Experimental Investigation of Phase-Separation Effectiveness of Combined Impacting Tee Junctions

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***Abstract*—An experimental investigation was conducted with a novel system of two combined vertical impacting tee junctions in order to study the phase-separation capability of the system for air-water two-phase flows. The idea was to extend the range of inlet conditions (inlet gas and liquid superficial velocities, J_{G1} and J_{L1}, respectively) under which full separation of phases can be achieved, using only impacting tee junctions. Beyond the range of full separation, the effect of J_{G1} and J_{L1} on phase-separation effectiveness in the annular flow regime was studied for the entire range of gas extraction ratios (0 to 1). Data were obtained at a nominal pressure of 200 kPa (abs) and ambient temperature, with equal-sided tee junctions of internal diameter 13.5 mm. Results show that, compared to a system with a single impacting tee junction, the present design nearly doubles the J_{L1}, at a fixed J_{G1} and J_{G1} at a fixed J_{L1}, under which full separation of phases takes place. In the annular flow regime, decreasing J_{G1} or J_{L1} affects phase redistribution in a way that increases effectiveness of phase separation. A 'separation parameter', η has been defined to quantify this effect.**

***Index Terms*—two-phase flow, multiple vertical impacting tee junctions, full separation, partial separation, phase-separation parameter**

I. Introduction

Industrial operations ranging from mining hydrocarbons to power generation in nuclear reactors use piping networks that involves tee junctions of different kinds (diving or combining tees of branching and impacting type) for transportation of single or multi-phase fluids. Two-phase flows, particularly gas-liquid flows are very commonly found in these industrial operations. When a gas-liquid two-phase flow encounters a dividing tee junction, redistribution of phases takes place in the two outlets almost inevitably [1]. As a result, a liquid-rich and a gas-rich streams are produced. Often times, this phenomenon creates undesirable working conditions for devices downstream of the dividing junction, due to change in the quality of the mixture. However, recent studies have shown that this phenomenon of redistribution of phases can be utilized to achieve partial to complete phase separation [2]. Phase separation is a desirable phenomenon in many practical applications where single-phase flow can enhance heat transfer or decrease power consumption for condensation or evaporation (e.g., multi-channel heat exchangers, refrigeration and air-condition cycles, etc.). In addition, tee junctions can serve as smaller, cheaper and less cumbersome substitutes of traditional gravity-based separators.

In the literature of two-phase flows, branching and impacting tees are treated independently. While there is a wealth of literature on two-phase flows passing through branching tees, limited research has been done on impacting tees. Two-phase flow through an impacting tee junction has been studied under various conditions or inlet/outlet parameters. Researches have been conducted on the effects of operating pressure [3], geometry of the junction [3-5], inlet flow regime [6,7], inlet liquid and gas superficial velocities [6-8], angle of inclination of inlet/outlets [8] and inlet quality [7,9]. Most of these works presented phase redistribution data showing that equal-phase split occurs only at specific conditions. A limited amount of work focused on achieving total/partial phase separation using a single impacting tee junction can also be found in literature [10-13].

Recently, some researches have been carried on, where multiple branching tee junctions were used to enhance phase separation [14-20]. To the best of our knowledge, till date, no evidence of work on multiple impacting tees for phase separation can be found in the open literature. The present investigation exclusively focuses on enhancing phase separation effectiveness using multiple impacting tee junctions with horizontal inlet and vertical outlets. With this aim, air-water two-phase flow has been passed through a test loop of two combined vertical impacting tee junctions. Limiting conditions of inlet gas and liquid superficial velocities (J_{G1} and J_{L1}) at which full separation of phases (all of the input gas and liquid passing through top and bottom outlets respectively) can be achieved has been determined experimentally. Beyond the range of full-separation, partial phase-separation data has been generated for a number of points in the annular flow regime, within J_{G1}= 20-40 m/s and J_{L1}= 0.01-0.18 m/s. To analyze the effectiveness of phase separation of the present design, a 'separation parameter' is also defined in this paper.

