# Numerical Analysis of Two Phase Flow Patterns in Vertical and Horizontal Pipes

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*Abstract:-* This paper is provided a numerical simulation of flow patterns (bubble, slug/ Taylor bubble, churn/ stratified wave flow, annular) of air-water two phase flow. ANSYS FLUENT program with VOF homogenous model through unsteady state turbulent flow employed to study the effect of holdup, void fraction and liquid film thickness on the pressure drop through the vertical and horizontal pipes with the 90º elbow. K-ε (Realizable) model has been used in order to solve the turbulent flow with bubble and slug flow patterns; whereas (RNG) model with churn and annular flow patterns by depending on the values of viscosity and density of the flow mixture.

*Key-Words: -* flow patterns, VOF, two phase, holdup, void fraction, numerical analysis

## 1 Introduction

Two-phase flow is part of a multiphase flow due to consists of two materials and classified as a homogeneous system, for example, air-liquid, air-solid or heterogeneous system, for example, liquid-liquid, liquid-solid. It is considered unsteady flow and more complex from single phase flow due to the difference between of the material properties of each phase. Air-Liquid flow is a homogeneous flow but at the same time considered unsteady flow due to the difference between the components of the material of each phase. It is contained in the more from phenomenon at the flow in vertical and horizontal pipes with 90° elbow depending on superficial velocity of air $U_{sa}$ and superficial velocity liquid $U_{sw}$. Wongwises and Pipathattakul (2006) [1] have been remarked that when liquid superficial velocity increased, the value of void fraction will be decreased because of the replacement of gas with a l iquid. They have explained the value of void fraction decreased when inclined more than horizontal pipes because the liquid is naturally pulled to the bottom by gravity force and especially when the angle of the pipe is increased causing decreasing in the void fraction. Loilier (2006) [2] has explained the distribution of patterns flow through horizontal pipe. Noted the flow patterns depend on the diameter of the pipe and the difference of superficial velocity of gas and liquid. As well as on the properties of the materials that carried out inside the pipe in order to form many types of the regime through two phase flow. Speeding and Benard (2007) [3] have been remarked that the flow in the vertical pipe is slug pattern, then after the flow leaves the elbow and enter to the horizontal pipe becomes the stratified flow. They explained that the gravity and lifting forces available in the vertical pipe that helps the mixture to rise that will be absent in the horizontal pipe. Riva and Del (2009) [4] have studied churn flow for air-water two-phase in the vertical pipe. It has been observed that the cresting wave increases when gas superficial velocity increasing and drag force will increase by the effect of the gravity force in this pattern. They have noted when the liquid continues with entering, it helps to make the wave in growing and film of the liquid thickness will increase. It is shown that the pressure drop decreases when the air flow rate increases and this is explained by increasing the air superficial velocity which will become a t ransition to annular flow and cause the decrease in the thickness of the liquid. The churn flow of the air will be in the core of the pipe but it is not high enough to carry the liquid upward. MukhtarAbdulkadir (2011) [5] has studied the bubble and slug of air-silicone two-phase flow in the vertical and horizontal pipes with the 90º elbow. It has been observed that the amount of liquid is increased at the upstream pipe from downstream pipe due to the effect of the elbow and gravitation force, therefore, the value of a void fraction during the upstream pipe will be less than the downstream pipe. When the air superficial velocity has increased the value of film thickness decreases through the transition between the patterns. It has also been shown the length of slug increases by increasing the air superficial velocity and axial-distance of the pipe. Mazumder (2012) [6] has studied analysis performing four different 90° elbow of two-phase flow by using simulation experimental and ANSYS FLUENT. It presented the study to explain the characteristic of flow behaviors for two-phase flow. Aung and Yuwono (2013) [7] have noted that the liquid superficial velocity and air superficial velocity have nearly less number of bubbles with having a linear flow. The air will be separated from the water at the exit of the elbow due to the difference in densities. They have observed that the number of bubbles is increased with increasing the liquid superficial velocity and the constant value of the air superficial velocity. The bubbles will occupy the upper part of the elbow; air is pushed to the core of the downstream pipe so the air takes a long time until gets the separation. It has been shown that when the Reynolds number is increased, the pressure drop will be increased at the downstream pipe due to the large effect of secondary flow. Yadav et al. (2014) [8] have observed that the bubbles move through the vertical pipe and enter the elbow due to the effect of secondary flow. They have noted that when the bubbles enter the downstream pipe, they will gather at the top of the pipe due to the difference in the structure of flow regime. It has been shown that the bubble size increases when the superficial velocity of gas increases due to the coalescence between the small bubbles with gravitational effects. The increase of the bubble flow will cause a pressure drop at the vertical pipe. It is remarked that the secondary flow is generated by both two-phase flow and single phase flow through 90° elbow and causes the dissipation in the void fraction. Saidj et al. (2014) [9] have been observed that the value of the void fraction increased by increasing gas superficial velocity and loss in the value of the pressure. They have noted that the patterns, stratified wavy flow, plug flow, and slug flow happened through the horizontal pipe while slug flow and churn flow patterns happened at the vertical pipe. It has been shown that the slug length is increased by passing flow from upstream to downstream pipes. It turns out that by increasing the gas superficial velocity; it will be unsteady through the horizontal pipe and will increase the fluctuation to the move-wavy making up the biggest waves in any access to the slug or plug patterns. Vieira et al. (2014) [10] have noted that the value of liquid film thickness increases with increasing water flow rate. They observed that the void fraction increases with air flow rate and decreases by increasing water flow rate. T he waves are formed through increasing water flow rate, which causes increasing the value of liquid film thickness. It has been remark that the crest of waves decreases by increasing water flow rate, which causes decreasing the liquid film thickness. It has been noted that when the operation system at relatively low pressure and relatively low gas and liquid flow rates, large bubbles (slug) having diameter reaches to the diameter of the pipe are created and be long- sized.

