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PRESSURE DROP DURING CONDENSATION IN MICROCHANNELS

Tian Yi Song[2], Guang Xu Yu[1], Xue Hu Ma[2], John W Rose[1] and Hua Sheng Wang[1]

[1]School of Engineering and Materials Science, Queen Mary, University of London, Mile End Road, London E1 4NS, UK
[2]Dept of Chemical Engineering, Dalian University of Technology, Dalian 116012, Liaoning, China
j.w.rose@qmul.ac.uk; h.s.wang@qmul.ac.uk

ABSTRACT

The paper reports preliminary results from a new research programme for making accurate heat transfer and pressure drop measurements during condensation in microchannels. While commissioning the apparatus a dummy test section was used with identical channel and header geometry to that to be used in the main test program (The final test section will comprise a relatively thick copper test section containing 98 accurately located thermocouples for measuring the temperature distribution from which local heat flux and temperature at the microchannel surface will be obtained). While using the dummy test section (without embedded thermocouples) the opportunity was taken to make accurate pressure drop measurements while measuring the vapor flow rate and total heat transfer rate based on coolant measurements. Data have been obtained for FC72 and steam. Approximate comparisons with available pressure drop calculation methods are presented.

INTRODUCTION

Pressure drop in boiling and condensing flows in pipes and channels are generally calculated by approximate methods where a single-phase flow correlation is used to determine a frictional component of the pressure gradient which is multiplied by an empirical (Lockhart-Martinelli) two-phase parameter to give the frictional pressure gradient for the two-phase case. For the single-phase pressure gradient calculation the flow is treated either as a liquid or gas flow. The flow rate used may be the total flow rate for the two-phase mixture or, when using the single-phase gas, the total flow rate multiplied by *quality* or, when using single-phase liquid, the total flow rate multiplied by (1-*quality*) [see Wang et al. (2003)].

In all cases the result obtained is an expression for the frictional two-phase pressure *gradient* as a function local quality. To calculate the pressure *drop* over a finite length of channel it is necessary to calculate local quality using some method for calculating heat transfer. The calculation of two-phase pressure drop therefore generally involves correlations for both heat transfer and pressure drop and iteration may be needed.

For microchannels, calculation methods for heat transfer and frictional pressure gradient have been proposed by Koyama et al. (2003), Cavallini et al. (2005, 2009), and Bandhauer et al. (2006) and Agarwal and Garimella (2009). The method of Koyama et al. involves 7 disposable constants in a heat-transfer correlation and 3 disposable constants in a pressure-gradient correlation. The method of Cavallini et al. (2005, 2009) involves 0 disposable constants in a heat-transfer correlation and 9 disposable constants in a pressure-gradient correlation. The method of Bandhauer et al. (2006) and Agarwal and Garimella (2009) involves 0 disposable constants in a heat-transfer correlation and 4 disposable constants in a pressure-gradient correlation. In all cases the disposable constants were found from the respective authors' own experimental data for R134a. Cavallini et al. also used their own data for R236ea, R410A and other researchers' data for R134a, R22, R404a and R744.

A wholly theoretical approach, which has no recourse to experimental data (Wang and Rose (2005, 2006, 2010)), is based on the Nusselt approximations and laminar annular flow. This determines the local heat flux (and condensation mass flux) for given distribution of surface temperature. The pressure gradient in the vapor core is found using a standard approximate technique for one-dimensional flow with transpiration. The local pressure gradient depends on the local vapor velocity and condensation mass flux.

In this paper preliminary pressure drop measurements are reported for condensation of FC72 and steam in a multi-microchannel tube. Approximate comparisons are made with available correlations.

APPARATUS, PROCEDURE AND MEASUREMENTS

Figure 1 shows a flow diagram of the apparatus and indicates the vapor and coolant circuits and all temperature, pressure and flow rate measuring positions. The apparatus was designed for both heat transfer and pressure drop measurements. This paper reports pressure drop data obtained while commissioning the rig prior to simultaneous heat transfer and pressure drop measurements. In the present work a dummy test section (see Figs. 2 and 3) was used. This had channel and header dimensions identical to those of a new test section for simultaneous heat-transfer and pressure drop measurements and having 98 very small thermocouple holes for determination of the temperature distribution throughout a thicker copper test section. The test section used in the present work was made in two halves with mating surfaces lapped flat. Six channels 1.5 mm x 1.0 mm and outer O-ring grooves were machined in the lower half. The upper and lower outer surfaces were cooled separately with flow rates adjusted to be the same for both surfaces. The whole apparatus between the boiler inlet and test section outlet were thermally well insulated.

