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A simple methodology to incorporate flashing and variation of thermophysical properties for flow boiling pressure drop in a microchannel

Ashif Iqbal, Manmohan Pandey*

Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati, 781039, Assam, India

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ABSTRACT

This paper proposes a simple approach to model the complex interplay among the various thermophysical phenomena occurring in flow boiling. In order to assess the need for such a model, flow boiling pressure drop of FC-72 in a single trapezoidal microchannel with a hydraulic diameter of 111 μm is measured by varying heat flux and mass flux. The pressure drop obtained is in the range of 10–45 kPa, which does not compare well with the existing models based on constant properties. Therefore, a new predictive approach is developed for meticulous evaluation of pressure drop across a microchannel with flow boiling. It uses the separated flow model with evaluation of thermophysical properties at local pressure, thus incorporating the effect of flashing on thermodynamic quality, and the effect of heat flux on the two-phase multiplier. Relations based on a modified form of Clausius-Clapeyron equation are employed for evaluation of local thermophysical properties for fluids. This methodology is combined with different empirical correlations from the literature to predict pressure drop. The proposed predictive methodology, comprising close form equations, is physically sound and yet easy to implement, and reproduces large pressure drop experimental data better than the existing methods.

1. Introduction

Dissipating high amount of heat flux is an important issue of modern thermal management with the ever increasing demands for high performance and miniaturization. Flow boiling microchannel heat sinks have emerged as one of the most effective solutions for cooling high and ultrahigh heat flux devices such as high performance computer chips, laser diodes and nuclear reactors [1]. Design of these miniature devices requires a proper estimation of two-phase heat transfer, which, in turn, necessitates accurate prediction of pressure drop in flow boiling. The total two-phase pressure drop of a fluid is the sum of the frictional pressure drop, the acceleration pressure drop, and the gravitational pressure drop. The frictional pressure drop can be determined by different two-phase models, and this has been an active research area for the last two decades. In order to calculate two-phase pressure drop, extensive theoretical and experimental studies have been conducted. Since the mechanisms occurring in two-phase flow have not been effectively understood, a number of empirical correlations have been proposed instead [2].

Two-phase pressure drop in microchannels is relatively high as compared to conventional channels, due to their very small sizes and moderate mass fluxes, the latter being so in order to achieve reasonable heat transfer coefficients. Due to the large pressure gradient, the saturation temperature — and hence the thermophysical properties — vary along the length, and the effect of flashing becomes significant. The flashing phenomenon in mini-/microchannels occurs when the pressure at some axial location of the channel drops below the saturation pressure of the fluid, and the liquid at that location becomes superheated temporarily. Dario et al. [3] incorporated the effect of flashing on thermodynamic quality considering a linear pressure profile for heat transfer calculation. Very informative observations were reported by Mirmanto [4,5], by putting pressure sensors along the length of a microchannel. It was observed that the pressure profile along the length was nonlinear, especially at higher heat flux, due to rapid bubble generation and non-uniform distribution of nucleation sites [4]. Pressure drop reported in the experiments [4] was high (up to 75 kPa), therefore, the existing modelling approach, based on system pressure, cannot predict these experimental data accurately. Another group of researchers [6] tried to validate the existing correlations for two-phase pressure drop with their experimental data considering properties at system pressure, but ended up with a significant deviation. Cioncolini and Thome [7] considered the local pressure for evaluating thermophysical properties and calculated two-phase pressure drop, using the homogenous model. The evaporative channel was discretized into equal length subchannels, and the local pressure drops were computed using the local values of thermophysical properties, and the subchannel

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* Corresponding author.
E-mail addresses: ashif.iqbal@iitg.ac.in (A. Iqbal), manmohan@iitg.ac.in (M. Pandey).

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pressure drops were added to get the total pressure drop [7]. In an earlier work [8], pressure drop for flow boiling in a microchannel was predicted using the homogenous model including the effect of local thermophysical properties and flashing. The Clausius-Clapeyron equation, which uses the ideal gas equation for the vapour phase, was employed for evaluation of local thermophysical properties [8]. However, the ideal gas equation is not valid for refrigerants and dielectric fluids, since the compressibility factor is not close to unity.

For the electronic cooling applications, dielectric fluids (FC-72 and FC-77) are suitable because they are thermally and chemically stable, compatible with sensitive materials, nonflammable, and practically nontoxic [6,9]. However, there are limited number of studies [6,9–14] on flow boiling pressure drop of dielectric fluids in microchannels, i.e., channels that fulfil condition [10] ($Bd^{0.5}Re = 160$), under which microscale confinement effects are exhibited. Park et al. [6] investigated the two-phase pressure drop of FC-72 and stated that pressure drop increased with increasing vapor quality and mass flux, and was nearly independent of heat flux for any given exit quality and mass flux. In view of the importance of dielectric fluids, further research on their flow boiling pressure drop characteristics and development of predictive tools for the design of microchannel heat sinks is the need of the hour.

