characteristics there is a need to precisely identify the flow regimes. Several experimental techniques were adopted in the past to study the two phase flow patterns. Guilizzoni [9] studied the flow pattern of two phase flows from the change in density of the phases sampled using impedance probe. But the impedance probes interrupts and changes the characteristics of the fluid flow. Later it was found that nonintrusive techniques such as gamma ray or X-ray based techniques do not disturb the flow. Kumar et al. [10] and Ikeda et al. [11] used Gamma ray tomography to measure the void fraction in two phase flows and X-rays to characterize the two phase flows respectively. The amount of the received Gamma ray was used to characterize the flow pattern. The change in dielectric constant of two phase medium is used in determining the void fraction using the capacitance probe to determine the flow regime. Jaworek et al. [12] developed a capacitance sensor operating at 80MHz to measure the void fraction in air water two phase flow. Image analysis and Particle Imaging velocimetry techniques were used to study the gas-liquid slug flow along vertical pipes and to characterize the two phase flows.

Very few works have been done earlier using Infrared sensing technique to study the two phase flow patterns. One such work is by Ruixi et al. [13] where the voltage output from the sensor is used to characterize the two phase flow pattern. In the experiments a lower voltage around 0.46 indicates a water flow and a higher voltage indicates air. The elongated portion at higher voltages indicates a slug flow. However the fluctuations obtained at the lower voltages as shown in figure 3 were observed in the experimental results. Arunkumar et al. [14] designed a pair of parallel copper electrodes on the two sides of a glass tube acts as a dielectric sensor for two phase flow regime identification. The principle involved in the measurement is that the changes in effective permittivity of the two phase fluid mixture. The effective permittivity of the medium changes as the void fraction in the glass tube changes and causes variation in the capacitance value across the electrodes. Adhavan et al. [15] used an infrared sensor for identifying the two phase flow regimes. The current flowing across the receiver is used in characterizing two phase flow and three flow regimes were identified using this technique. The basic principle behind measurement was that the current changes with intensity of IR rays falling on receiver and on the basis of current output the flow pattern was characterized. However experimental results in figure 4 shows comparatively lesser fluctuations because of refined acquisition speed and good ambient conditions (dark room environment) maintained throughout the experiment.

Figure 3: Slug flow pattern characterization [13]  Figure 4: Slug flow pattern characterization [15]  

Void fractions can be monitored by capacitance probes by measurements between the two electrodes or multiple pairs of electrodes. The change in void fraction leads to change in capacitance in view of the changes in the dielectric constant changes between the vapour and liquid. The capacitance between two flat plates is given by the relation
While that of a cylindrical capacitor with two concentric cylinders having outer and inner radius as $r_o$ and $r_i$ respectively, with a given space between them is given by

$$C = \varepsilon\frac{A}{l} \quad (5)$$

$$C = \frac{2\pi\varepsilon L}{\ln(r_o/r_i)} \quad (6)$$

Depending on the orientation of the capacitor plates with respect to the flowing fluid, the capacitances get arranged either in series or parallel configurations. The laminar two-phase flow meter proposed to be developed behaves similar to that of an open-channel. This means that the fluid flows in the channel, but the liquid surface is also exposed the vapour zone, similar that of a canal or river. The idea of the flow meter is that there is laminar, two-phase flow which passes through a number of tall, narrow channels. In this laminar flow, the liquid and gas phases get separated into a stratified flow. Such a flow leads to the development of a slope down the channel length due to the difference in viscosity between the liquid and gas and the friction with the narrow channels as shown in figure 5. The viscous force between the liquid and the wall is more than that between the gas and the wall and this leads to a negative slope of the liquid level as it travels. Figure 6 shows the schematic of the proposed typical laminar flow stratified flow meter.

5. CFD Modeling

Due to the complex behaviour of two phase gas liquid or vapour liquid flow, they are mostly being studied experimentally. Large number of empirical correlations were developed for describing the flow but most of them are only valid in a limited range of operating conditions. The growing computer facilities has helped to sort this problem to some extend as it has provided much flexibility to construct and use large scale computational models to calculate these complex two phase flow types. Thus experimental research is not always needed [2]. CFD is a powerful tool to understand and analyze the characteristics of two phase flows. Modelling of two phase simulation involve three basic steps. The first step is the definition of the number of phases and consideration of the possible flow regime. Next step is the formulation of basic flow governing equations which represent the mathematical statement related to conservation laws of physics. The final step involves solving of these equations that describe the mass, momentum and energy conservation in the selected domain.
The CFD simulations were performed by using the commercial software ANSYS Fluent which is capable of doing all CFD process in a single interface. Various multiphase models are available in ANSYS of which VOF model is being opted for studying the two phase flow regime. VOF model is being considered as the direct method of predicting interface shape between the two immiscible phases. In two phase flow modelling only a single set of equation is used for the purpose of tracing the void fraction of individual phases in VOF model [1]. In the VOF method the sum of the volume fraction of gas and vapour phases are taken as unity. The evaluation is being done by solving the momentum and continuity equation.

5.1 Geometry and meshing
A three dimensional model of a horizontal rectangular channel with length, height and width as 305mm, 74mm and 1mm respectively has been created in ANSYS design modeler. The rectangular channel was chosen as the geometry so that the flow becomes similar to that of an open-channel. This means that the fluid flows in the channel, but the liquid surface is also exposed the vapour zone, similar to that of a canal or river. A fine quadrilateral mesh of the geometry is being done using ANSYS mesh modeler. Number of elements and nodes for meshing was 30960 and 25000 respectively.

