Numerical Investigation of Liquid Carryover in T-Junction with Different Diameter Ratios

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Abstract. In offshore Malaysia, T-junction is installed at the production header as a compact separator to tap produced gas from reservoir as fuel gas for power generation. However, excessive liquid carryover in T-junction presents a serious operational issue because it trips the whole production platform. The primary objective of present study is to numerically investigate the liquid carryover due to formation of slug, subsequently its liquid carryover at different diameter ratio. The analyses were carried out on a model with 0.0254 m (1 inch) diameter horizontal main arm and a vertically upward side arm using Volume of Fluid Method. Three different sides to main arm diameter ratio of 1.0, 0.5 and 0.3 were investigated with different gas and liquid superficial velocities. The results showed that, while the general trend is true that smaller diameter ratio T-junction has lesser liquid take off capacity, it has a very high frequency of low liquid carryover threshold. In other words, under slug flow, smaller diameter ratio T-junction is constantly transporting liquid even though at a lesser volume in comparison to regular T-junction.

Keywords: T-junction; liquid-gas separation; separation efficiency

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 three main components, namely main arm, run arm and branch (or side) arm. T-junction configuration is most often seen in the offshore production platform where the T-junction is used to tap gas directly from the production header. The tapped gas is channeled downstream as fuel gas for power generation or source gas for other purposes. When a two-phase mixture flows pass a T-junction, lighter phase will incline to enter the branch arm while the heavier phase tends to continue flowing into the run arm. The higher the density difference between the two-phase, the better the phase separation is. Liquid carryover occurred when gas phase take-off to the branch arm reaching a certain limit, creating sufficient suction pressure to draw heavier liquid phase into the branch arm. Liquid carryover is a frequent problem that occurs in T-junction whereby excessive amount of liquid is taken off into the gas stream and channeled into downstream equipment which is not designed to handle liquid. Consequently, platform trips and production has to halt to drain out the excessive liquid.

The deceivingly simple T-junction with a simple geometry is an unbelievably complicated topic [1]. The geometry alone consists of eight different parameters that could have many combinations. Compounding to the complexity are flow parameters such as flow rate and operating pressure etc., and fluid properties such as density, viscosity and surface tension...
variation. Experiments performed for side arm pointing at 6 o’clock position showed a significant pressure loss between the inlet and side-arm but a pressure increase in the run arm [2, 3]. This recovery is attributed to an affect similar to that of Bernoulli for single phase flows, produced as a result of the decrease in the mixture velocity in the run arm [2]. Under the dominance of gravity, the liquid will be accelerated, leading to pressure drop. When the side arm is pointing at 12 o’clock, the liquid take-off in the side arm is flowing against the gravity. The force by which the liquid climbs up the side arm is its own momentum force minus the gravity force. The momentum transfer by the gas phase is important if liquid is to take-off in the side arm as reported by [5], [6], in their experiments, concluded that a lower pressure gradient in the branch arm provides the momentum change for the fluids moving from the inlet into the branch arm. [7] studied the effect caused by a reduction in side-arm diameter concluded that less liquid take-off in a reduced diameter T-junction. [8] experiment also showed that there is an increase in the fractional liquid take off with a decrease in the branch arm diameter. However, his experiments showed negligible impact of diameter ratio in stratified flow but more liquid take off in the regular T compared to a reduced T for stratified-wavy flow. [9] studied the scale effect of branch arm to main arm diameter ratio on phase split of liquid-gas flow at T-junction for annular and stratified flow. For the small scale T-junction, with 1.5” diameter pipe, data shows that decreasing the diameter ratio of a T-junction leads to lower liquid take off for both stratified and annular flow. For the larger scale T-junction, with 5” diameter pipe, similar conclusion was reached. However, he reported that the effect of diameter ratio is most significant at lower gas rates while least at lower liquid and high gas flow rate conditions. [10] experiment also showed reduced liquid take off with reducing T-junction diameter ratio. Interestingly, there are very limited research which focus on the flow regime behavior before the two-phase flow reach the T-junction and its separation thereafter. The objective of the present paper is to investigate the effect of T-junction’s diameter ratio on liquid carryover in slug flow regime.

2. Methodology

Governing Equations

Unlike the approach followed in [11, 12, 13] by the same group of authors, this paper used Volume of Fluid (VOF) Method to simulate the T-junction liquid carryover. The authors found that it was difficult to use Eulerian Multiphase Model to mimic the required flow regime. Even though mass flux values taken directly from Baker’s map were taken as inputs, the Eulerian Multiphase Model cannot reproduce the flow regime contour visually. Consequently, an alternative mathematical model for T-junction was sorted after. In the VOF Model, only one momentum equation is required to represent the entire gas-liquid mixture. The mixture mass conservation equation and the momentum for the mixture are given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

$$\frac{\partial}{\partial t} (\rho \mathbf{U}) + \nabla \cdot (\rho \mathbf{UU}) = -\nabla p + \nabla \left[ \mu \left( \nabla \mathbf{U} + \nabla \mathbf{U}^T \right) \right] + \rho \mathbf{g} + \mathbf{F}$$

respectively, where \( \rho \) is the mixture density, \( \mathbf{U} \) is the mixture velocity, \( p \) is the mixture pressure, \( \mu \) is the mixture viscosity, \( \mathbf{g} \) is the gravity acceleration and \( \mathbf{F} \) is the body force vector. Equations (1) and (2) need to be complemented by the \( \alpha_s \)-phase continuity equation from VOF given by