In the present work, flow boiling experiments are conducted through a single microchannel using FC-72 and a relatively high pressure drop is observed. For high pressure drop, the effects of flashing and variation of thermophysical properties are significant. Therefore, a new methodology is developed, which is simple but successful (compares well with experimental data) to evaluate flow boiling pressure drop by incorporating the flashing effect and local thermophysical properties. The present approach includes a modified form of Clausius-Clapeyron equation to characterize the saturation line on the P-T plane for fluids whose vapor phase has nearly constant compressibility factor in the range of operation. The equations governing the proposed methodology are derived in an elegant close form, consisting of a system of ODEs, and their simulation is computationally inexpensive.

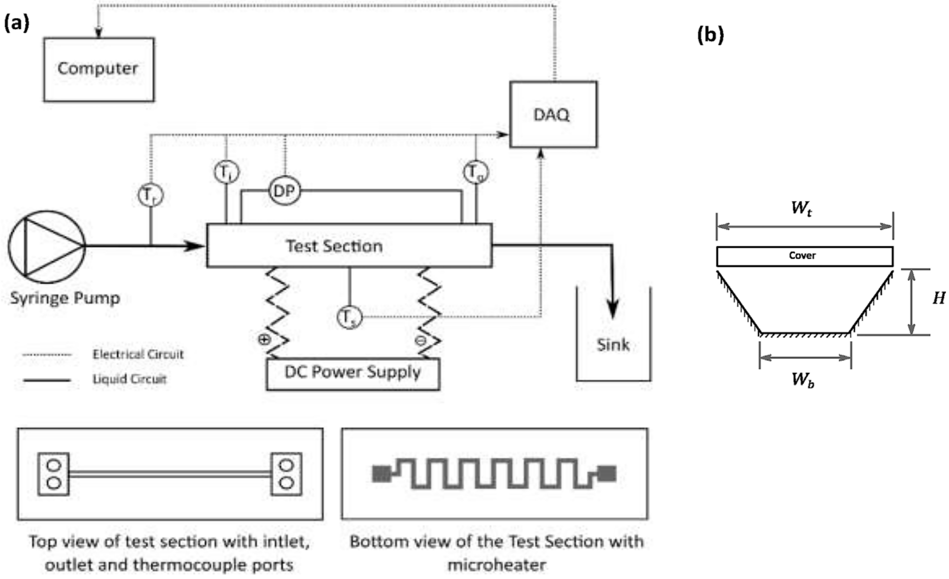
2. Experimental setup and procedure

A schematic of the experimental setup employed in the measurements is shown in Fig. 1(a). The setup consists of a syringe pump, a differential pressure gauge, the test section, a DC power supply, and a data logger to record inlet/outlet temperatures of FC 72 and surface temperature. All devices were connected using silicone tubing (Master Flex). A pre-calibrated syringe pump (Cole Parmer) was used for metering and controlling the mass flow rate of FC 72.

Table 1
Estimation of error in various parameters measured and derived in the experiments.

Parameter	Value/Range	Uncertainty (%)
Top width (W_t)	245 μm	± 0.43
Bottom width (W_b)	115 μm	± 0.85
Height (H)	90 μm	± 1.11
Length (L)	20 mm	± 0.50
Hydraulic Diameter (D_H)	111 μm	± 1.48
Heated Area (A_{ht})	6.74×10^{-7} m^2	± 0.33
Heat Flux (q_{eff})	4–8.5 W/cm^2	± 5.01 to ± 2.03
Mass flux (G)	431–690 kg/m^{2}s	± 5.32 to ± 2.52
Pressure drop (Δp)	10–45 kPa	± 7.02 to ± 3.13

A pre-calibrated digital pressure gauge (Deltabar PMD75) was used to measure the pressure drop across the microchannel. A contact probe was used to make electric contact between microheater and DC power supply. K-type thermocouples (Cole-Parmer) were placed inside the inlet and outlet reservoirs. Another K-type thermocouple was placed on the bottom surface (microheater side) of the microchannel to measure the wall temperature. All the thermocouples were connected to a data logger which logs the temperatures. The test sections were fabricated using microfabrication facility available at CEN, IIT Bombay. Double-sided polished (100) p-type, 2″ silicon wafer with resistivity 4–7 Ω-cm was used for fabrication. Microchannel was etched using chemical etching process and a trapezoidal cross-section was obtained as shown in a cross sectional view of Fig. 1(b). It was then bonded with a quartz plate at the top. The fabrication process was the same as that used by Singh et al. [15]. Detailed geometrical specifications of the microchannel employed in the experiment are given in Table 1. The following procedure was adopted while performing the experiments. The flow was started and then an input electric power was provided by supplying a fixed voltage and current using a DC power supply. Continuous monitoring of the inlet and outlet temperatures and pressure drop was undertaken to check for steady state. Once steady state condition was achieved, all relevant parameters such as pressure drop, inlet–outlet temperatures, power supplied and flow rate were recorded. The above procedure was repeated for other values of flow rates and heat fluxes.



Top view of test section with intlet, outlet and thermocouple ports

Bottom view of the Test Section with microheater

Fig. 1. (a) Schematic of the experimental setup (b) Cross section of the test section.