Phase Separation of Gas-Liquid Two-Phase Flows in Multi-tube T-Junction Separators

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Abstract: A simple T-junction can be used as a partial phase separator for gas/liquid flows, but its separation efficiency is low. A multi-tube T-junction separator consists of several T-junctions in one unit in order to improve the separation efficiency. Using air and water as working fluids, separation experiments were carried out with a simple T-junction and with multi-tube T-junction separators with a horizontal main pipe and vertically upward branch(es) with stratified and plug flow at inlet. The results show that for these two flow patterns the separation efficiency of the two phases for any multi-tube T-junction separator is much higher than that of the corresponding T-junction. Increasing the number of connecting tubes in the multi-tube T-junction separator can increase the separation efficiency. Generally, for stratified flows and plug flows, complete separation of the two phases can be achieved by the multi-tube T-junction separator with 5 or more connecting tubes; increasing the gas or the liquid flow rate will be detrimental to two phase separation with a drop in peak separation efficiency.

Keywords: gas-liquid flow; T-junction; phase separator; separation efficiency; flow pattern

1. Introduction

Gas-liquid two-phase flows exist in many types of equipment in industries as diverse as hydrocarbon production, chemical, metallurgical and electrical power industries as well as in nature, e.g., in volcanoes and geysers. In order to improve the safety and efficiency of the industrial processes there are often requirements for the two phases to be separated. Conventional equipment uses gravity to achieve separation. This demands low gas velocities and so the equipment takes the form of large vessels which are obviously expensive especially if for high pressure operation. If used on off-shore oil/gas production there is the additional cost of the steel-work support required. In addition to the cost, there is the worry of the large inventory of flammable material that this equipment can hold.

It has been observed that when a gas/liquid flow arrives at a dividing T-junction, i.e., one with one inlet and two outlets, then there is an inevitable separation of the phases and so it can be used as a partial phase separator. Compared to conventional vessel separators, a simple T-junction can be considered as a continuous, compact, economical and safer phase separator. In addition, it is easy to be installed and to be renewed.

Azzopardi and Smith [1] identified that when there was an upwards side-arm from a horizontal main pipe there would be mainly gas emerging from that side-arm. However, as more gas was taken off, a hydraulic jump occurred at the junction. The increase in liquid level caused liquid to emerge through the side-arm lowering the effectiveness of the unit as a separator. Wren and Azzopardi [2] and Baker et al.[3] overcame the problem by providing a second junction, with a downwards side-arm, just downstream on the main pipe. If the liquid level in the down leg was held at a constant level, the only liquid emerged through that exit. Also, the hydraulic jump was eliminated. The fluids emerging from the upwards side arm and the main pipe were combined. The flow was controlled by action of a valve on the main pipe just downstream of the two junctions. When the valve setting was optimized, the gas emerging from the combined outlet was found to have <8% by volume of liquid and so be suitable to pass into a vertical “scrubber”. Bevilaqua et al.[4] proposed a multiple T separator. This used several upwards branches as well as some sections with a downwards slope and a upwards slope. Good separation was reported.

In the original work on phase division, results were presented as the fraction of incoming liquid emerging from the side-arm plotted against the equivalent fraction for the gas. The locus of possible separations passed through (0, 0) when there was an infinitely large resistance in the side-arm to (1, 1) when all the flow was diverted into the side-arm. The actual separation depended on the pressure drop in the pipes/equipment downstream of the two outlets. However, this approach does not show clearly the effectiveness of phase separation. Recently, a new criterion, i.e., separation efficiency [5], has been proposed for evaluating the phase separation effect of two-phase flows at T-junctions and the concept and the model of ideal separation for the two phases have been deduced correspondingly. For every pair of two

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phase flow rates, a peak separation efficiency may be achieved with its possible maximum value of 100% at the inlet mass quality. Therefore, the separation effect of two-phase flows at T-junctions or compact separators, such as cyclones, can be assessed.

