Numerical simulation of two-phase slug flow with liquid carryover in different diameter ratio T-junction

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Abstract. A smaller diameter conduit pointing at 12 o’clock position is typically hot-tapped to a horizontal laying production header in offshore platform to tap produced gas for downstream process train. This geometric feature is commonly known as T-junction. The nature of multiphase fluid splitting at the T-junction is a major operational challenge due to unpredictable production environment. Often, excessive liquid carryover occurs in the T-junction, leading to complete platform trip and halt production. This is because the downstream process train is not designed to handle excessive liquid. The objective of this research is to quantify the effect of different diameter ratio on phase separation efficiency in T-junction. The liquid carryover is modelled as two-phase air-water flow using Eulerian Mixture Model coupled with Volume of Fluid Method to mimic the slug flow in the main pipe. The focus in this paper is 0.0254 m (1 inch) diameter horizontal main arm and vertical branch arm with diameter ratio of 1.0, 0.5 and 0.3. The present research narrowed the investigation to only slug flow regime using Baker’s map as reference. The investigation found that, contrary to common believe, smaller diameter ratio T-junction perform worse than larger diameter ratio T-junction.

1. Introduction
T-junction is an appendage of small diameter pipe, which is attached to the main pipe to tap the fluid source from the main stream. A T-junction consists of a main arm, run arm and side arm as shown in figure 1.

Figure 1. T-junction and its components.
T-junction configuration is most commonly deployed in offshore platform where it is used to tap gas directly from the production header. The tapped gas is channel downstream as fuel gas for power generation plant or as source gas for other purposes. When a two-phase mixture flows pass a T-junction, lighter phase will preferentially enter the branch arm, while the heavier phase tends to continue flowing into the run arm [1]. Deployment of T-junction as a mini ‘phase separator’ has substantial advantages over conventional separators due to its simple installation, saving in terms of cost, space and minimal maintenance [2]. However, liquid carryover is a frequent problem that occurs in T-junction whereby excessive amount of liquid is take off into the gas stream and channeled into downstream equipment which is not designed to handle liquid. Consequently, platform trip and production must be stopped to allow offshore crews to manually drain out the excessive liquid.

2. Literature review

The initial focus for studying the phase separation at T-junctions with a reduced side-arm diameter was for industrial situations, where the branch arm of a piping system could have a smaller diameter than the main pipe (D_3 < D_1, D_3 = D_2). Reduced diameter T-junction referred to the diameter ratio of the branch arm D_3 to the main arm D_1. Diameter of main and run arms are usually the same. A reduction in the branch arm diameter will have two distinct effects; the pressure drops and the entrance area available for liquid take off. It is well known that the distribution of the phases at a T-junction depends not only on the geometry and approaching flow pattern but also rely on the two downstream pressures and the pressure drop across the T-junction. Pressure drop measurements around T-junction showed a loss between the inlet and side-arm but a pressure recovery in the run arm due to Bernoulli’s effect [3]. The pressure drop in the branch arm can be attributed to the sudden momentum change for the fluids moving from the inlet into the branch arm [4]. The effect caused by a reduction in side-arm diameter, as first suggested by Azzopardi [5], would be to reduce the axial distance available for phase take-off to occur. This reduces the liquid travel time, the time available for the liquid to flow into the side-arm instead of flowing straight into the run arm. As such there is less chance of the liquid to be dragged towards the side-arm. By the same token, smaller diameter side arm will have lesser liquid carryover issue than a regular T-junction. Pandey et al [6] carried out experiment to verify the effect of side arm diameter ratio on phase split for stratified flow and plug flow. Experiments have been performed with kerosene and water in a reduced diameter T-junction whose branch arm is 0.0127 m in diameter while the main and run arms are 0.0254 m (diameter ratio: 0.50) and compared with phase split result obtained from a regular T-junction. There is an increased in the fractional liquid take off with a decrease in the branch arm diameter. Azzopardi [7] studied the effect of branch arm to main arm diameter ratio on phase split of liquid-gas flow at T-junction for annular and stratified flow. The data were taken at 2 scales: small scale T-junction with main arm diameter of 0.038 m and side arm bore of 0.038 m, 0.025 m and 0.0127 m; large scale T-junction with main arm diameter of 0.125 m and side arm bore of 0.125 m and 0.076 m. The medium was air and water. For small scale T-junction, decrease in diameter ratio of a junction leads to lower liquid take off for both stratified an annular flow. For the larger scale T-junction, data supports that decrease in side arm diameter results in lower liquid take off. The effect of diameter ratio is most significant at lower gas rates while least at lower liquid and high gas flow rate conditions. Marti and Shoham [8] carry out experiment to compare the reduced tee data and regular tee data for horizontal branch arm. Main arm diameter of 0.051m was paired with side arm of 0.051m (regular T) and 0.0255m (reduced Tee). At very low gas fraction intakes, less liquid was diverted for reduced T-junctions than for regular T-junctions as the pressure drop at the T-junction, due to increased gas velocity in the reduced diameter side arm, was not yet significant enough to compensate for the dominating axial inertia forces within the liquid phase. Furthermore, effect of reduced tee is more pronounce in lower superficial liquid velocity. This was due to the accelerated gas velocities in the reduced T-junction forcing a greater proportion of the liquid phase to be drawn off its axial course into branch arm. More recently, Pao et al. [9,10,11] investigated methane and water separation in a T-junction numerically by varying the diameter ratio, density and
inlet saturation of gas phase. They found that the optimum range of diameter ratio is between 0.5 and 0.75, the differential density has an adverse effect on the separation efficiency and inlet gas saturation is inversely proportional to the gas extraction.

