Prediction of Two-Phase Frictional Pressure Drop in Copper Minichannel Solar Water Heater

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Abstract

The use of minichannel technology to improve the thermal efficiency of solar thermal collectors has been demonstrated by our group with test data obtained from aluminum minichannel solar water heater tested throughout a year [1]. A second phase of this project intends to study the performance of minichannel collectors operating at medium temperatures with the purpose of generating steam. Due to the increased temperature, copper minichannel tubes have been selected for the construction of the solar collector. This poster presents preliminary simulations of two-phase pressure drop predictions in copper minichannel tubes. Two pressure drop correlations were used for comparison: 1. Muller-Steinhagen and Heck, and 2. Souza and Pimenta. The model is first validated against experimental data for refrigerant R134a. Then the model is used to predict pressure drop inside copper minichannel tubes using water as the working fluid. This is a first step for our final goal simulating two-phase flow phenomena in minichannel solar thermal collectors. The construction of the collector is currently underway.

Introduction

Our group is currently working on the design of a copper minichannel solar thermal collector for the purpose of steam generation at temperatures slightly above 100 °C. From our results of our previous work on aluminum minichannel solar water heater, we observed that is is possible to reach saturation temperatures for water [1]. However, due to yield strength limitations of aluminum at medium temperatures, we are developing a copper minichannel solar thermal collector.

Having the ability to predict two-phase heat transfer and pressure drop in the copper minichannel tubes enables us to accurately design and optimize an efficient solar collector.

The objective of this poster is to predict two-phase pressure drop in copper minichannel tubes at operating conditions typical of a solar thermal collector.

Methods

The mathematical model of calculating the two-phase pressure drop using Muller-Heck and Souza-Pimenta correlations are described in [2, 3]. Those correlations were implemented in Engineering Equation Solver (EES) to simulate and calculate the two-phase pressure drops at given saturation temperature for a range of inlet qualities and mass fluxes of the fluid [5]. The first set of simulations assumed flow inside a circular pipe using R-134a refrigerant as the working fluid with the purpose of validation against experimental results found in [4]. After validation, the mathematical models was applied to copper minichannel tubes with two-phase water mixtures as the working fluid at typical conditions that would be used in solar collector experiments.

Mathematical Model

Muller-Steinhagen & Heck's Friction Pressure Drop Correlation:
The two-phase friction pressure drop correlation by Muller-Steinhagen and Heck utilizes properties of the liquid and vapor during the two-phase phenomena [2]. Using the pressure drop for single-phase respectively for liquid and vapor:

$$\left(\frac{\mathrm{dp}}{\mathrm{dL}}\right)_{\mathrm{frict},l} = f_l \frac{G^2}{2\rho_l d} = A$$
$$\left(\frac{\mathrm{dp}}{\mathrm{dL}}\right)_{\mathrm{frict},v} = f_v \frac{G^2}{2\rho_v d} = B$$

Methods *(cont'd)*

where G is the mass velocity (kg/m²-s), ρ is the density (kg/m³), d is the tube diameter (m), and subscripts v and l represents vapor and liquid, respectively. The f is the friction factor given as,

$$f_l = \frac{64}{Re_l}, \quad f_v = \frac{64}{Re_v} \quad \text{for} \quad Re_l, Re_v \leq 1187$$
$$f_l = \frac{0.3164}{{Re_l}^{1/4}}, \quad f_v = \frac{0.3164}{{Re_v}^{1/4}} \quad \text{for} \quad Re_l, Re_v > 1187$$

and Re, Reynolds number, is represented as,

$$Re_l = \frac{Gd}{\mu_l}, \qquad Re_v = \frac{Gd}{\mu_v}$$

where μ is the dynamic viscosity (kg/ms). For a rough linear increase of frictional pressure drop with increasing quality of x < 0.7, this can be written as:

$$\Gamma = A + 2(B - A)x$$

However, to cover the full range of vapor quality, 0 ≤ x < 1, the frictional pressure gradient (kPa/m) for two-phase flow is rewritten as,

$$\left(\frac{\mathrm{dp}}{\mathrm{dL}}\right)_{\mathrm{frict},tp} = \Gamma(1-x)^{1/3} + Bx^3$$