The superheater was not operated in the present tests. All tests were made with incomplete condensation in the test section and excess vapor condensed in the post condenser. For the tests with steam, condensate from the post condenser was not returned to the boiler during operation. The flow rate of steam to the test section was determined by a steady flow energy balance with the measured power input to the boiler (including a small correction for the heat loss between the evaporator and test section (see Lee and Rose (1984)). For some tests, condensate from the post condenser was collected over a measured time interval and weighed. Agreement in flow rate with that obtained by measuring the power input to the boiler was around 2%.

For the tests with FC72 the apparatus was operated in closed-loop mode while adjusting the condensate return pump occasionally by hand to maintain a steady level in the condensate accumulator. The vapor flow rate was determined from the condensate return flow meter.

Figures 4 shows, for all data, the pressure drop between inlet and exit of the test section measured by the differential pressure transducer plotted against the difference in saturation pressures based on the measured temperatures at the two locations. The good agreement gives confidence in the reported pressure drop measurements. The small deviations for FC72 are thought to be due to either an insufficiently accurate saturation pressure-temperature relationship or small amounts of impurities in the fluid.

For each fluid in turn measurements were made of pressure drop and total heat transfer in the upper and lower coolant channels. The tests were done at essentially constant coolant flow rate for a range of coolant inlet temperatures.

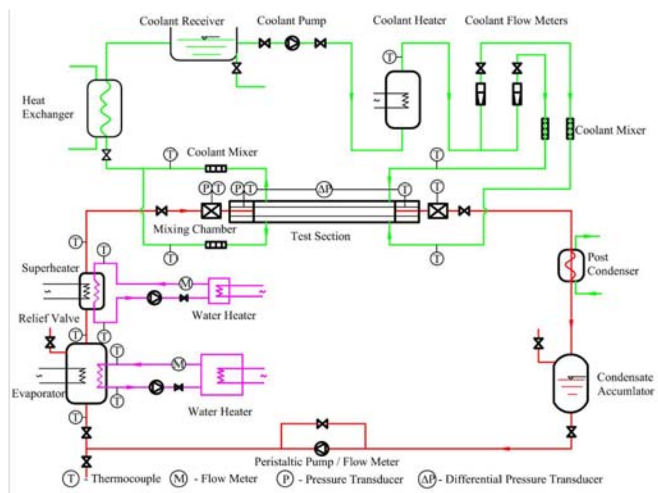


Fig. 1 Schematic of Experimental Rig

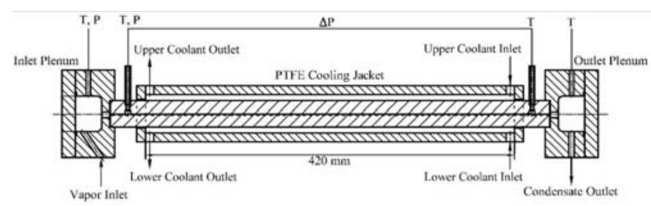


Fig. 2 Test section

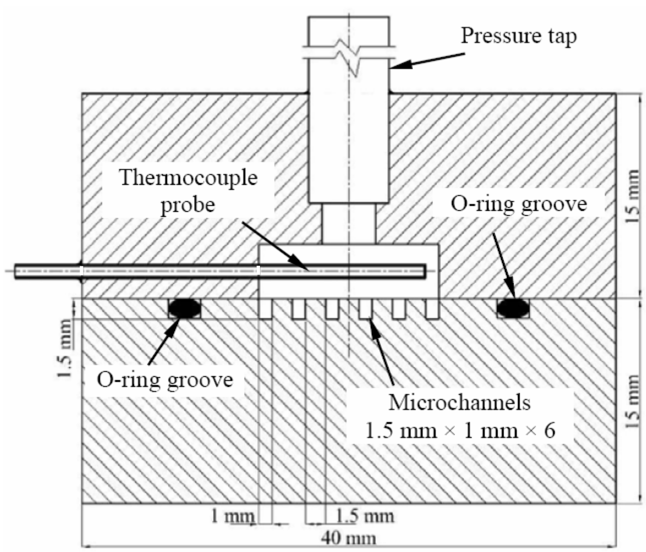
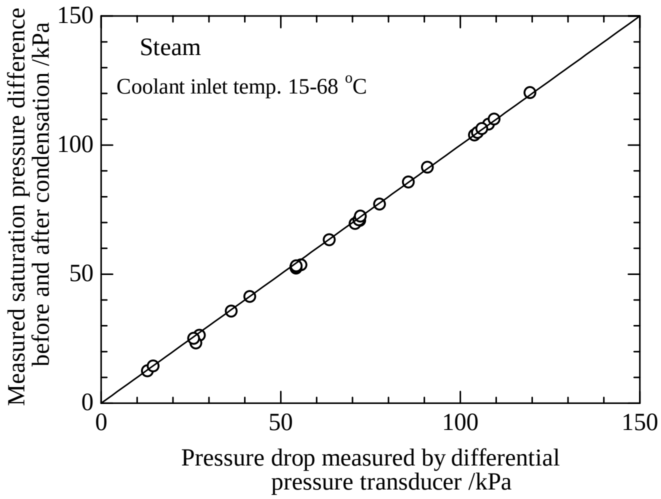