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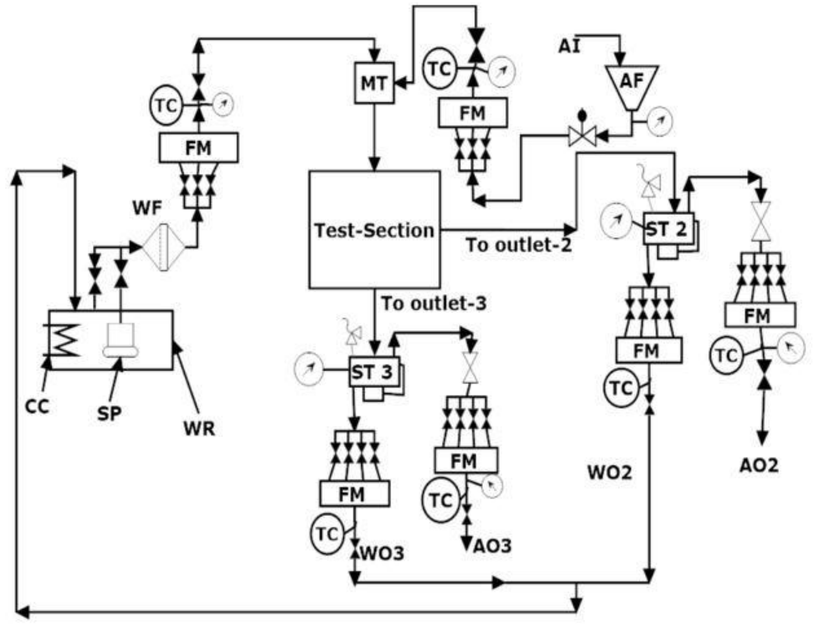

Symbol	Description
AF	Air filter
AI	Air inlet
AO	Air outlet
CC	Cooling Coil
FM	Flow meter
MT	Mixing tee
SP	Submersible pump
ST	Separation Tank
WF	Water filter
WO	Water outlet
WR	Water reservoir
	Control valve
	Valve
	Pressure controller
	Pressure gauge
TC	Thermocouple
	Safety valve

Figure 1a. Schematic diagram of the test loop.

II. EXPERIMETAL TEST LOOP AND PROCEDURE

Fig. 1a shows a schematic diagram of the experimental facility. Compressed air from the building supply line was passed through an air filter and a pressure controller before entering one of the three calibrated inlet air rotameters (of overlapping ranges). By controlling the air mass flow rate (W_{G1}) through the appropriate rotameter, air at desired inlet velocity, J_{G1} was passed to the test section. A submersible pump was used to circulate distilled water from the water reservoir to the test loop. Water temperature was maintained with a cooling coil placed in the water reservoir and a water filter was used. Inlet water mass flowrate (W_{LI}) was measured and controlled with one of three inlet water rotameters, to get desired the inlet velocity, J_{L1}.