Souza & Pimenta's Friction Pressure Drop Correlation:

The two-phase friction pressure drop correlation by Souza and Pimenta utilizes properties of the liquid and vapor during the phenomena, as well as a two-phase multiplier and Lockhart-Martinelli's parameter [3]. The two-phase multiplier is similar to *Chisholm (1968, 1973, 1983)* with some variation:

$$\phi^2 = 1 + (\gamma^2 - 1)x^{1.75}\left(1 + 0.952\gamma {X_{tt}}^{0.4126}\right)$$

γ is a physical property index, and X_{tt} is Lockhart-Martinelli's parameter:

$$\gamma = \left(\frac{\mu_v}{\mu_l}\right)^{0.5}\left(\frac{\mathrm{v}_v}{\mathrm{v}_l}\right)^{0.125}$$
$$X_{tt} = \left(\frac{\mu_l}{\mu_v}\right)^{0.1}\left(\frac{\mathrm{v}_l}{\mathrm{v}_v}\right)^{0.5}\left(\frac{1-x}{x}\right)^{0.9}$$

In the equations above, μ represents the dynamics viscosity (kg/ms), and v is the specific volume (m³/kg). The frictional pressure drop is know represented by

$$\Delta P_{frict,tp} = \frac{f_l G^2 L \mu_l \phi^2}{2d}$$

The frictional pressure drop is converted into frictional pressure gradients by dividing by the length of the tube.

Results and Discussion

To validate the correlations by Muller-Heck and Souza-Pimenta, a simulation of refrigerant R-134a flowing through a 10.92 mm diameter circular tube is compared with experimental data from Ould Didi et al. as seen in Figure 1 [4]. The mass velocity, G, is set to 300 kg/m²s at a saturation of temperature of T_{sat} = 4 °C.