5.2 Solution strategy and boundary conditions
The analysis is being carried out under no slip conditions. Since the two phase flow is time dependent an implicit unsteady study needs to be done. The effect of gravity on the flow characteristics were considered. The number of eulerian phases were given as two in the VOF model. The inlet condition for both the phases are being taken as velocity inlet and the outlet boundary condition was given as pressure outlet. The operating pressure is being taken as 1.01325 bar during the flow analysis. In this work air water two phase system is being considered for analysis with water as the primary phase and air as the secondary phase. The phase interaction needs to be specified for the VOF model. Effect of surface tension on the flow characteristics should be considered so for that one of the surface tension model need to be applied.

Continuum Surface Force (CSF) model needs to be applied for calculating the surface tension force. For both the phases velocity inlet condition was specified for the inlet surface. In this type of boundary condition both the velocity profile and volumetric fraction of the phases needs to be specified. The inlet surface is being face split for the above mentioned factor. Volume fraction of air at the upper half of the inlet surface was 1 and that at the lower half was 0. This means that air enters the domain through the upper half and water enters through the lower half. The outlet surface was modelled as pressure outlet with a constant pressure of 0 Pa. No slip condition was assumed for the channel wall. Solution method used for pressure velocity coupling was PISO algorithm and a second order upwind scheme is used for determination of flow characteristics. Modelling is done in transient state and details of time step can be found from the table shown below.

| No. | Title                           | Description |
|-----|---------------------------------|-------------|
| 1   | Time step method                | Fixed       |
| 2   | Time step size                  | 0.001       |
| 3   | Number of time steps            | 20000       |
| 4   | Max iteration / time step       | 20          |

6. Results and discussion
Analysis was done with the velocity of water and air taken as 0.121 m/s and 6.56 m/s respectively. These velocities were selected as per the pressure drop correlation ensuring that both the liquid and gas phase are having laminar flow. The use of tall narrow rectangular channel and the velocity mentioned above has forced the flow into laminar two phase flow. In this laminar flow, the liquid and gas phases get separated into stratified flow as shown in figure 7. Since the mixture density is proportional to its phase composition, the distribution of air and water in the channel can be clearly seen.
In the volume fraction of air contour red colour refers to the presence of air while the dark blue colour refers to the presence of water. Meanwhile in the volume fraction of water contour red colour shows water and dark blue colour shows air. Such a flow leads to the development of a slope down the channel length due to the difference in viscosity between the liquid and gas and the friction with the narrow channels. The viscous force between the liquid and the wall was more than that between the gas and the wall and this leads to a negative slope of the liquid level as it travels. The stratified flow is observed as a liquid medium flowing at the bottom of the tube and the gas medium occupying the remaining part. Gravity plays a vital role in stratified flow. When superficial gas velocity is high and superficial liquid velocity was very low, stratified flow occurs.

![Figure 7: Volume fraction contour of air and water for stratified laminar flow](image)

Figure 7: Volume fraction contour of air and water for stratified laminar flow

Development of stratified flow during the flow time of 1 second is shown in figure 8 and the formation of negative slope can be clearly seen from the contour given below. Figure 9 shows the mass flow rate plot of air water mixture against the flow time. Effect of viscosity, friction and gravity leads to the separation of the two phases by a smooth air water interface leading to the evolution of stratified flow. It is found that the mass flow rate of air shows an increasing trend whereas the mass flow rate of water shows a decreasing trend. The total flow time taken for the simulation was 1 second. The mass flow rate of air water mixture also shows an increasing trend as the flow time increases. It is mainly because of the higher velocity of air when compared with velocity of water. The mass flow rate of the air water mixture was found to be 0.49 kg/s.

![Figure 8: Contour of volume fraction obtained after a flow time of 0.3, 0.5 and 1 second](image)
Volume fraction for water was plotted against time of flow as shown in figure 10. Total time of flow is being taken as 1 second and with increase in flow time the volume flow rate of water shows an increase. When the flow time reaches 1 second the volume fraction of water was found to be 0.35. The volume fraction of air has dropped from a value of 1 to 0.65 during the flow time whereas the volume fraction of water increases from 0 to 0.35 during the flow time. Figure 11 shows the pressure contour for the stratified two phase flow and from the plot we could find the pressure drop during the flow as 600 Pa. Highest pressure region was shown at the water inlet and the pressure at the air inlet was found to be around 340 Pa.
7. Conclusion
The two phase stratified air water flow pattern is obtained when the inlet velocity of air and water was 6.56 m/s and 0.121 m/s respectively. Mass flow rate of the mixture shows an increasing trend with increase in flow time. Pressure contour was analysed and pressure drop during the two phase flow was found to be 600 Pa. Volume fraction of water after a flow time of 1 second was found to be 0.35. Simulation was only done with one set of velocity and for validating further simulation needs to be done with other set of velocities. The problem with the CSF model is the discontinuity in the domain, such as an interface and cannot be solved by a finer mesh. So proper meshing needs to be done for improving the accuracy of results. The geometry used for simulation is not provided with any development section and buffer zone. Development section will help in making the flow fully developed before entering the test section. Buffer zone will reduce unwanted fluctuation in the simulation result at the pressure outlet section.

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