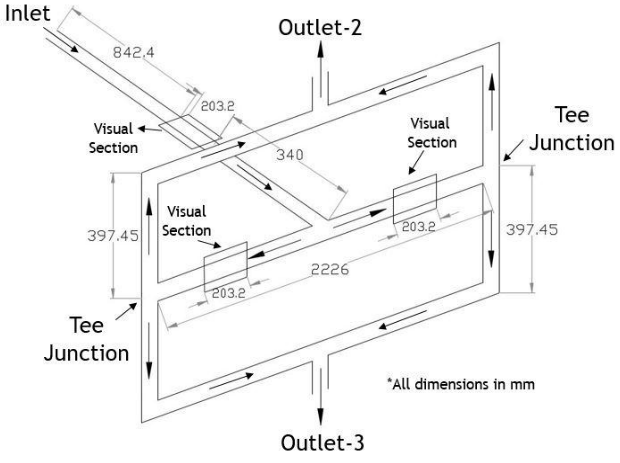

Figure 1b. Details of the test-section

Air and water from the inlet were mixed in a mixing tee before entering the test-section shown in Fig. 1b. A visual section made of acrylic resin, at 62 pipe diameters from the mixing tee, helped determine the inlet flow regime. The visual section was 15 pipe diameters long. The combined tees were located further 32 pipe diameters away from the visual section. Initially, the flow enters a horizontal impacting tee junction made of acrylic resin, with diameter of 13.5 mm and outlet lengths of 81 pipe diameters. Visual sections were placed in the outlets of the junction, 50 pipe diameters away from it, to determine the flow regimes. These outlets act as inlets to the two vertical impacting tee junctions. Symmetry of the test loop ensured that inlet flow is split evenly in the horizontal junction and two identical flows enter the vertical junctions. The outlets of the vertical impacting tee junctions were 29.5 pipe diameters long. The top outlets of both vertical impacting junctions were combined (outlet-2) and passed to a separation tank, where air and water were separated. The two bottom outlets were also combined in a similar manner (outlet-3) and the flow was passed through another separation tank. There are banks of four air rotameters and four water rotameters, connected to each of the separation tanks. The outlet air and water mass flow rates, coming from the top and bottom outlets (W_{G2}, W_{L2} and W_{G3}, W_{L3}), were measured with these outlet rotameters. Air from the outlet rotameters was released to the atmosphere and water was returned to the reservoir, thus completing the loop.

All experiments were performed with test-section pressure (P_S) fixed at 200 kPa (abs). For full-separation data, all air was passed through the top outlet ($W_{G1} = W_{G2}$ & $W_{G3} = 0$). With water inlet velocity (J_{L1}) fixed, the air inlet velocity J_{G1} was increased gradually, until traces of water started coming from the top. This was determined from visual observation of the transparent tygon tube connecting the outlet and the separation tank. The readings of the various pressure gauges, rotameters and thermocouples were recorded at this point, to get the limiting condition of phase separation, at the fixed J_{L1}. Similar procedures were followed for other inlet liquid velocities.

For inlet conditions where total phase separation cannot be achieved, partial phase-separation data were obtained by fixing both J_{G1} and J_{L1}. The fraction of inlet air passing through the top outlet ($F_{G3} = W_{G3}/W_{G1}$) was varied from 0 to 1, by controlling appropriate outlet air rotameters. The fractions of liquid passing through each outlet ($F_{L2} = W_{L2}/W_{L1}$ and $F_{L3}=W_{L3}/W_{L1}$) were determined by measuring W_{L2} and W_{L3} from the outlet water rotameters. The procedure was repeated for the six annular data sets listed in Table I.

TABLE I. ANNULAR DATA POINTS

Data Set	J_{G1} (m/s)	J_{L1} (m/s)	Flow regime
An 1	40	0.01	Annular
An 2	40	0.04	Annular
An 3	40	0.18	Annular
An 4	20	0.04	Annular
An 5	25	0.04	Annular
An 6	30	0.04	Annular

III. RESULTS AND DISCUSSION

A. Full-separation Data

Values of J_{G1} and J_{L1} are calculated from the measured gas and liquid inlet mass flow rates, W_{G1} and W_{L1}, respectively, using the equations:

$$J_{G1} = \frac{4W_{G1}}{\pi D^2 \rho_G} \quad (1) \quad , \quad J_{L1} = \frac{4W_{L1}}{\pi D^2 \rho_L} \quad (2)$$

Here, ρ_G and ρ_L are the densities of air and water in the test-section and D is the test-section diameter. The data for limiting values of J_{G1} and J_{L1} for full separation were plotted on Mandhane et al. flow-regime map [21]. The observed inlet flow regimes corresponding to each set of J_{G1} and J_{L1}, were consistent with the flow regimes indicated in this map. Current results (shown as solid squares in Fig. 2) were compared with limiting conditions of full separation for a single junction (shown as open squares in Fig. 2) reported in [10]. Fig. 2 shows that with the present design, the limiting values of J_{L1} for full separation, at a fixed J_{G1}, are almost twice of the values in [10]. Beyond the curve of full separation, formed by the solid squares in Fig. 2, only partial-separation of phases could be achieved.