Results and Discussion *(cont'd)*

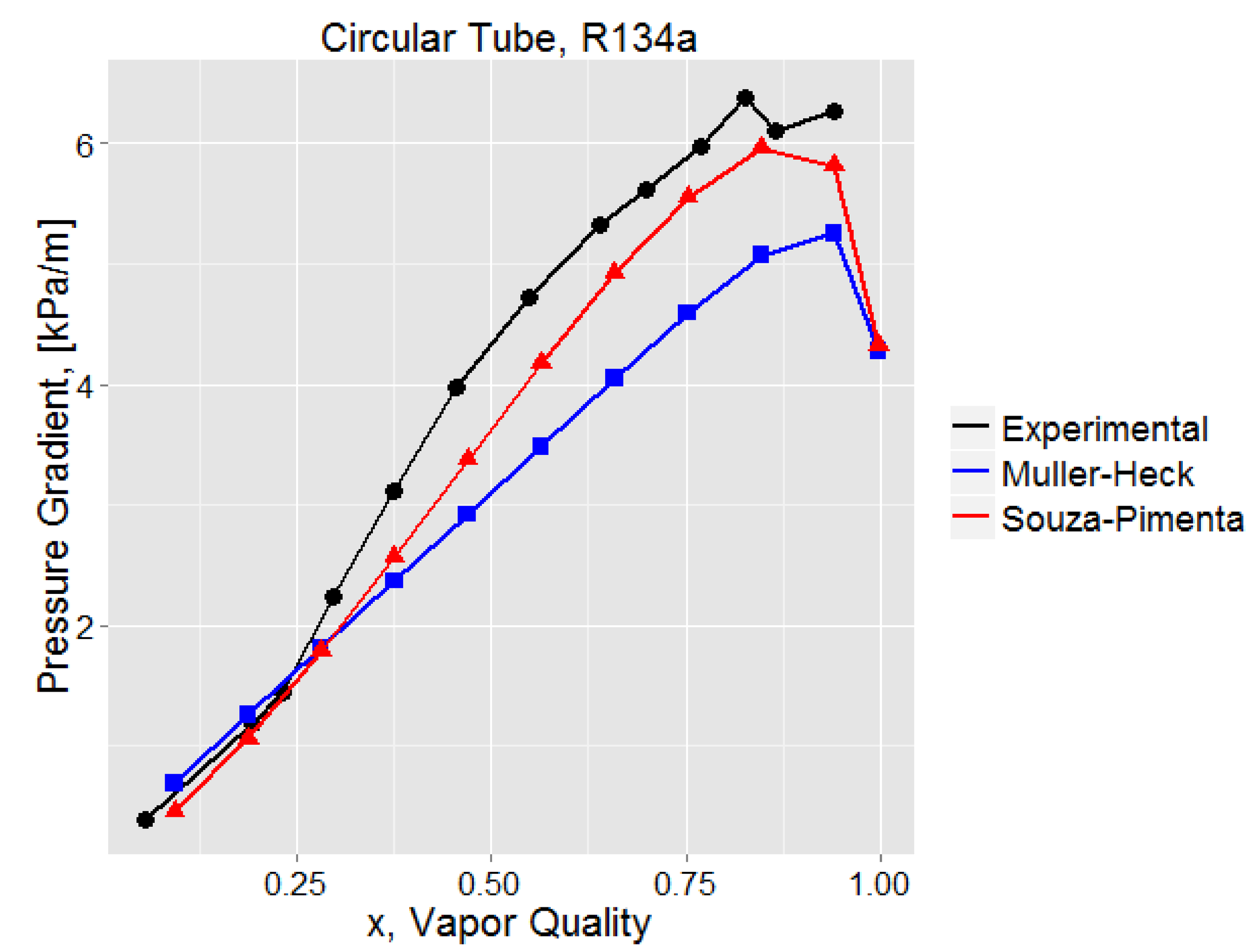

Figure 1. Comparison of the two pressure drop correlations with experimental data from Ould Didi et al. [4]. R134a as the working fluid, flowing through a 10.92 mm diameter circular tube at T_{sat} = 4 °C and G = 300 kg/m²s.

It is clear that the frictional pressure drop results from Souza-Pimenta resembles the experimental data closer than Muller-Heck's correlation.

Both Muller-Heck and Souza-Pimenta's two-phase frictional pressure gradient correlation were applied to copper minichannel tubes with a cross section design developed by our group. The dimensions and cross-section of our copper minichannel tubes in millimeters and a minichannel tube in production process at Ohio University are shown below. The length of our tubes are 1.810 m.