A T-junction separator has been installed and successfully operated on a hydrocarbon processing plant as a partial phase separator [6]. However, the separation efficiency of the two phases at the simple T-junction is too low to apply it commercially in most industrial processes. A novel multi-tube T-junction separator consisting of several T-junctions in one unit, which is similar to the junction unit of Wang et al.[7], has been proposed for efficiently separating the two phases and preliminary experiments showed a promising results of remarkable improvement on the separation efficiency for two-phase flows[8]. There is little separation data of gas-liquid two-phase flows up to now reported for such multi-tube T-junction separators. The present study has been undertaken to investigate the phase split and separation efficiency of gas-liquid two-phase flows at such multi-tube T-junction separators. By employing air and water as two working fluids, some factors affecting the phase split and the separation efficiency of the two phases have been investigated for the gas-liquid two-phase flows at the T-junction units with a horizontal main pipe and a vertically upward branch

2. Experimental

A schematic diagram of the experimental system is given in Fig 1. Air and deionized water were used as the working fluids. Compressed air was drawn from buffer vessel (V) and water from a water tank (V_1) by means of a centrifugal pump (P). They were mixed at a simple T-junction mixer (M) and then flowed through a horizontal pipe to a T-junction separator unit (T). The inflow of air and water to the mixer were metered by calibrated rotameters. The air pressure in the buffer vessel was maintained at 0.1MPa (g). The two outlets from the branch and the straight arm of the unit emerged to a cyclone separator (S) and a tank separator (V_2), respectively. The gas flow rate to the cyclone is metered by a calibrated wet gas flow meter and the water flow rate was metered by weighing the storage tank (V_3) in a fixed time. All the pipes including the pipes constructing the T-junction unit and around the T-junction unit were of 10 mm internal diameter. The distance between the mixer and the T-junction unit was 250 upstream pipe diameters in order for the flow to develop fully.

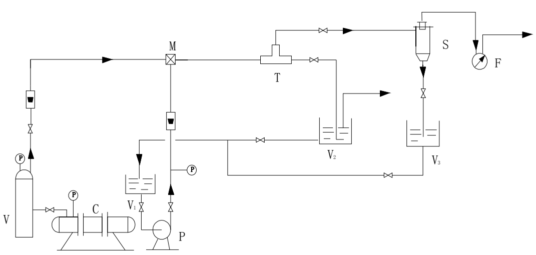

Figure 1. Schematic diagram of gas-liquid flow facility

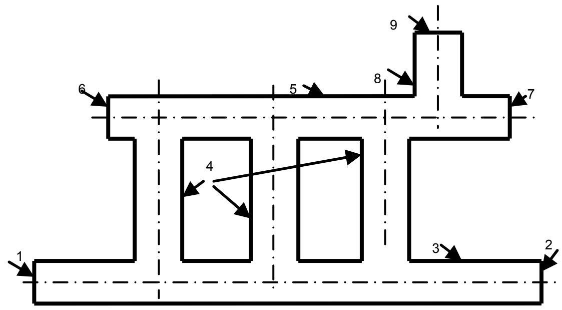

Figure 2. schematic diagram of united T-junction separator used in experiments

1,2- Inlet and liquid outlet, open; 3-main pipe; 4-connecting tubes (risers); 5-header; 6,7-sealed; 8-branch; 9- gas outlet

A simple T-junction and multi-tube T-junction separators have been studied. They were all made of transparent glass tubes to permit observation and had internal diameters of 10 mm. The structure of the multi-tube T-junction separators utilized is shown in Fig 2. The main entrance pipe was mounted horizontally and one or more of the outlets at the bottom connect with the upper header tube. The distance between the inlet tube and the upper header was 60 mm and the distance between the centerlines of two vertically connecting tubes was 30 mm. At the top header, there is a branch (or side arm) as the other outlet. In the case shown, there are three connecting tubes and hence it has been termed a multi-tube T-junction separator with 3 connecting tubes (risers). Two other units, with 5 and 7 connecting tubes, respectively, were also studied.

The gas-liquid flow patterns in the inlet tube were well predicted by the flow pattern maps of Mandhane et al.[9] as shown in Fig 3. The flow patterns of the experimental conditions were deliberately chosen to be stratified and plug flows to investigate the effects of the flow pattern, gas superficial velocity and liquid superficial velocity as well as T-junction structure on the phase separation of the two phases.

3. Results and discussion

There are many reports on the phase maldistribution of gas-liquid two-phase flows at simple T-junctions [10]. This paper will focus on comparison of the phase separation of gas-liquid two-phase flows at the simple T-junction and the multi-tube T-junction separators and examine the effect of inlet flow patterns, gas superficial velocity and liquid superficial velocity on the phase separation.