## 2 CFD ANSYS Fluent

ANSYS FLUENT is solved with 3D drawing of the geometry of the system. The geometry drawing with inlet air-water flow is co-current through the pipes. The structured computational grids; the mesh consists of 638295 nodes and 1730560 elements tetrahedral, as shown in Fig. (1). The inflation is five layers with k-Ɛ (RNG and Realizable) models to solve the numerical finite volume code ANSYS FLUENT 16.1. The value of the distance to the first layer from the wall is 0.001 cm.

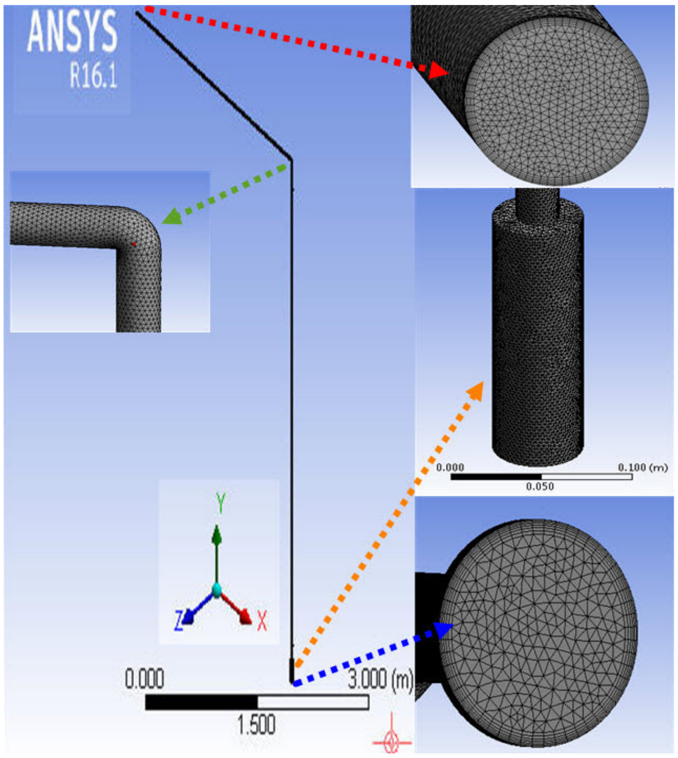

Fig. (1): The unstructured mesh for geometry.

## 2.1 ANSYS FLUENT Method

Multiphase flow model through ANSYS FLUENT program consists of three models (Eulerian, Mixture and VOF) models used with two-phase flow. VOF homogenous model is used to simulate the numerical ANSYS FLUENT and experimental apparatus by flow patterns (bubbles, slug/ Taylor bubble, churn/ stratified wave flow and annular) and pressure drop effect at each pattern and steps of ANSYS FLUENT code 16.1.

## 2.2 Boundary condition

1. The inlet boundary for two-phase flow

Superficial velocity of air: $U_a = \frac{Q_a}{A_m}$ (1)

Superficial velocity of water: $U_w = \frac{Q_w}{A_m}$ (2)

Where:

$$A_m = A_a + A_w \tag{3}$$

2. The outlet boundary

$$\frac{dU_m}{dx} = \frac{dV_m}{dy} = \frac{dW_m}{dz} = 0 \tag{4}$$

3. The mixture of two-phase flow is assumed to be no – slip boundary condition on the wall of the pipe, defined as:

$$U_m = V_m = W_m = 0 \tag{5}$$

## 2.3 Governing Equations

The governing equations of flow explain the solution of (air-water) two-phase flow through domain by the balance of mass and momentum equations depending on v olume fraction values to each phase.

### 2.3.1 Conservation of mass

The continuity equation is solved by the volume fraction of one or more of the phase. For the $q^{th}$ phase, this equation has the following form [11].

$$\frac{1}{\rho_q}\left[\frac{d}{dt}\left(\alpha_q \rho_q\right) + \nabla.\left(\alpha_q \rho_q \overrightarrow{V_q}\right) = S_{\alpha_q} + \sum_{P=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right)\right] \tag{6}$$

$\dot{m}_{pq}$ is the mass transfer from P to $q$ and $\dot{m}_{qp}$ is the mass transfer from $q$ to P. $S_{\alpha_q}$ is Source term.

The general of continuity equation for mixture flow is given by

$$\frac{d\rho_m}{dt} + \frac{d}{dx_i}\left(\rho U_m\right) = 0 \tag{7}$$

### 2.3.2 Conservation of momentum

The momentum equation is solved throughout the domain depending on the volume fractions of all phase, which is illustrated by vectors through the properties $\rho$ and $\mu$, given as

$$\frac{d}{dt}\left(\rho\vec{V}\right) + \nabla.\left(\rho\vec{V}\vec{V}\right) = -\nabla P + \rho\vec{g} + \nabla.\left[\mu\left(\nabla\vec{V} + \nabla\vec{V}^T\right)\right] + \vec{F} \tag{8}$$

The general of momentum equation for mixture flow, given by

$$\frac{d\left(\rho_m U_j\right)}{dt} + \frac{d}{dx_j}\left(\rho_m U_i U_j\right) = -\frac{dp}{dx_i} + \rho_m g_j + \frac{d}{dx_j}\left[\mu_m\left(\frac{dU_i}{dx_j} + \frac{dU_j}{dx_i}\right) - \rho_m \overline{u'_i u'_j}\right] + \vec{F} \tag{9}$$

# 3 Results and Discussion

### 3.1 Liquid film thickness

Fig. (2) shows the values of liquid film thickness with r/R ratio of a cross-section of bubble flow at $U_{sw}$ = 1.3 m /s and $U_{sa} = 0.11$ m/s. Liquid film thickness is growing through bubble flow due to the increased holdup value because this increment is a result of increasing of water superficial velocity, as shown between 1.2 and 1.8 at x-axes.