$$\frac{\partial \alpha_s}{\partial t} + \mathbf{U} \cdot \nabla \alpha_s = 0$$

where \( \alpha_s \) is the volume fraction of gas.
3. Results and Discussion

Validation of Slug Flow with Experiment

The validation makes use of [17], who conducted experiment in transparent rectangular conduit of 4 m long, 100 mm height and 30 mm width. The slug flow measurement of 5 s was taken with 5 m/s superficial inlet air velocity and 1 m/s superficial water inlet velocity. In order to achieve the superficial velocities described by the experiments, a cross sectional plane very near to the inlet was cut out and the averaged superficial velocities of each phase was adjusted on that plane to be as close as possible to the experimental values by tuning the mass flow rate. Figure 1 showed the side to side comparison of the present simulation model at 1.92 s, 1.96 s and 2.06 s respectively. There are some discrepancies which could be attributed to the inaccurate boundary conditions, particularly at the downstream of the conduit. Nevertheless, the present model is able to mimic the two-phase slug flow captured by experiment.

Figure 1. Comparison of experimental image of Christophe et al. [17] and the present simulation model

T-junction Separation with Reduced Branch Arm Diameter and Slug Flow

The schematic model of the T-junction is shown in Figure 2. The main and run arms were 0.0254 m (1 inch) in diameter and was kept constant. Three different branch arm diameters with the same height of 0.3 m were used, resulting in branch to main arm diameter ratio of 0.3, 0.5 and 1.0, respectively.

Figure 2. Schematic diagram of the T-junction for parametric study

The air and water mass flow rate (kg/s) were carefully calibrated so that the inlet flow generated the required slug in the main arm. After some tedious trial and error experiments, air and water velocities were set at 1 m/s and 2 m/s for each phase in a combinatorial fashion, making up 4 combination of velocities with identifiable high and low values. Table 1 listed the corresponding inlet air and water mass flow rate and the associated superficial velocities for the parametric study. This resulted in 12 simulations (4 variation of superficial velocities for 1.0, 0.5 and 0.3
diameter ratios). The liquid holdup and its frequency at the outlet of side arm were recorded from 0 to 5 seconds. In the present, the liquid holdup is defined as

$$H_L = \frac{A_L}{A}$$  \hspace{1cm} (4)

where $A_L$ is the cross-sectional area occupied by the liquid and $A$ is the total cross-sectional area of the pipe. Liquid carryover is assumed to occur when $H_L \geq 0.75$ at the side arm outlet.

| Superficial velocity | Mass flow rate | 1 m/s | 2 m/s |
|----------------------|----------------|-------|-------|
| Air flow rate (kg/s) | 0.000621       | 0.001241 |
| Water flow rate (kg/s) | 0.506         | 1.012 |

Table 1. Air and water mass flow rate for parametric study

The mechanism of liquid carryover in branch arm under approaching slug flow regime in the main arm is shown in Fig. 3 in order to illustrate the physical meaning of this parametric study.

In Figure 3(a), a slug body is approaching the T-junction. The liquid slug body is fully bridging the upper part of the pipe, with clearly identifiable slug nose and tail. In Figure 3(b), the slug body passed through the T-junction and broken up. The liquid jumped into the branch arm to about 0.2 m height, covering almost two third of the height of the branch arm. Liquid carryover occurred in the branch arm. When the liquid filled up 75% of the cross-section of the branch arm outlet, liquid holdup = 1. Figure 3(c) showed that the tail of the slug body is about to pass through the T-junction. The outlet of the branch arm is now completely filled with water. The air pocket is about to pass through the branch arm and portion of air started slipping into the appendage. The bottom of the branch arm is partially filled with air water and partially filled with air. The top section of the branch arm is fully saturated with water. Figure 3(d) showed that
the slug body completely passed the T-junction. All the holdup water in the branch arm has fallen back into the main arm. The branch arm is now filled up again with air, but traces of water can still be detected. Note that traces of water are detected close to the inner surface of the branch arm. The air velocity has barely enough momentum to drag the water film up into the branch arm.

Figure 4 summarized the normalized percentile versus different range of liquid holdup for four different cases of velocities and for three different diameter ratios. It is clearly evident that smaller diameter ratio T-junction has a better separation efficiency, or less liquid carryover, concurred the conclusion from [1, 3, 7, 9]. A further careful study revealed that while this is overall true for \( H_L \geq 0.75 \), smaller diameter ratio T-junction showed a very high percentile frequency when \( H_L \leq 0.2 \) compared to equal diameter T-junction. This is an interesting observation that was never reported in open literature. The numerical results showed that smaller diameter ratio T-junction has very low liquid carryover threshold, which was later confirmed by in-house experiments.

![Figure 4](image)

Figure 4. Liquid holdup distribution versus percentile frequency for diameter ratio (a) 1.0; (b) 0.5 and (c) 0.3

4. Conclusion

A numerical study is carried out using FLUENT software Volume of Fluid Method to investigate the effects of liquid holdup in a T-junction under different branch to main arm diameter ratios under the influence of different superficial phase velocity for slug flow. Numerical experiments found that liquid holdup in the branch arm decreases with decreasing
diameter ratios, consistent with experimental conclusion. However, the smaller diameter ratio T-junction has very low liquid carryover threshold.

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