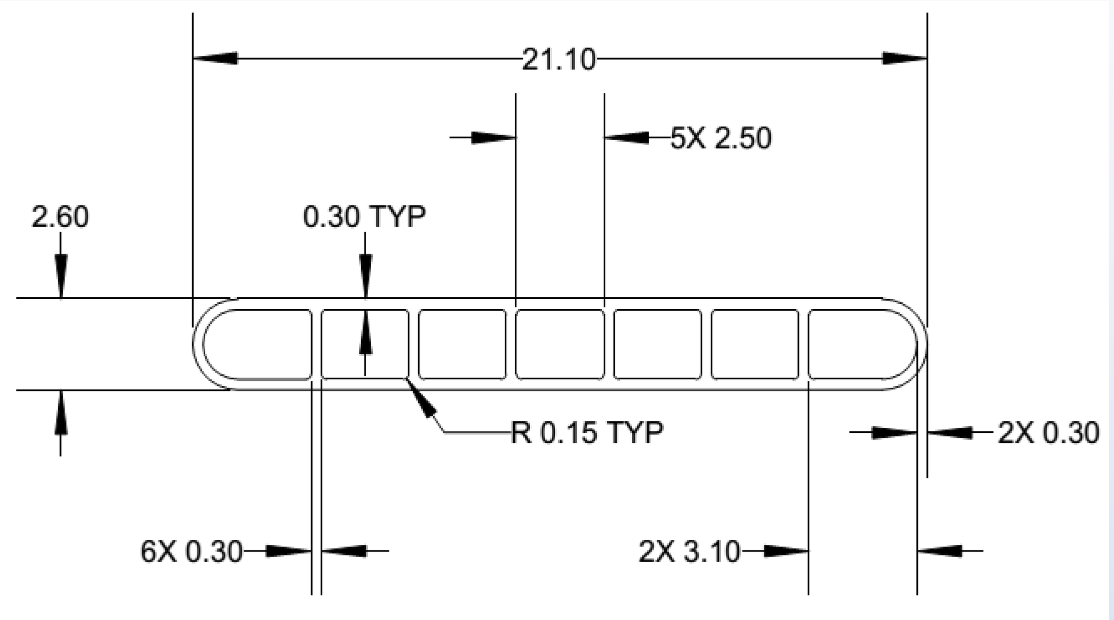

Figure 2. Cross-sectional drawing of the copper minichannel tube.

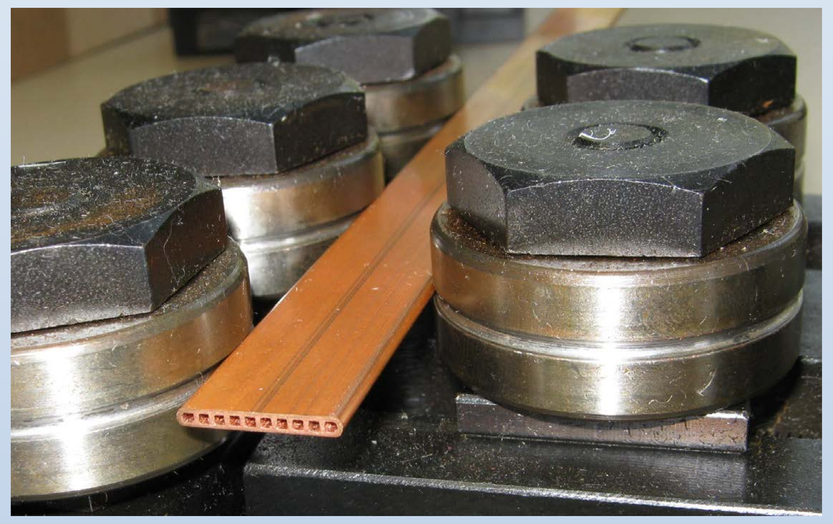

Figure 3. Copper minichannel tube being manufactured at Ohio University.

The mass flux is set to 22 kg/m²s (approximately similar to the aluminum minichannel solar water heater) and a saturation temperature of T_{sat} = 100 °C.