Fig. (3) explains the values of liquid film thickness with r/R ratio of cross-section of plane of annular flow at $U_{sw}$ = 0.2 m/s and $U_{sa}$ = 14 m/s. Note that the liquid film thickness will be slightly in annular flow due to the increase of air superficial velocity which causes an increment of void fraction and decrease holdup, as shown between 0.9 and 1.9 at x-axes.

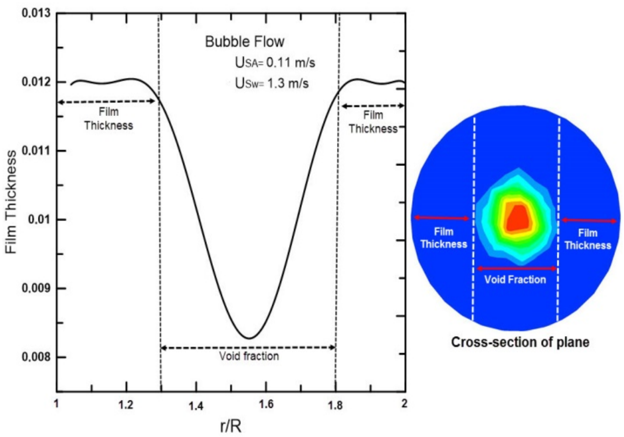


Fig. (2): The increment value of liquid film thickness at cross-section plane of bubble flow.

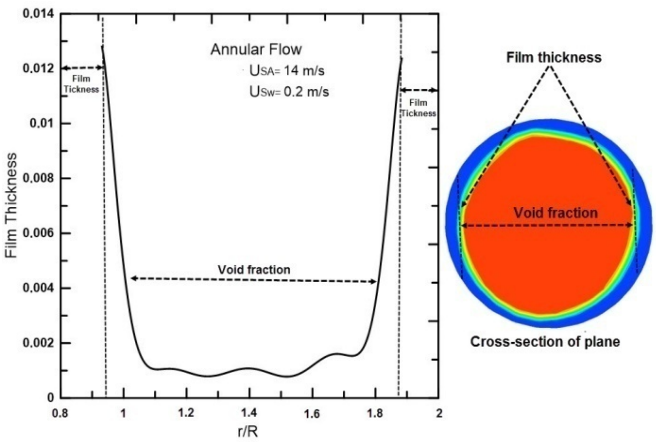


Fig. (3): Distribution of the value of liquid film thickness at cross-section plane of annular flow.

## 3.2 Distribution of the void fraction through cross-section of plane

Figs. from (4) to (11) represent the void fraction values with r/R ratio of the cross-section of a plane through flow patterns (bubbles, slug, churn/ stratified wave flow and annular) in the vertical and horizontal pipes. It is observed that the values of void fraction increases at the flow rising in the vertical pipe and when the mixture continues to flow into the horizontal pipe.

Fig. (4) shows the behavior of void fraction of bubble flow pattern in the vertical pipe. It is noted the value of void fraction when $U_{sm}$ = 0.65 m/s at l/d ratio 41 are few because the effect of gravity force increases through this ratio, which causes an increase in the value of holdup and decrease void fraction values in this region. The void fraction increases when $U_{sm}$ is 0.74 m/s at l/d ratio 83 due to the increase of the buoyancy force as the flow rises in the vertical pipe. Moreover, some of merging and coherence of the bubbles is happened to form bubble with large size so it will increase the void fraction. At $U_{sm}$ is 0.83 at l/d ratio 187 the void fraction becomes with high value because the mixture flow reaches to the fully developed region. The increase of the process of merging and coherence of bubbles, which occur with increased buoyancy force to get the largest number of gaps causing the increase in the void fraction value. It has been shown that the values of r/R from 0.9 to 1.4 are unstable. This indicates to the holdup value in this region which is fluctuated between values 1 and 0 for containing small bubbles that cause the decrease and increase in the value of the void fraction.

Fig. (5) shows the behavior of the void fraction through bubble flow pattern in the horizontal pipe. The void fraction increases as the mixture flow continues until it reaches the fully developed region, so the high velocity converge bubbles formed through the vertical pipe and merge them to consist gaps with large size causing the increase of the void fraction. The void fraction starts to increase after 1.5 the value of the ratio r/R due to the influence of buoyancyforce then the bubbles are separated from the water and will accumulate at the top of the pipe. The ratio value between 1 and 1.4 explains the fluctuated of the value of holdup and the amount of water accumulate at the bottom of the pipe.