The objective of this paper is to use commercial CFD Software FLUENT to simulate a two-phase liquid carryover to the branch arm of T-junction with different diameter ratio. Specifically, the research aims to correlate T-junction diameter ratio on liquid/gas separation and to predict the fraction of liquid taken off in a T-junction at different air and water inlet velocity.

3. Methodology
This research aims to correlate the effect of T-junction diameter ratio and different superficial velocity of air and water at the inlet on the fraction of liquid carryover in the branch arm. The T-junction with desired geometry is modelled in 3D using ANSYS FLUENT software. In the present paper, Eulerian Mixture Model coupled with Volume of Fluid Method is used to model the air-water separation in T-junction. The schematic model of T-junction is shown in figure 2.

![Figure 2. Schematic model of T-junction and its parameters.](image)

Table 1 listed the input data for the benchmark and the variation of parameters for present study. The volume fraction of the air-water is assumed 50-50. Phasic velocities are prescribed at the pipe inlet while the atmospheric pressure is assumed at both the outlet.

| Input parameters | Wren [12] | Present studies |
|------------------|-----------|-----------------|
| Diameter, \(D_1\) & \(D_2\) (mm) | 127 | 25.4 |
| Diameter \(D_3\) (mm) | 76, 127 | 127, 25.4, 7.62 |
| Length, \(L_1\) (mm) | 4000 | 1500 |
| Length, \(L_2\) (mm) | 4000 | 500 |
| Length \(L_3\) (mm) | 500 | 300 |
| Water density, \(\rho_l\) (kg/m³) | 998.2 (water) | 998.2 (water) |
| Air density, \(\rho_g\) (kg/m³) | 1.225 (air) | 1.225 (air) |
| Water velocity, \(V_l\) (m/s) | 0.0283, 0.0401, 0.0535, 0.404, 0.558 | 1, 2 |
| Air velocity, \(V_g\) (m/s) | 4, 12, 24 | 1, 2 |

Before the full study was conducted, mesh dependency test is carried out to ensure the produced solution is mesh independent and to determine the optimum mesh density for simulation. Figure 3
show two cases of different mesh densities used for testing. The averaged pressure in the branch arm is used as convergent criteria for mesh independent solution study.

![Figure 3](image)

**Figure 3.** Meshing at element size of (a) 2.0 and (b) 1.0 mm.

![Figure 4](image)

**Figure 4.** Branch pressure convergence against mesh density.

Figure 4 shows the convergence behavior of averaged branch pressure versus mesh density per mm$^3$. When the mesh density increases, the averaged branch pressure increases until approximately 300 elements per mm$^3$, whereby the averaged branch pressure fluctuated within a very narrow margin. Figure 4 also showed that the averaged branch pressure converges from below. Apparently, the smaller the element mesh size, the bigger the number of element division, thus, the longer CPU hour is needed to run the simulation. It was decided that the lowest bound for mesh density of 450 elements per unit of mm$^3$ is acceptable in terms of accuracy and computational time. This translated into approximately 120 hours per simulation.

There are seven possible types of flow regimes for two-phase flow. The flow regime is dependent on mass flow rate of each phase, pipe diameter and fluid properties. Some distance, which was tested by trial and error in the present study, is required for a flow regime to fully develop. Inlet mass flow rate for each phase are manipulated to reproduce different flow regime. Flow regime maps are used to identify types of flow regime based on the fluids inlet parameters. Different flow regime map introduced by different author refers only to specific pipe diameter and type of mediums. The Baker (1954) map [13] for two-phase flow in horizontal pipes is the most commonly used flow regime map.
for air-water flow because it covers pipe diameter up to 10 cm, as shown in figure 5. To use the map, mass flux, \( G \), of gas and liquid phase, gas parameter, \( \lambda \), and liquid parameter, \( \psi \), need to be determined using equation (1) – (3).

\[
G = \frac{m}{A} = \rho v
\]

(1)

\[
\lambda = \left( \frac{\rho_G \rho_L}{\rho_u \rho_w} \right)^{\frac{1}{2}}
\]

(2)

\[
\psi = \left( \frac{\sigma_w}{\sigma} \right) \left( \frac{\mu_L}{\mu_u} \right)^{\frac{1}{2}} \left( \frac{\mu_w}{\mu_u} \right)^{\frac{1}{2}}
\]

(3)

Figure 5. Baker’s flow regime map [13].

The value of the \( x \)- and \( y \)-axis are then determined to locate the interested flow regime in Figure 5.