B. Partial-separation Data

Partial-separation data were plotted in terms of F_{G3} versus F_{L3}. Fig. 3 shows the effect of inlet liquid velocity, J_{L1}, on the partial separation for three annular points (An 1, An 2, and An 3 in Fig. 2), with J_{G1} fixed at 40 m/s. As expected, the tendency of liquid to enter the top outlet (outlet-2) increases with the increase in J_{L1}. At J_{L1} of 0.01 m/s, with only 33.7% of inlet gas, 100% inlet liquid enters the bottom outlet. This value increases to 93.1%, at J_{L1} of 0.18 m/s. The effect of J_{G1}, on partial phase-separation, at fixed J_{L1} is illustrated in Fig. 4. With a decrease in J_{G1}, the partial phase-separation curves move in counter-clockwise direction, signifying higher fraction of inlet liquid entering the bottom outlet with lower fraction of inlet gas. At J_{G1} of 14.6 m/s, 100% of inlet liquid enters the bottom outlet, with no gas going in i.e. full separation of phases takes places. Fig. 5-8 shows how the present design of two combined vertical impacting tee junctions affects the partial phase separation in annular flow regime, in comparison to an otherwise identical system with a single vertical impacting tee junction. In all four data sets, F_{L3} increases for corresponding value of $F_{G3,}$ when comparing the present system with the single junction used in [10].

C. Phase-separation Parameter

It is evident from partial- and full-separation data that decreasing J_{G1} or J_{L1} and increasing the number of tee junctions have a positive effect on phase separation of a two-phase flow. In order to quantify this effect, a 'separation parameter' can be defined considering the fractions of both inlet gas and liquid entering the same outlet. In this paper, a separation parameter is defined as:

$$\eta = (F_{G2} - F_{L2}) \times 100\% \quad (3)$$

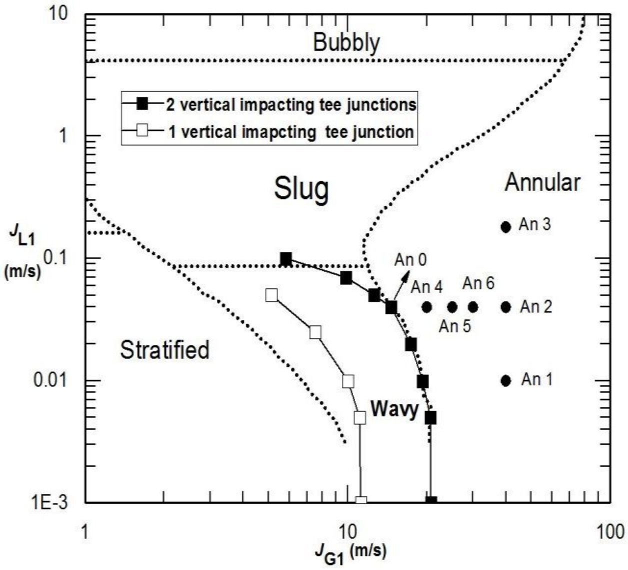

Figure 2. Full separation data plotted on Mandhane et al. Flow-regime map [21].

When $F_{G2} = 1$ and $F_{L2} = 0$, i.e., all gas passes through the top outlet, with no liquid, (3) gives η = 100%, indicating full separation. Equation (3) can also produce negative values of η indicating that a higher proportion of the inlet gas is exiting through the bottom outlet, which is possible for some conditions as shown later. Theoretically, (3) can produce the limiting value η = -100%, corresponding to all gas exiting from the bottom and all liquid exiting from the top, which is physically impossible. The separation parameter, η has been plotted as a function of F_{G3} for each data set in this investigation. The points (0, 100) and (1, 0) in these plots correspond to the points (1, 0) and (1, 1) in the partial-phase separation (F_{G3} versus F_{L3}) plot, indicating two extreme conditions: full separation and zero separation of phases respectively.