Figure 3 Section through test section at pressure and temperature measuring points



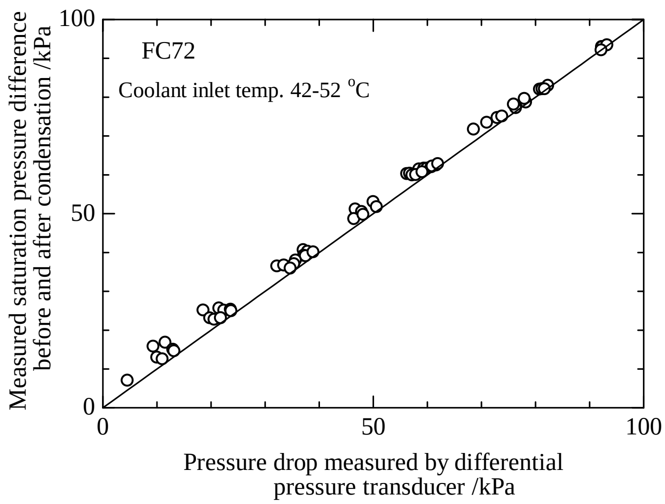


Fig. 4 Comparison of pressure drop measured by the differential pressure transducer at inlet and exit of the condensing with the difference in saturation pressures corresponding to the measured temperatures at inlet and exit.

RESULTS

The frictional pressure drop over the channel length was determined by adding the momentum or deceleration pressure rise due to condensation to the measured total pressure drop. The pressure rise over the channel length due to condensation (momentum or deceleration pressure rise) was determined using the methods described by Koyama et al. (2003), Cavallini et al. (2009) and Agarwal and Garimella (2009). Al three methods gave essentially the same results. The pressure rise due to condensation was typically around a quarter of the measured pressure drop.

The results are shown in Figs. 5 and 6 where friction pressure drop is plotted against mass flux for steam and FC72 respectively. The friction pressure drop is seen to increase with vapor mass flux with no significant dependence on heat flux or condensation rate for the experimental range (approximate range of mean heat flux based on channel area for steam 130 kW/m^2 to 170 kW/m^2 and for FC72 10 kW/m^2 to 30 kW/m^2).

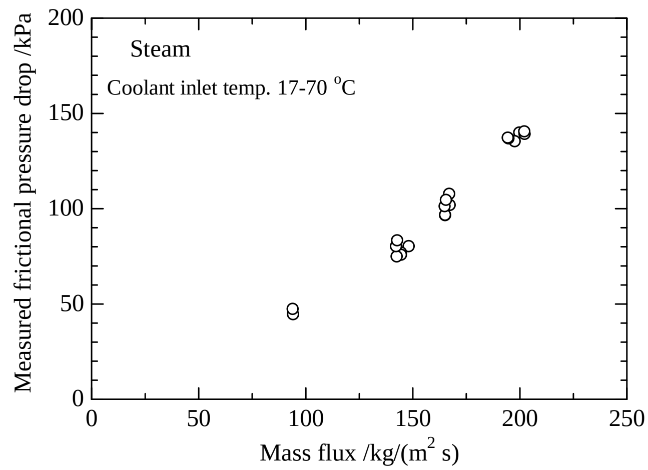


Fig. 5 Measured friction pressure drop for steam.