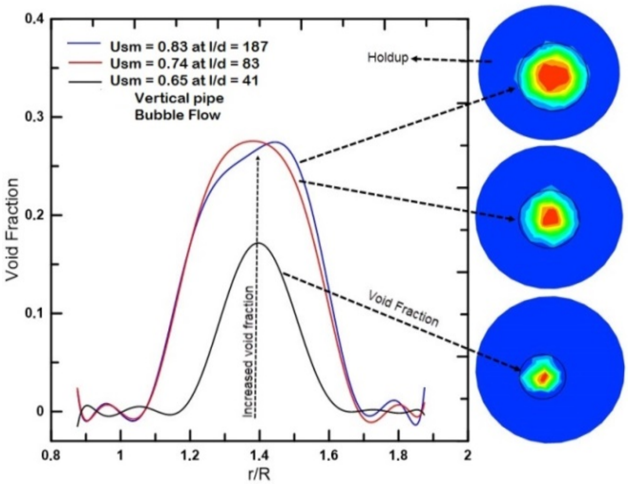


Fig. (4): The void fraction of bubble flow in the vertical pipe for cross-section of a plane.

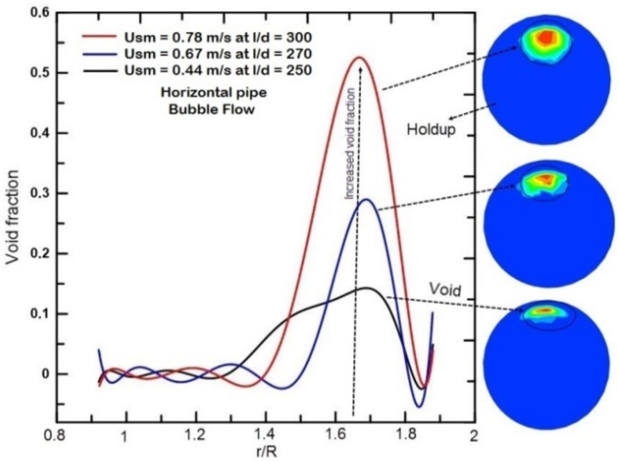


Fig. (5): The void fraction of bubbles flow in the horizontal pipe for cross-section of a plane.

Fig. (6) explains the behavior of void fraction of slug flow pattern in the vertical pipe. Notice that the movement of the large bubble has an irregular shape through rising in the vertical pipe. However, the effect of the gravity force tries to pull the big bubble down while the effect of buoyancy force tries to lift it to the top of the pipe. When the bubble keeps away from the effect of these forces it will get instability in the value of the void fraction. The void fraction values are more stable at $U_m$ 1.62 m/s and l/d ratio 187 due to decreasing the effect of gravity force and increasing the effect buoyancy force. The Taylor bubble flow happens in the center of the pipe causing stable values of void fraction. This is noted during the cross-section of the plane on the side of the curve.

Fig. (7) represents behavior of void fraction through slug flow pattern at the horizontal pipe. It is observed that the void fraction values of r/R ratio between 0.8 and 1.3 at x-axial are equal to zero because it represents the holdup value accumulation in the bottom part of the pipe which is illustrated during cross-section of plane. The ratio between 1.6 and 2 increasing values of void fraction because it represents the air accumulation in the top part of the pipe which is illustrated during cross-section of plane.

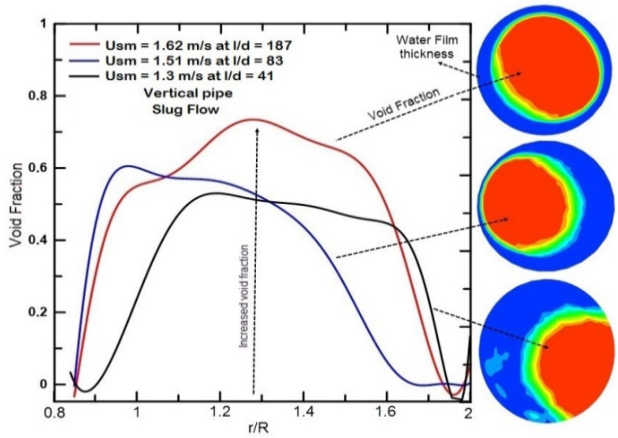


Fig. (6): The void fraction of slug flow in the vertical pipe for cross-section of a plane.

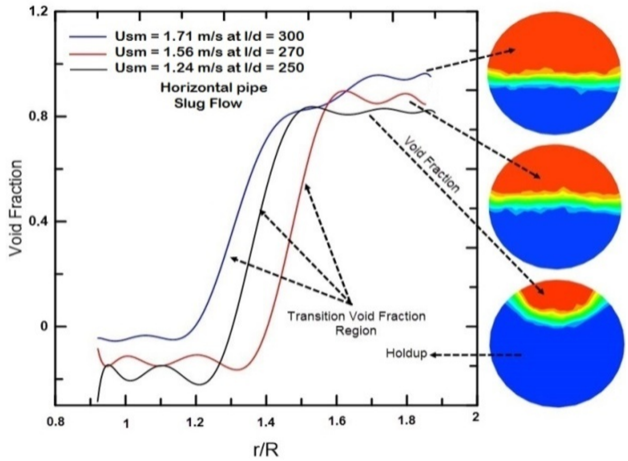


Fig. (7): The void fraction of slug flow in the horizontal pipe for cross-section of a plane.