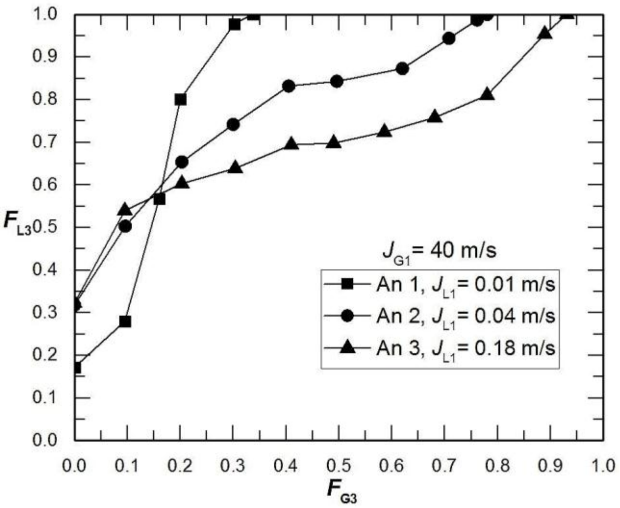

Figure 3. Effect of J_{L1} on partial-phase separation with two vertical impacting tees.

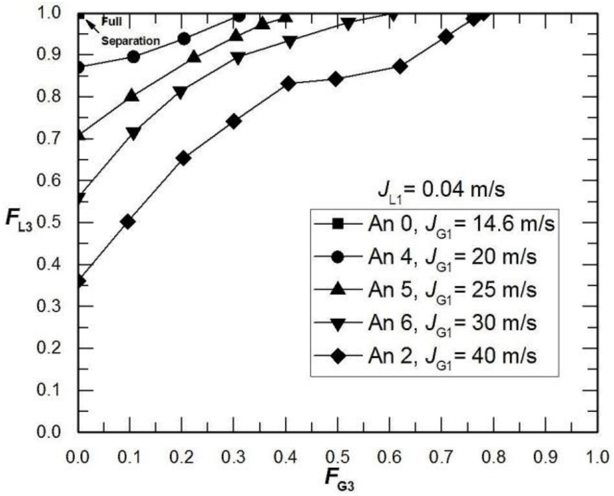

Figure 4. Effect of J_{G1} on partial-phase separation with two vertical impacting tees.

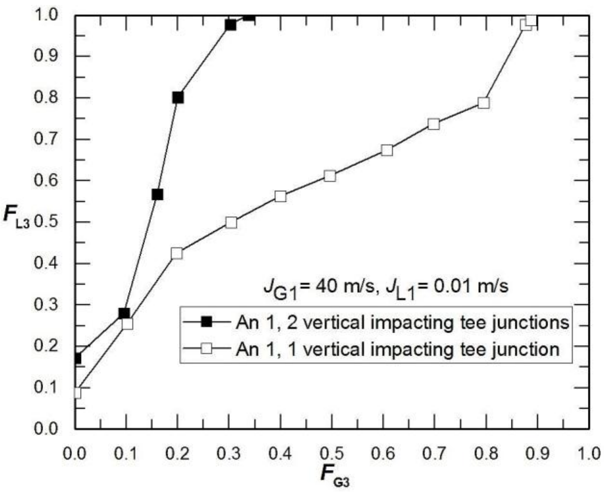

Figure 5. Comparison between the present data and the data in [10] for An 1 inlet condition