Results and Discussion *(cont'd)*

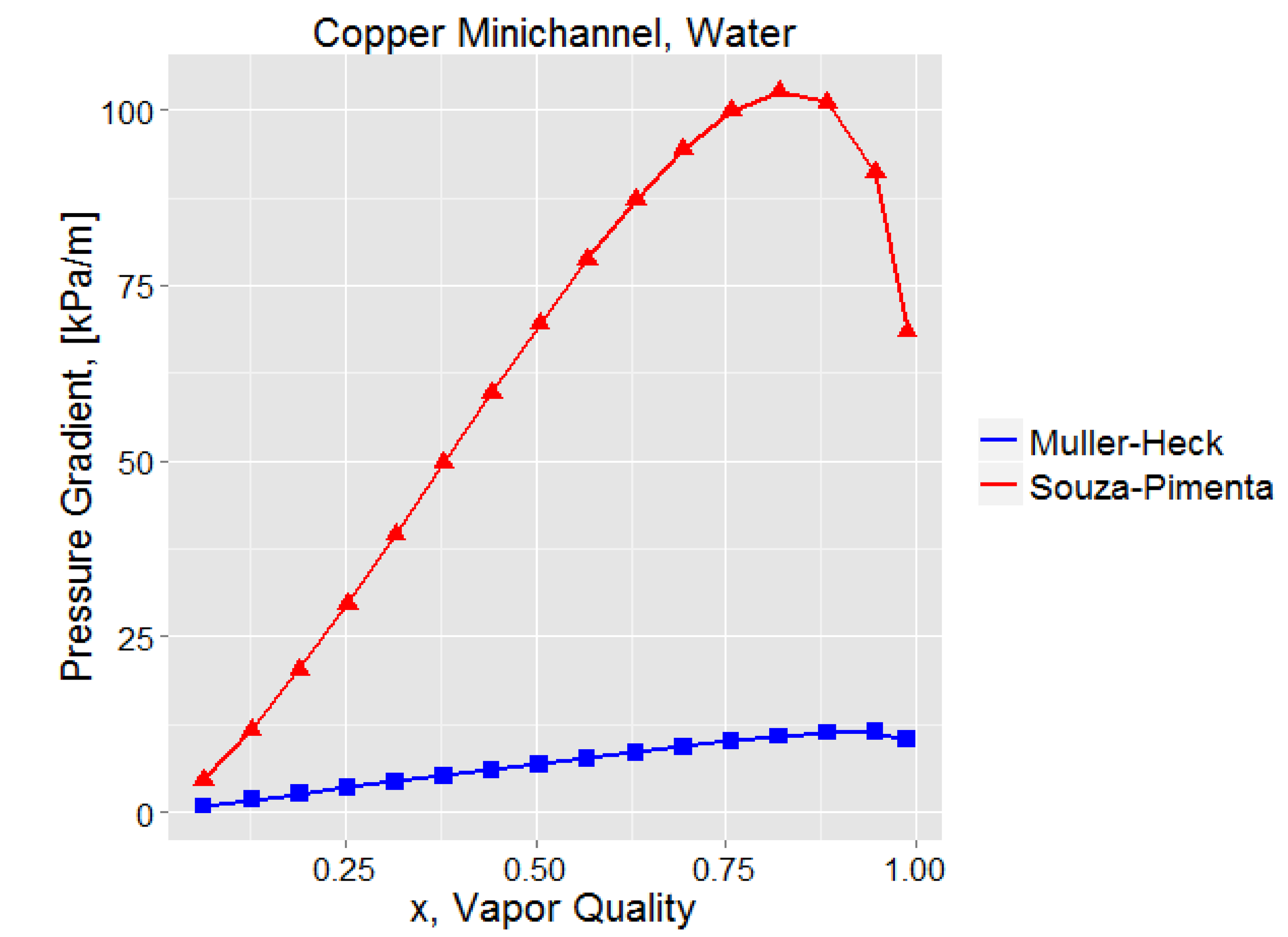

Figure 4. Comparison of the two pressure drop predictions in a copper minichannel using water as the working fluid, T_{sat} = 100 °C, and G = 22 kg/m²s

The two correlations generate significantly different results. Other correlations will be tested and the effects of mass flux and the reduction of hydraulic diameter, due to the use of minichannel tubes, will be investigated.

Conclusion

Simulation and validation of the two-phase pressure drop correlations by Muller-Heck and Souza-Pimenta are shown. Souza-Pimenta's correlation to a circular pipe compared to experimental data shows a reasonable fit. However when both correlations are fitted for a copper minichannel tube, significant differences in pressure drop are obtained. More analysis needs to be performed.

Future work includes finding a better fit for approximating two-phase pressure drop especially for minichannel tubes and validating against experimental data that utilizes minichannel tubes; developing a model for calculating boiling heat transfer coefficient; running experiments and collecting data with the copper minichannel solar thermal collector.

References

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