Fig. (8) explains the behavior of void fraction of churn flow pattern in the vertical pipe. It is noted that the increase of void fraction value through this pattern is due to the high air superficial velocity, which causes the generation of air gaps inside the pipe. The values of the void fraction are unstable at the beginning of the entry due to the distance in the transition region between the slug and churn flow pattern. The many explosions that generate too big bubbles cause the fluctuation in the values of void fraction explained by the first plane at l/d ratio 41 and $U_{sm}$ 8.3 m/s. When $U_{sm}$ of 10.4 m/s at l/d ratio 187 the value of the void fraction is increasing due to the high air superficial velocity and decreases the value of liquid film thickness. The air superficial velocity through this pattern is not enough to raise the water to top the pipe; therefore, the increasing amount of air at the upper region of the pipe causing increasing in the void fraction in that region. Fig. (9) shows the behavior of void fraction of stratified wave flow in the horizontal pipe. It is observed that the values of void fraction increase at increaser$U_{sm}$ and l/d ratio. Increasing the void fraction values compared to case in Fig. (7) is due to increased air superficial velocity used at this pattern.

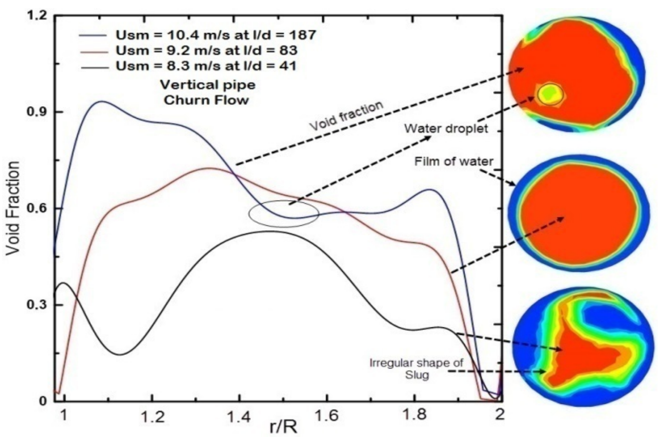


Fig. (8): The void fraction of churn flow in the vertical pipe for cross-section of a plane.

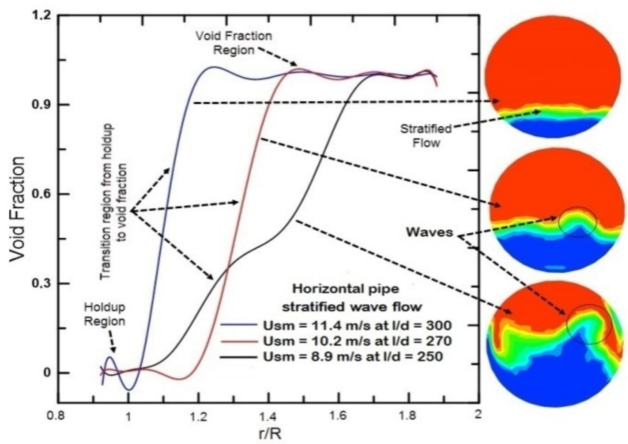


Fig. (9): The void fraction of stratified wave flow in the horizontal pipe for cross-section of a plane.

Figs. (10) and (11) observed the same behavior of void fraction that gets through annular flow in the vertical and horizontal pipes. Note that the liquid film thickness decreases when the flow goes up in the vertical pipe and continues the mixture flow to the horizontal pipe, with increasing $U_m$, the values of the void fraction increase. The cross-section of the plane when $U_m$ is 16.4 m/s at 41 of l/d ratio in vertical pipe and $U_m$ is 15.6 m/s at 250 of l/d ratio during the horizontal pipe, the liquid film thickness increase. But when $U_m$ is 18.7 m/s at 187 of l/d ratio in the vertical pipe and $U_m$ is 18.4 m/s at 300 of l/d ratio during the horizontal pipe, the liquid film thickness decrease increasing void fraction value. The increments of the liquid film thickness means increasing the value of the holdup while decreasing it means increase void fraction values.

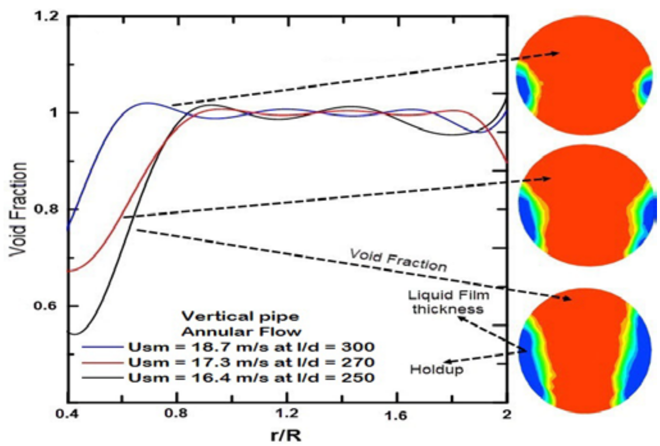


Fig. (10): The void fraction of annular flow in the vertical pipe for cross-section of a plane.

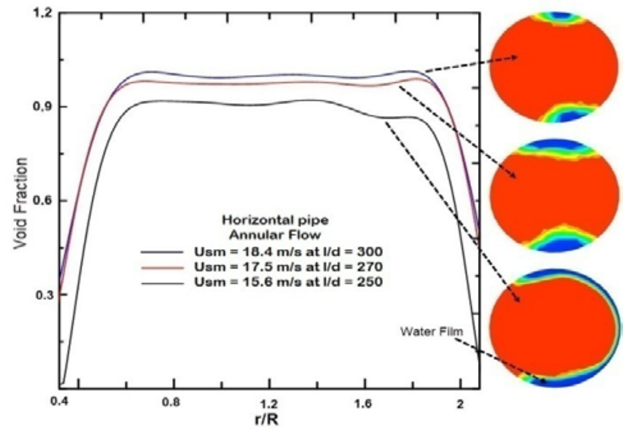


Fig. (11): The void fraction of annular flow in the horizontal pipe for cross-section of a plane.