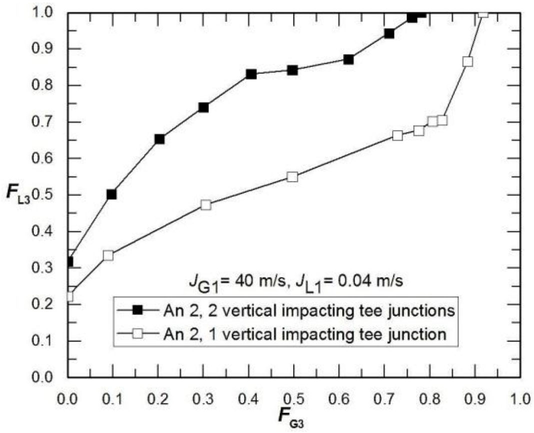

Figure 6. Comparison between the present data and the data in [10] for An 2 inlet conditions

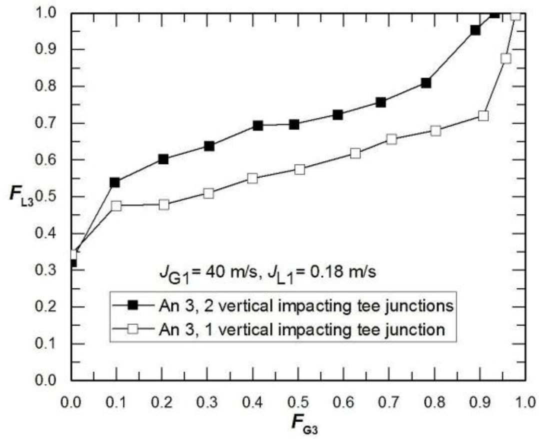

Figure 7. Comparison between the present data and the data in [10] for An 3 inlet conditions

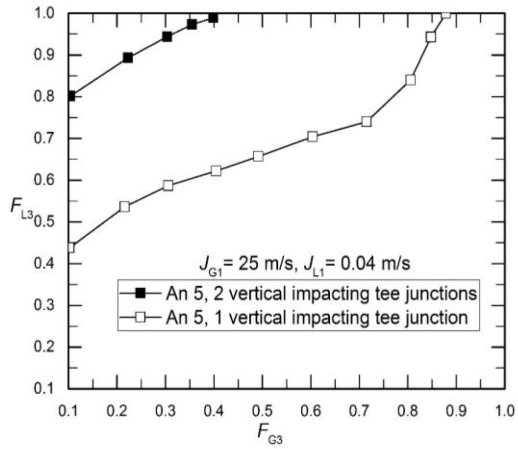

Figure 8. Comparison between the present data and the data in [10] for An 5 inlet conditions

Fig. 9 shows the effect of J_{G1} on the separation parameter, η, for five annular points, with J_{L1} fixed at 0.04 m/s. It is evident from this figure that as J_{G1} decreases, η increases for every corresponding F_{G3}. With decreasing J_{G1}, the last point in each curve (where all liquid enters the bottom outlet) climbs up the line, connecting zero to full separation. This is a clear indication of increase in the effectiveness of phase separation. At J_{G1} of 14.6 m/s, η is 100% at F_{G3}= 0, indicating full separation of phases. The effect of J_{L1} on phase separation, at fixed J_{G1}= 40 m/s, is demonstrated in Fig. 10. With decreasing J_{L1}, η moves closer to 100%, with lower value of F_{G3}, thus positively influencing separation effectiveness. Fig. 11-14 shows how the present design of two combined vertical impacting tee junctions affects partial-phase separation effectiveness in the annular flow regime, compared to a single vertical impacting tee. In all four annular data sets, η increases at corresponding values of F_{G3}, when the present design is used.