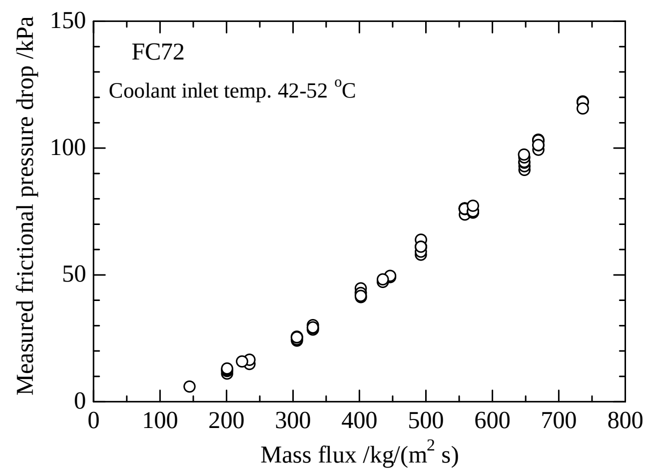


Fig. 6 Measured friction pressure drop for FC72

COMPARISONS OF EXPERIMENTAL DATA WITH CALCULATION METHODS

In order to calculate the dissipative or frictional pressure drop, using any of the calculation methods, it is necessary to use a heat-transfer correlation, together with vapour and surface temperatures, to determine the local heat flux and hence the local vapor quality. This enables calculation of local friction pressure gradient which must be integrated to obtain the pressure drop over a given length of channel. In the present preliminary investigation neither local surface temperature nor local heat flux were obtained. For purpose of approximate comparison with calculation methods, the quality was taken to vary linearly from the inlet value (unity) to the value at exit as determined from the coolant measurements. The model of Wang and Rose (2005, 2006, 2010) suggests that this is not too bad an approximation and will give accurate results near the inlet and exit. In the present measurements the smallest exit quality was around 0.5 for steam and 0.4 for FC72.

Comparisons of the correlations with the data are given in Figs. 7 and 8. For steam the data are surprisingly well predicted by two of the correlations while the third over predicts the friction pressure drop by a factor of around 2.5. For FC 72 the correlation which is least good for steam best predicts the FC72 data. The other correlations under predict the friction pressure drop for FC72 by up to around 40% and 60% respectively.

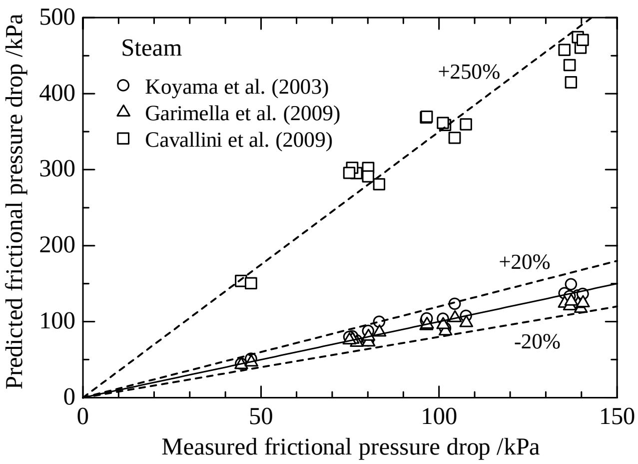


Fig. 7 Calculated versus measured friction pressure drop for steam.

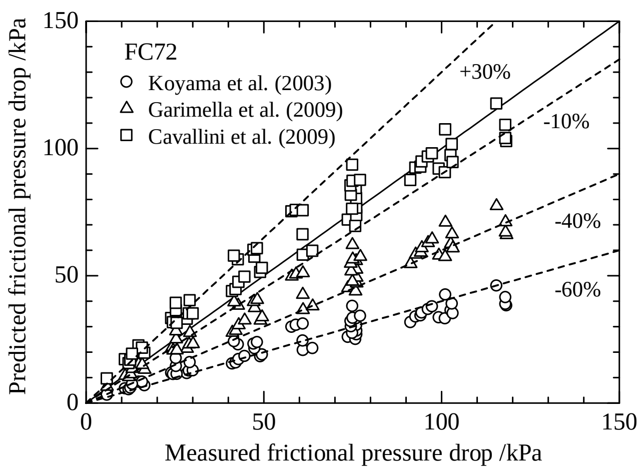


Fig. 8 Calculated versus measured friction pressure drop for FC72.

CONCLUDING REMARKS

Two of the pressure drop calculation methods, based on data for R134a, predict the present steam data surprisingly well. Two calculation methods underpredict the present FC72 data, the method of Cavallini et al. (2009) being closet to the measurements. It is not thought that using a linear dependence of quality on distance along the channel, for the purpose of making the comparisons, invalidates these general conclusions.

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