3.1 Effect of T-junction configuration on phase separation

The effect of the T-junction configuration on the phase split at the stratified flow with the flow conditions of S2 is shown in Fig 4. The operating conditions for these data are: inlet gas superficial velocity 0.45 m/s and inlet liquid superficial velocity 0.06 m/s. It can be seen that all the data points are located under the diagonal line (equal split line) and deviated away from the diagonal line. It means that the gas dominates the take off and the phase separation is quite good. It can also be seen that the split data are further away from the equal split line for the multi-tube T-junction separators than for the simple T-junction and as the number of the connecting tubes (risers) is increased the split data are deviated further away from the equal separation line. This can be seen more clearly with the separation efficiency plots as shown in Fig 5 where the separation efficiency data points for the multi-tube T-junction separators with 5 and 7 connecting tubes are all set on the two ideal separation lines. This means that the separation processes of the two-phase flows for these multi-tube T-junction units with 5 or more connecting tubes complies the ideal separation[5] and the complete separation, or the highest separation efficiency of 100%, of the two phases can be achieved. The highest separation efficiency that the multi-tube T-junction unit with 3 connecting tubes can reach is 95%, whilst for the simple T-junction it is 85%.

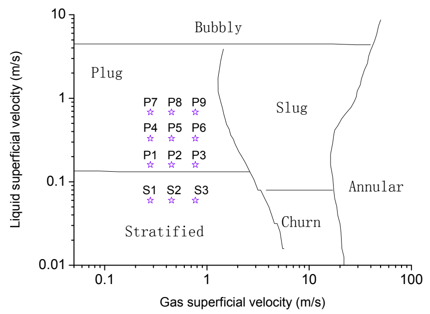

Figure 3. Flow conditions for the split experiments on the flow pattern maps of Mandhane et al.[9]

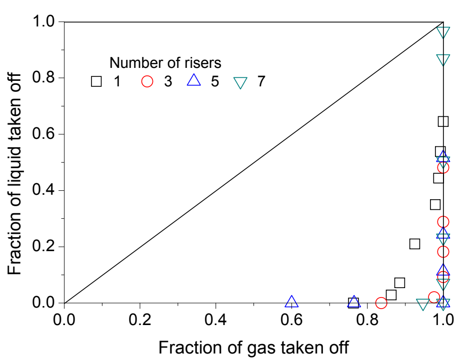

Figure 4. Phase split results of different T-junction units under a stratified flow at the conditions S2

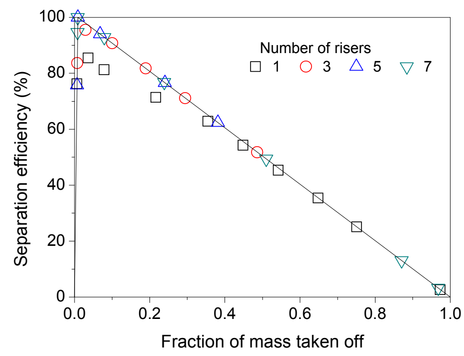

Figure 5. Separation efficiency plots of different T-junction units under the stratified flow of Fig 4

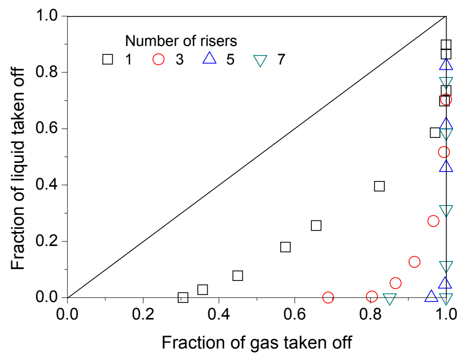

Figure 6. Phase split results of different T-junction units with plug flow at the conditions P5

Fig 6 shows the effect of the configuration of the T-junction units on the phase split when the inlet flow pattern is plug flow at the flow conditions of P5. The inlet gas superficial velocity is fixed at 0.45 m/s and the liquid superficial velocity at 0.33 m/s. It can be seen from the figure that as the number of the connecting tubes is increased the split data are further away from the equal split line. Fig 7 is the equivalent separation efficiency plot to Fig 6. The peak separation efficiency increases with the number of the connecting tubes in the multi-tube T-junction unit. The reason for this phenomenon may be that there are several dividing T-junctions and combining T-junctions in one multi-tube T-junction separator and every dividing T-junction or every combining T-junction acts as a partial phase separator when gas-liquid two-phase mixture flows through it. Therefore, a multi-tube T-junction separator with more connecting tubes can achieve more effective phase separation when the two-phase mixture flows through it. It can also be seen from the figure that all the data points for the multi-tube T-junction with 7 connecting tubes lay on the ideal separation lines and the complete phase separation can be achieved at the inlet mass quality. The phase separation