IV. Conclusions

New experiments were generated with air-water two-phase flow in a system of two combined vertical impacting tee junctions, at 200 kPa (abs) operating pressure and ambient temperature. Full separation data were obtained by keeping J_{L1} fixed and varying J_{G1}, until a condition was reached where liquid started flowing from the top outlet. Beyond this limit of full separation, only partial-phase separation is possible and data were generated for annular flow regime in this region. A separation parameter was introduced and used to analyze phase separation effectiveness of this new design of combined tee junctions. Experimental results were compared with similar experiments from [8, 10], where a single impacting tee junction was used. Based on overall analysis, the following conclusions can be drawn:

- The range of inlet parameters (J_{G1} and J_{L1}) at which full separation of phases can be achieved with the present system increases to almost twice, when two combined vertical impacting tee junctions are used instead of a single junction of the same kind.
- Decreasing J_{G1} or J_{L1} shifts phase redistribution curve towards the point (1, 0) in F_{G3} versus F_{L3} plot, which is the point of full separation.
- With decreasing J_{G1} or J_{L1}, phase separation parameter, η moves closer to 100%, with lower value of F_{G3}, thus positively influencing separation effectiveness.

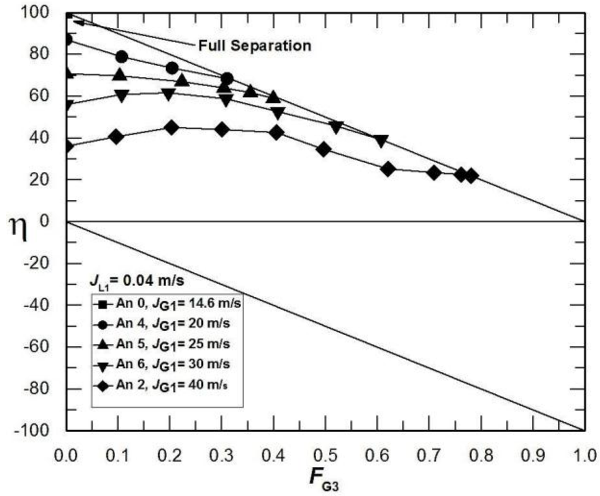

Figure 9. Effect of J_{G1} on phase-separation parameter with two vertical impacting tees.

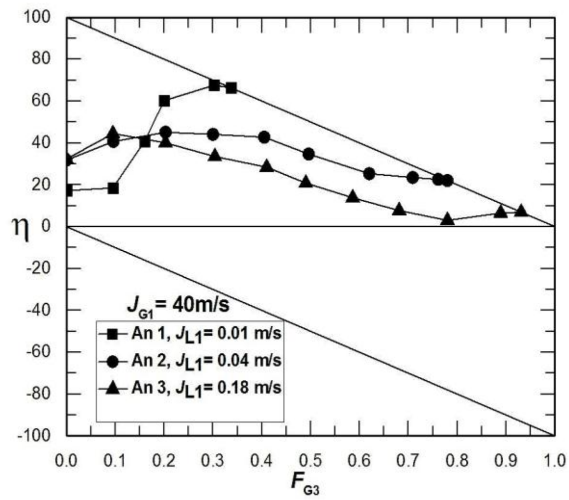

Figure 10. Effect of J_{L1} on phase-separation parameter with two vertical impacting tees.

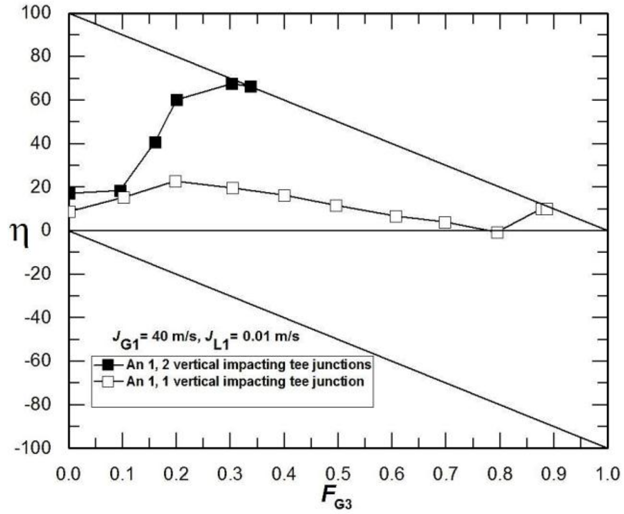

Figure 11. Separation effectiveness of the present system relative to a single tee for An 1 data set

