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Pressure drop in a horizontal, equal-sided, sharp-edged, combining tee junction with air–water flow

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ABSTRACT

Experiments were conducted on the two-phase pressure drop through a horizontal, equal-sided, sharp-edged, combining tee junction of diameter 37.8 mm with air–water mixtures at a nominal absolute pressure of 150 kPa. The new experimental data were used to assess the performance of existing models and to develop a new empirical model for the pressure-drop prediction. The experiments were conducted in a new facility with 41 pressure taps distributed over the three legs of the tee to provide accurate measurements of the pressure drop. The test matrix covered wide ranges of mixture qualities on the three sides of the junction and of distributions of liquid and gas flows between the two inlets. It is shown that previous modelling methods are not capable of consistent prediction of the data and a new empirical model is proposed based on the present data and using a new approach in formulating the irreversible component of the pressure drop. The new model produced excellent agreement with the data.

1. Introduction

Two-phase flows commonly occur in engineering systems like oil pipelines, steam power plants, evaporators, condensers, and nuclear reactors. Within these systems' piping networks both dividing tee junctions (branching and impacting), where one inlet stream is divided into two outlet streams, and combining tee junctions, where two inlet streams are combined into a single outlet stream, are common. As the tee junctions contribute to the total head loss and distribute the working fluids within the piping networks, knowledge of how they affect the flow structure is a critical part of the design and operation of these systems.

Single-phase tee junctions have been studied extensively both numerically and experimentally. Classic experimental works like [1–4] studied various configurations of sharp-edged, horizontal, combining and dividing tees with multiple pipe diameters and diameter ratios. They showed that for a given tee configuration, the total pressure loss is only a function of the mass distribution between the inlet(s) and outlet(s) of the tee and that empirical correlations much better predict the data than theoretical attempts. Their methods and results are still common references for predicting single-phase pressure losses through tees. Even with their foundational works, much more study has been contributed experimentally and numerically since (e.g., [5–13]).

With regards to two-phase flow, there have been many studies on tees looking at their various configurations. Particular attention has been paid to dividing tee junctions of both the branching type, where the two outlets are perpendicular to one another, and also the impacting type, where both outlets are perpendicular to the inlet. Studies on the phase redistribution through both branching and impacting tee junctions have produced valuable correlations/models for prediction and highlighted the need for further study (e.g., [14–18]). Other works have looked instead at the pressure losses caused by tee junctions, again in both branching and impacting types, and again produced valuable results and shown the need for further work in the area (e.g., [17,19–22]).

In contrast, there has been very little investigation of two-phase flow passing through combining tee junctions, where the two inlets are perpendicular to one another. To the best of the authors' knowledge, the only published studies are [23–26]. The study of St. Pierre and Glastonbury [23] performed an experimental investigation of the pressure losses caused by a combining tee junction with air–water mixtures in a test facility using two horizontal, unequal sided tees at a nominal pressure of $P = 310$ kPa and room temperature. Both tees had a main pipe inlet (M) and outlet (C) diameter, D, of 38.1 mm, but the perpendicular branch inlet (B) had diameters of either 25.4 mm or 12.7 mm. Their study covered a range of outlet mixture qualities from $0.0 < x_C \leqslant 0.5$, outlet mass flows from $0.151 \leqslant W_C \leqslant 0.529$ kg s^{-1}, and various mass distributions between the two inlets. They measured the pressure distribution with water and mercury manometers and seven pressure taps

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in each of the three sides of the tee. They reported the use of manometers, particularly during slugging, as inaccurate since the fluctuations in level made taking readings very difficult. From their experiments they proposed three separate models for prediction which will be referred to later.

Schmidt and Loth [24] also performed an experimental investigation of the pressure losses caused by a combining tee junction, but used refrigerant R12 with reduced pressures from $0.2 \leqslant P/P_{\text{critical}} \leqslant 0.75$ and an equal sided junction of diameter 27.3 mm with a vertical-up flowing branch. They measured the pressure distribution along all three sides of the tee using four pressure taps in each inlet, and eight pressure taps in the outlet. Along with their experiments, Schmidt and Loth [24] also proposed three models for prediction of the pressure losses which will be further discussed later. Approximately 1000 experiments were conducted with various inlet flow regimes, but the pressure-loss results were only reported in terms of the error their models incurred in prediction.

The most recent experimental studies of [25,26] focused on how the mixing in equal-sided combining tees affects the flow structure in each of the three sides of the tee junction, with specific interest in slugging. Their tests were primarily conducted using capacitance meters and visualization to monitor liquid hold up, but Belegratis [26] also measured the pressure losses caused by combining tees using two flow loops. One flow loop had a diameter of 67 mm and used mixtures of EXXsol D80 oil with either air at atmospheric pressure, or SF_6 gas at pressures of 2.0 and 4.7 atmospheres. In each of the three sides of the tee, pressure readings were made at two locations and the pressure gradient was calculated assuming that the pressure taps were located in the fully-developed region. The second loop had a diameter of 38 mm and used air–water mixtures at atmospheric pressure. Pressure readings were made at two locations in each inlet and four locations in the outlet. While Belegratis [26] did not directly report his pressure loss results, he reported testing the models found in [23,24] and found them insufficient for prediction of his data, with deviations ranging from 80% to well over 3000%.