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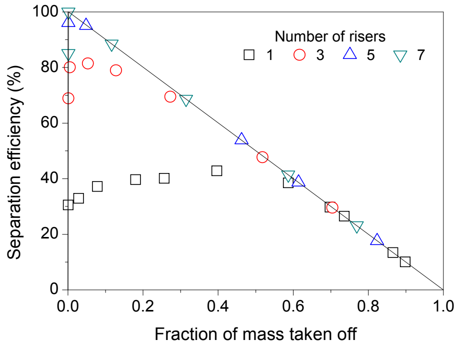

Figure 7. Separation efficiency plots of different T-junction units under the plug flow at the conditions P5

for the case of 5 connecting tubes is very similar to the case of 7 connecting tubes. Their highest separation efficiencies can reach up to 100%. The highest separation efficiencies for the cases of 3 connecting tubes and simple T-junction are 81% and 42%, respectively.

It was found through the experimental results that under the stratified flow pattern, the multi-tube T-junction separators with 5, 7 or more connecting tubes can totally meet the ideal separation and their highest separation efficiencies can reach 100% when gas-liquid two-phase mixture flows through them. However, under the plug flow pattern, which is a more mixed flow of the two phases, to achieve the complete separation will needs more connecting tubes in the multi-tube T-junction separator. For example, when the gas and liquid superficial velocities, under the slug flow, are 0.28 and 0.16 m/s, respectively, a multi-tube T-junction separator with 5 connecting tubes can achieve complete separation whereas when the gas and liquid superficial velocities are increased to 0.45 and 0.33 m/s, respectively, it needs a 7 tube version to achieve the complete separation. It means that the higher the two-phase mixture velocity under the same flow pattern, the more the connecting tubes in the multi-tube T-junction separator needed for the complete separation.

3.2 Effect of gas superficial velocity on phase separation

Flow pattern plays an important role when examining the effect of gas superficial velocity on the phase separation. In stratified flow, the separation effect of the multi-tube T-junction separators is sufficient to separate the two phases fairly well totally. Therefore for a fixed liquid flow, any variation of gas flow has very little effect on the ideal separation. For plug flow, however, the gas flow rate has a significant impact on the phase separation. For example, Fig 8 shows the effect of the gas superficial velocity, at the same liquid velocity with plug flow at inlet, on the phase split with 7 connecting tubes. For the flow with lower gas velocity, the separation is exactly according the ideal separation and the complete separation can be achieved. But for the higher gas velocity case, the data points deviated from the corner (1.0, 0) and the complete separation could not be achieved though other data were located as ideal separation. It means that increasing gas velocity at the plug flow regime makes the two-phase flow be mixed further and enlarge the separation difficulty.

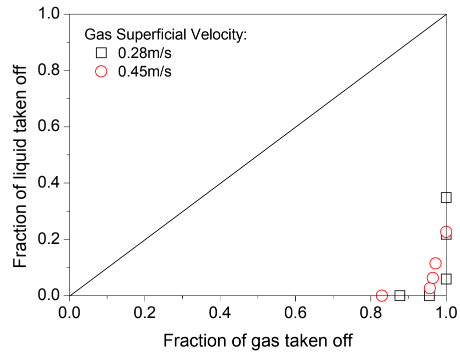

Figure 8. The effect of the gas superficial velocity on the phase split under the plug flows at a united T-junction separator with 7 connecting tubes. Liquid superficial velocity at 0.68 m/s

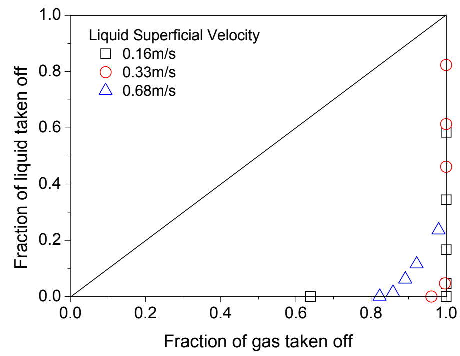

Figure 9. The effect of the liquid superficial velocity on the phase split under the plug flows at the multi-tube T-junction separator with 5 connecting tubes. Gas superficial velocity at 0.45 m/s

3.3 Effect of liquid superficial velocity on phase separation

Fig 9 shows the effect of liquid superficial velocity on the phase separation for the multi-tube T-junction separator with 5 connecting tubes under the plug flow pattern. The gas superficial velocity was fixed at 0.45 m/s, the liquid velocity changes from 0.16 m/s to 0.68 m/s. it can be seen from the figure that at the lower liquid velocity, the two phases can be separated completely and increasing the liquid velocity is harmful to the phase separation and results in the drop of the separation efficiency.