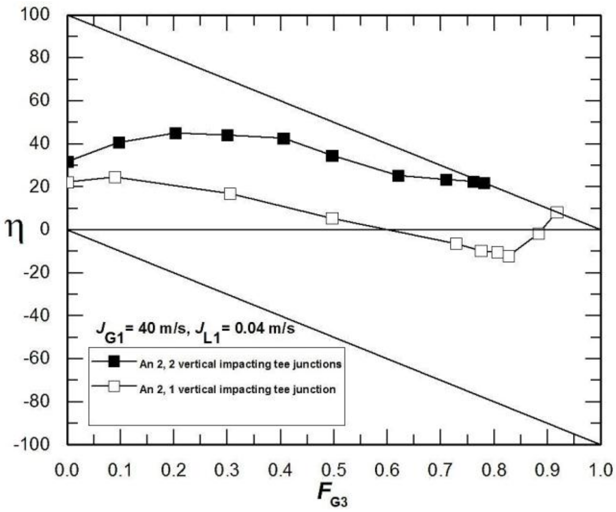

Figure 12. Separation effectiveness of the present system relative to a single tee for An 2 data set

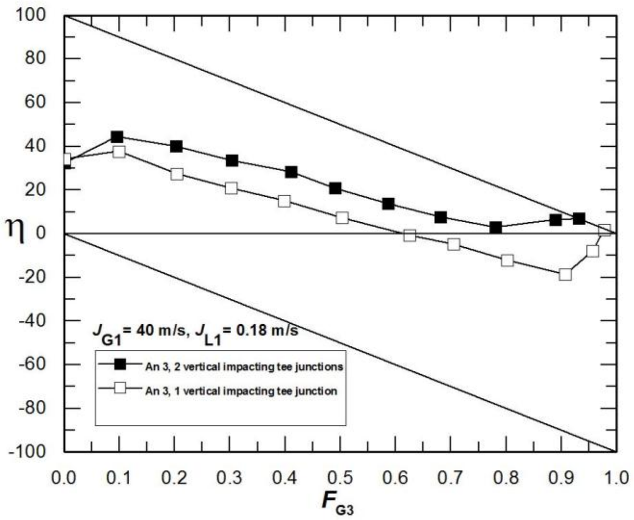

Figure 13. Separation effectiveness of the present system relative to a single tee for An 3 data set

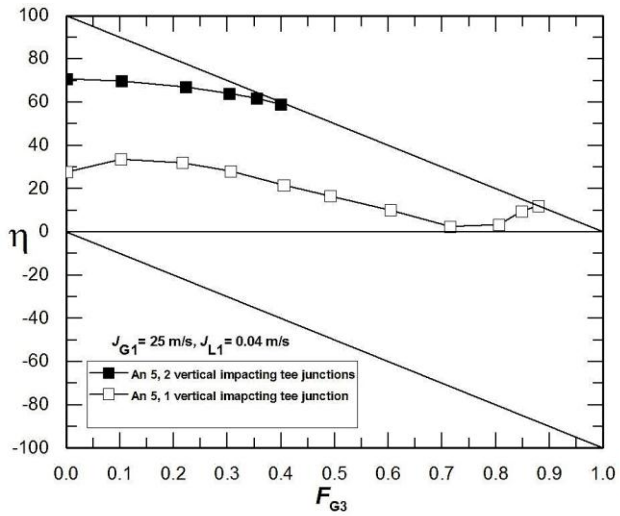

Figure 14. Separation effectiveness of the present system relative to a single tee for An 5 data set

- The separation parameter, η is higher for all values of F_{G3}, when using the present system compared to a system with a single tee junction.
- Using two combined vertical impacting tee junctions increases overall effectiveness of phase separation of two-phase flows and there is scope of further research on the use of such a system as partial to complete phase separator.

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