It is clear from the above review that there is a serious lack of experimental data on the two-phase pressure drop in combining tees, particularly of the horizontal, equal-sided configuration, and no predictive models that can be used with confidence. The objectives of the present study are to generate new experimental data for pressure losses in air–water mixtures combining in an equal-sided horizontal tee, to use the data in evaluating the existing pressure-loss models, and to create a new empirical model capable of predicting the data well.

1.1. Problem definition

Consider a simple horizontal, sharp-edged, equal-sided combining tee of a given cross-sectional area, A, with two inlets perpendicular to one another and a single combined outlet. For the case of incompressible single-phase flow, the system may be completely described by the mass fraction of flow entering from the branch, λ, and the outlet mass flow rate, W_C. For gas–liquid flow through the same tee and assuming fixed fluid properties, four parameters are required to completely describe the flow: the mass fraction of outlet gas entering from the branch, λ_G, the mass fraction of outlet liquid entering from the branch, λ_L, the quality of the outlet flow, x_C, and the total outlet mass flow rate, W_C. In either the single- or two-phase flow situation, the pressure losses due to the junction are defined in Fig. 1 by extrapolating the fully-developed, linear pressure profiles to the junction's centre. The extrapolated pressures at the junction's centre for the main inlet, branch inlet, and combined outlet are P_M, P_B, and P_C, respectively. The difference between P_M and P_C is the main-to-combined pressure loss, ΔP_{M-C}, and the difference between P_B and P_C is the branch-to-combined pressure loss, ΔP_{B-C}. Therefore, both ΔP_{M-C} and ΔP_{B-C} are functions of λ_G, λ_L, x_C, and W_C.

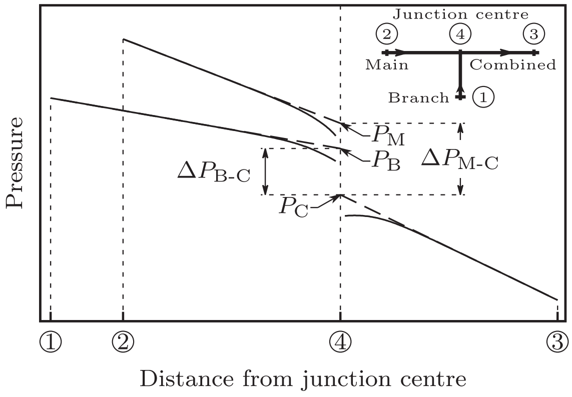

Fig. 1. Illustration of the pressure profile through a combining tee junction.

2. Experimental investigation

2.1. Test facility

A new facility, shown schematically in Fig. 2, has been constructed to accurately measure the pressure distribution in all three sides of a horizontal combining tee junction for air–water mixtures. A controllable amount of distilled water was pumped from a reservoir, maintained at a constant temperature by a cooling coil, through a filter and then split into two streams; one stream directed to the branch inlet ($W_{L,B} = W_{L,C}\lambda_L$) and one stream directed to the main inlet ($W_{L,M} = W_{L,C}[1 - \lambda_L]$). Each water flow was measured by a separate bank of rotameters. The air was received from a central compressed supply line and passed through a regulator, a filter, a pressure controller, and then also split into two streams; one stream directed to the branch inlet ($W_{G,B} = W_{G,C}\lambda_G$) and one stream directed to the main inlet ($W_{G,M} = W_{G,C}[1 - \lambda_G]$). Each air flow was measured by a separate bank of rotameters or turbine meters. After measuring the flow rates, the air and water were mixed at each inlet in identical mixers and then entered the test section of constant, uniform diameter 37.8 mm and passed through developing lengths of 76 and 87 diameters in the main and branch inlets, respectively, before the first pressure taps. The test section was equipped with visual sections at each inlet and the outlet, and the tee itself was machined from a clear acrylic block for flow visualization. A total of 41 pressure taps were machined into the bottom of the test section to allow accurate measurement of the pressure distribution. The locations of the visual sections and pressure taps are shown in Fig. 3. The combined outlet mixture was passed through a large separation tank which recycled the water back to the reservoir and discharged the air to a bank of turbine meters before exhausting to the atmosphere. The entire rig, from the inlet mixers to the separation tank, was carefully levelled and aligned. The temperature of the mixture was monitored with thermocouples placed at various locations around the rig. The pressures at the flow meter banks were measured with pressure gauges. The pressure taps were connected to a series of Rosemount 1151 and 3051 differential pressure transducers with small, clear tubes which were completely filled with water and purged frequently. The pressure at the centre of the junction was measured in each experiment with a designated pressure transducer relative to the atmospheric pressure, the pressure readings in the two inlets were measured relative to the last pressure tap in the outlet, and the pressure