### 3.3 Behavior of flow patterns found by CFD ANSYS FLUENT program at the vertical and horizontal pipes with 90º elbow

Figs. (12) to (15) explain the behavior of flow patterns (bubble, slug, churn/ stratified wave flow and annular) through the vertical and horizontal pipes with $90^O$ elbow. The flow patterns are obtained by using VOF homogenous model with unsteady turbulent mixture flow. The inlet mixture flow (air and water) is co-current to get matching between the air and water superficial velocities. It is assumed that air is the first phase and the water is the second phase with giving the value of surface tension 0.0704 at 35 c.

Assume the volume fraction of water to the body 1, this means the body will be filled with water and then air enters to get more accurate distribution patterns .Fig. (12) at the time t= 0.2s note the bubbles begin to form and rise in the vertical pipe and t=0.4s. Observed the shape of the bubble is changing due to increasing the superficial velocity of the bubbles at transition the flow from mixing chamber to the pipe (narrow region). Recover the spherical shape of the bubbles and continue in rising until reach to the $90^O$ elbow, as shown at times from 0.6s to 1.4s. Shows the bubble inside the elbow and separated from the water to accumulate in the top of the pipe due to the effect of the buoyancy force, as shown at times from 1.8s to 2.2s.

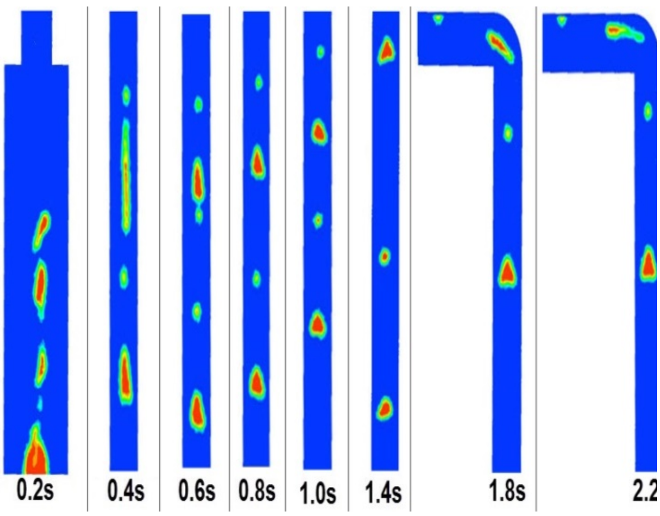


Fig. (12): Behavior bubbles flow pattern formed over time 2.2 second at the vertical pipe with $90^O$ elbow.

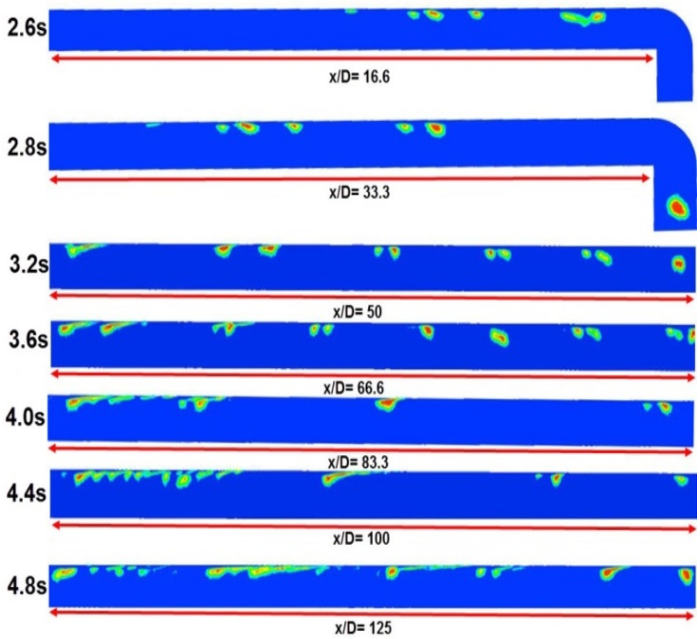


Fig. (13): Behavior bubbles flow pattern formed over time 4.8 second at the horizontal pipe with $90^O$ elbow.

Fig. (13) at times from 2.6s to 0.4s note the same of the behavior at 1.8s to 2.2s. Observed that the bubbles are formed as a group due to the increase of the void fraction values. That will be causing an increase in the number of bubbles in the horizontal pipe, as shown at times from 4.4s to 4.8s.

Fig. (14) notes big bubble begin to form and rise through the vertical pipe. Observed the form of slug is irregular shape at the beginning of the rise pipe. Due to the influence of buoyancy force, which do to lift the large bubble towards the top of the pipe. The gravity force do to pull down the bottom with effect of surface tension causing irregular motion to large bubbles, this was explained earlier, as shown at times from 0.2s to 0.6s. Observed through this times the slug will come close together and coherence to consist of Taylor bubble. Note through increase velocity to the big bubble until reach to the fully developed region. As a result of the high velocity of big bubble will separated part of them consisting of a number of small bubbles spread through the layer of water that separated between big bubbles, as shown at times from 0.8s to 2.6s. Fig. (15) at time t= 3.0s note slug will be inside the elbow and surrounded by water. Slug is a stratified flow region when the exit from the elbow region. Observed the behavior at these times is the slug in the horizontal pipe will separate from the water due to the effect of the buoyancy force but the gaps are accumulated at the top of the pipe, as shown at times to 4.5s. from 3.2s.