4. Results and discussion

4.1. Qualitative validation of flow regime based on Baker’s map

The contours obtained from current simulation were compared with results by de Schepper et.al [14] in figure 6, that carried out VOF method simulation on a 7 m long horizontal tube with 0.08 m diameter. Five flow regimes were compared which are stratified, stratified wavy, slug, plug and bubbly flow. It is clear from the comparison that the current model of slug flow pattern is much more realistic. It was found that without interface perturbation at the air-water contact, it is impossible for slug and plug flow to be generated. The perturbation may be achieved by either starting the flow as stratified wavy flow or artificially disturbed the air-water interface by FLUENT’s User Defined Function, e.g. using a simple sinusoidal function. This perturbation at the interface allows the high velocity incoming air from the inlet to pushes the waves to form liquid slug. The crest slowly increases until it reaches the top of the pipe to formed plug flow.
4.2. Quantitative validation with experimental data
Wren [12] preformed experiments on gas and liquid flow in a large diameter T-junction and correlated the flow split with T-junction geometry. In one of his experiment setup, two diameter ratio of branch arm to main arm were used (0.5 and 1.0) on 8 m horizontal pipe whereby the 1.5 m height T-junction is in the middle of the horizontal main pipe. For validation purpose, air velocity of 12 m/s and water velocity of 0.0283 m/s was selected to be simulated in a 3D regular T-junction with vertical branch arm with same dimension used in the experiment. Based on the phase split graph in figure 7, the current simulation result is comparable to Wren’s data. For liquid carryover to occur, the gas velocity need to be sufficient to overcome the liquid phase flowing inertia force and gravity forces that settle down the water. By reducing branch arm diameter, air velocity flowing in the branch will increase and cause a pressure drop in the branch arm. Subsequently, back pressure from the run arm will act on the pressure drop in the branch arm to suck up liquid in to the vertical branch arm. Therefore, the amount of liquid carryover is negligible unless a gas takes off reach its critical value.

4.3. Parametric studies
A parametric study was conducted to further investigate the behavior of phase splitting for different diameter ratio T-junction. The horizontal arm was 1.5 m long with vertical branch located 1 m away from the inlet. The main and run arms were 0.0254 m or 1 inch in diameter. Three different branches to main diameter ratios were investigated, namely 0.3, 0.5 and 1.0. The air and water inlet velocity was both prescribed as 1 m/s and 2 m/s, respectively, for each phase which made up of four combinations of velocities for each diameter ratio. Figure 8 shows phase split graph for slug flow regime that pass through a T-junction with diameter ratio of 1.0, 0.5 and 0.3. The data points were collected by varying the water inlet velocity from 1 m/s to 2 m/s while air inlet velocity was kept constant at 1 m/s for case figure 8(a), 8(c), 8(e) while for figure 8(b), 8(d) and 8(f), the air velocity was kept constant at 2 m/s. The results show that at higher water inlet velocity, the data points shifted towards liquid dominant region which indicates more liquid carryover into the branch arm.
Figure 7. Validation phase split graph.

Figure 9 shows phase split graph for slug flow regime that pass through a T-junction with diameter of 1.0, 0.5 and 0.3. The data points were collected by changing air inlet velocity from 1 m/s to 2 m/s while water inlet velocity was kept constant for case figure 9(a), 9(c), 9(e) at 1 m/s and case figure 9(b), 9(d), 9(f) at 2 m/s. At higher air inlet velocity, the data points shifted towards liquid dominance region, indicating more liquid carryover into the branch arm. This is mainly due to Bernoulli’s principle, whereby higher air velocity at branch arm creates a pressure drop, sucking up more liquid.
Figure 8. Phase split graph when increasing inlet water velocity from 1 m/s to 2 m/s for constant gas velocity 1 m/s in (a), (c), (e) and constant air velocity 2 m/s for (b), (d) and (f).

Figure 9. Phase split graph when increasing inlet air velocity from 1 m/s to 2 m/s with constant gas velocity 1 m/s for (a), (c) and (e) and constant gas velocity 2 m/s for (b), (d) and (f).
5. Conclusions
In petroleum industry, T-junctions are very common in piping networks as they are used to transport liquid within the industry. It is important to understand the correlation of diameter ratio of T-junction towards phase split on the two-phase flow. In this project, VOF formulation is selected as it provides excellent surface tracking ability specialize for stratified and slug flow whereby their interface is distinct. Air and water was used as the medium.

The current flow regime simulation using Eulerian Mixture Model coupled with VOF Method is comparable with published data based on Baker’s map flow regime. In fact, the current simulation achieved a better slug flow phenomenon in a horizontal pipe. Contrary to common believe that the smaller the diameter ratio, the better is the separation, it is found that 0.3 diameter ratio of branch to main arm lead to earlier liquid carryover when compared to 1.0 and 0.5 diameter ratio T-junction. This is because smaller branch diameter will increase air velocity within it, leading to greater pressure drop in the branch pipe which eventually causes earlier liquid carryover. Furthermore, liquid carryover into the branch arm also increases when both inlet air and water velocity increase.

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