Fig. (16) notes in these times the entry of the air will be in the form of a large bubble similar to Taylor bubble, as shown at times from 0.2s to 0.8s. Observed big bubble will rupture and explodes due to the high air superficial velocity with the effect of buoyancy force, thus forming a number of bubbles irregular shapes, as shown at times from 1.0s to 1.8s. Note through the rise in the vertical pipe will increase the value of void fraction due to the increase of the effect of buoyancy forces causing the increment of cavities in the region near the elbow. Shows the water at the end pipe will separate to consist of layer separated by the large gaps due to the effect of gravity force and the air superficial velocity at this pattern is not enough to lift the water with it, as shown at times from 2.2s to 4.2s.

Fig. (17) at times from 4.6s to 4.8s note at these times the air moves in the inner wall of the elbow while the water moves in the outer wall of the elbow. The value of Froude number Fr = 500 >1 is greater than unity, which applied by equation $Fr = U_m^2 / Rg \sin\varphi = 1$. Abdulkadir [1] explained if Fr>1 the air moves in the inner wall of elbow while if Fr<1 the air moves in the outer wall of the elbow, depending on $U_m^2 > Rg \sin\varphi$ this mean the water moves in outer wall of the elbow. The energy of waves decreases gradually after some distance because the effect of friction force then the height of waves decreased so the plug flow changes to stratified wave flow. After few minutes, the crest of the waves decreases and vanishes, and then the stratified flow appears. The flow at stratified type is divided to two parts; first at the bottom of the pipe is occupied by water due to the density. And the second part, the air will be occupied at the top of the pipe, as shown at times from 5.0s to 6.6s.

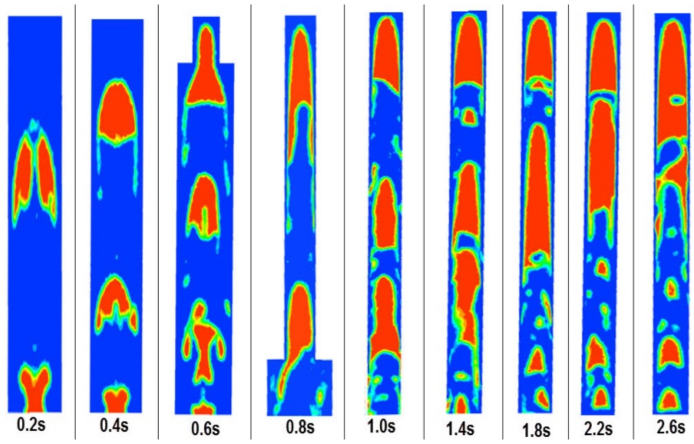


Fig. (14): Behavior slug flow pattern formed over time 2.6 second at the vertical pipe

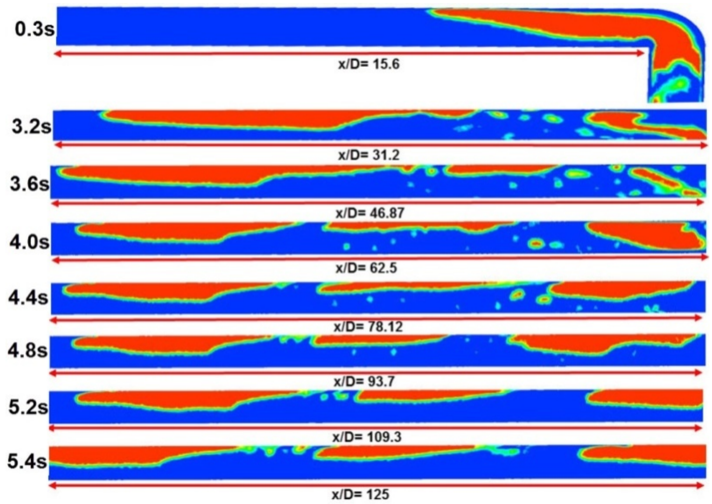


Fig. (15): Behavior slug flow pattern formed over time 5.4 second at the horizontal pipe with 90$^{O}$ elbow.

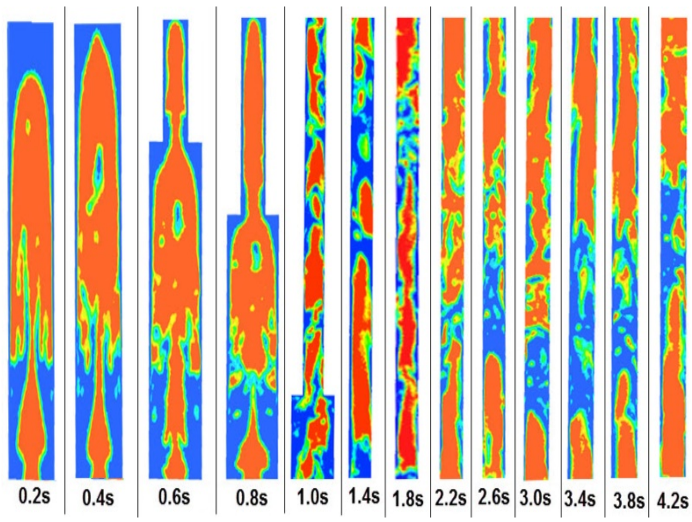


Fig. (16): Behavior churn flow pattern formed over time 4.2 second at the vertical pipe

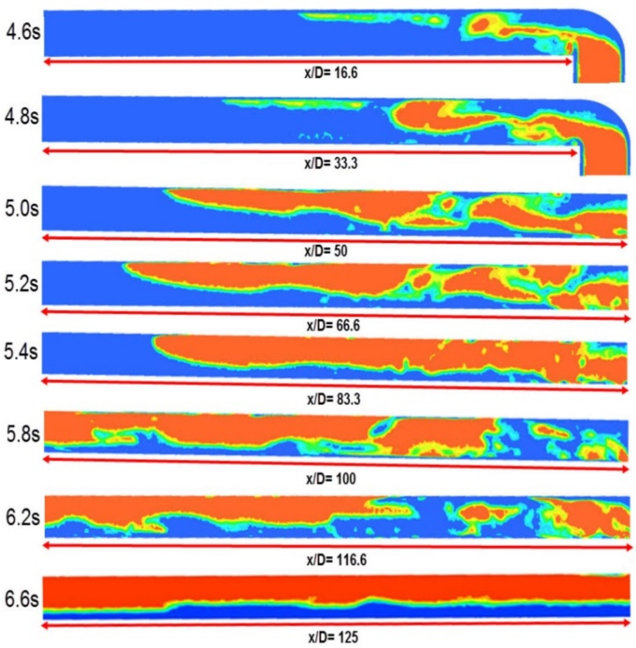


Fig. (17): Behavior churn flow pattern formed over time 6.6 second at the horizontal pipe with $90^{O}$ elbow.

Fig. (18) at times from 0.2s to 1.4s note the air flow in the core of the pipe and the water is liquid film thickness on the wall. At times from 1.8s to 2.2s observed consist waves on the wall of the pipe causing unstable in the value of liquid film thickness. At time t= 2.8s note the liquid film thickness become a more stable at the region above the waves. Fig. (19) at all the time note the same of behavior has been obtained in the vertical pipe.

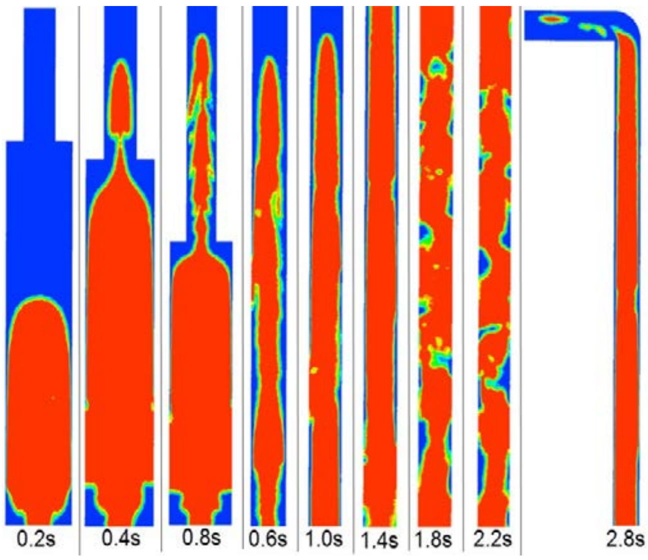


Fig. (18): Behavior annular flow pattern formed over time 2.8 second at the vertical pipe with $90^{O}$ elbow.

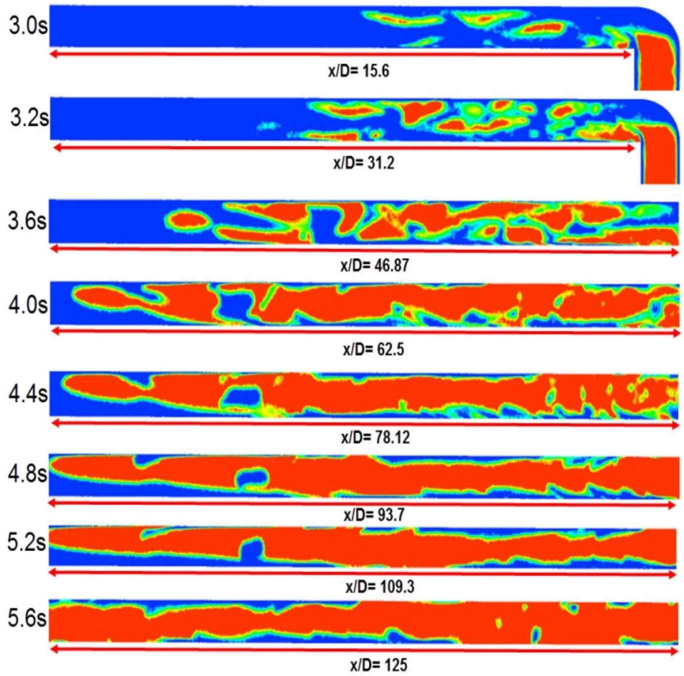


Fig. (19): Behavior annular flow pattern formed over time 5.6 second at the horizontal pipe with $90^{O}$ elbow.

# 4 Conclusions

ANSYS FLUENT program with VOF homogenous model through unsteady state turbulent flow employed to study the behavior of the flow patterns, void fraction and liquid film thickness through the vertical and horizontal pipes.

1. The value of liquid film thickness decreases with increased air superficial velocity while it increases with increased of water superficial velocity.

2. The void fraction value increases with the increase of air superficial velocity while the holdup increases with the increase of water superficial velocity.

3. The transition between flow patterns depends on the air superficial velocity.

4. The waves are formed on the wall in the annular flow will increase the air superficial velocity when passing through it, decreasing in the crest waves that formed in the annular flow when the increase in air superficial velocity.

5. The pressure decreases with increasing air superficial velocity while increases at increase water superficial velocity.

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