Diabatic flow boiling in circular transparent microchannels

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Abstract. The horizontally assembled circular microchannel (\(D_h = 543\ \mu\text{m}, \ L_{HT} = 60\text{mm}\)) made of transparent borosilicate glass is kept under constant wall heat flux conditions by means of a transparent metallic thin film deposit at the channel external wall as in Silvério and Moreira [1]. Heat transfer and pressure drop measurements are achieved by measuring the temperature and pressure at the channel inlet and outlet. Temperature is also measured along the channel outer wall. Experiments are carried with two different fluids, ethanol and methanol. Inlet liquid subcooling is of 297K, mass fluxes, \(G\), up to 689kg.m\(^{-2}\).s\(^{-1}\) and imposed heat fluxes, \(q^*\), up to 12.5W.cm\(^{-2}\) at \(\Delta T_{sub}\) from 0.8 to 50K. Synchronized high-speed visualization and microscope optics are used to determine dominant two-phase flow patterns and characterize hydrodynamic instabilities. Vapor qualities, \(\chi\), of -0.1 (indicating a subcooled liquid state) to 0.5 are under investigation. Semi-periodic variation of the flow patterns is noticeable for different flow conditions.

1. Introduction
Flow boiling in microchannels is of increasing interest in compact high heat flux electronic devices and components mainly due to its higher heat removal capability and higher heat transfer coefficients.

Several designs have been addressed to study two-phase flow heat transfer characteristics in channels of microscopic dimensions. Hetsroni et al [2] address periodic flow boiling in parallel triangular microchannels etched in a silicon substrate, using water and ethanol as working fluids. For the low vapor qualities investigated, the authors found that the period between successive events is dependent on the boiling number, \(B_o = \frac{\text{heat flux}}{\text{mass flux} \times \text{latent heat of vaporization}}\), and decreases with an increase on the boiling number. They also noticed the synchronized behavior of pressure and temperature oscillations. Wang et al [3] carried simultaneous measurements of temperature, pressure and visualization of water flow to investigate the effects of inlet/outlet configurations on flow boiling instabilities in parallel trapezoidal cross section etched in silicone substrate. They found that the heat transfer coefficient increases with vapor quality in the subcooled region (quality \(\chi < 0\)) due to a transition between partially to fully developed nucleate boiling and decreases with increasing vapor quality in the saturated boiling region (\(\chi > 0\)). Similar conclusion was found by Cortina Díaz and Schmidt [4] when investigating flow boiling heat transfer of water and ethanol in a single rectangular microchannel. Oscillations in wall temperature were reported by the authors to decrease for water as quality increases. The same was not observed for ethanol, as oscillations become more pronounced for increasing vapor quality. Yen et al. [5] studied the convective boiling in transparent single horizontal circular and square microchannels, combining visualization with temperature measurements. They found semi-periodic variations in the flow patterns due to the limited space for bubble growth in the radial direction that was responsible for large fluctuations on pressure.
The work addressed in the present paper combines pressure and temperature measurements with high-speed visualization measurements, to evaluate the behavior of methanol and ethanol flow boiling in microchannels. The role of imposed heat flux, fluid properties and inlet mass velocity on the variation of two-phase heat transfer coefficient and flow behavior are under investigation.

2. Experimental methodology
The experimental setup used in [6] was used in this experiment and is schematically shown in Figure 1. Sub-cooled liquid \( (T_{f,in} < T_{f,sat}) \) is supplied at constant flow rate by a New Era® 1010 syringe pump (uncertainty \( u_V = 1\% \)) to a horizontally arranged circular borosilicate glass channel from Vitrocom® with a diameter of \( D_h=542 \mu m (u_{Dh}= 10\%) \), 100mm long and 100\( \mu m \) wall thickness. The measurement section starts at 20mm from the tube entrance, where the flow is fully developed. It consists of a 60mm length externally coated with a thin transparent film of Indium Oxide deposited by radio frequency plasma enhanced reactive thermal evaporation (rf-PERTE) at low substrate temperature (<100ºC) with relatively high values of visible transmittance (81%).

The pressure drop along the channel is measured with an uncertainty \( u_p < 0.5\% \) with two pressure transducers ECO1 from Wika® (range 0-4bar) at stagnation chambers located at the inlet and outlet of the channel, respectively. The measured pressure drop thus includes the localized pressure drops at the inlet and exit of the microchannel. However, these are found to be negligible compared to the total pressure drop and, therefore, will be discard in our analysis. Also, the pressure transducer at the inlet measures the pressure of the liquid phase, whereas the one placed at the outlet, where both liquid and vapor phases are present, measures the two-phase boiling. Hence the two-phase contribution should be added through either a homogeneous approach or a Lockhart-Martinelli multiplication factor [7]. However, the results shown here correspond to the exact values obtained by the pressure sensors at the inlet and outlet of the microchannel during two-phase flow boiling in kPa.

The Power-Frequency relations for each measurement were derived by discrete Fourier transform (DFT) of the complex values of the Fourier coefficients \( X(k) \), computed with a fast Fourier transform (FFT) algorithm defined by

\[
X(k) = \sum_{j=1}^{N} x(j)e^{-\frac{2\pi i}{N}(j-1)(k-1)} \tag{1}
\]

where \( k \) represents the exponential signals, and has the value \( k=1,2,\ldots,N-1 \), \( N \) is the number of data points, \( j \) is the time domain incrementing index, and has the value \( n=1,2,\ldots,N-1 \), \( x(j) \) is the value of the data points in the time domain, \( i \) indicates a complex number. The fast Fourier transform algorithm implemented with Matlab® was used to solve the FFT and obtain the frequency distribution. The

![Fig. 1 Schematics of the experimental setup](image-url)
power spectral density, a measurement of the energy at various frequencies, is computed using the complex conjugate. The dominant frequencies are identified by the magnitude of the power spectral density.

The channel is externally coated with a thin film of InOx supplied with a constant current \((u_I < 0.14\%)\) by a DC power supply (GEN150-5, from TDK-Lambda®) to provide the flow with a constant wall heat flux. The heat flux transferred to the fluid \(q_s\) is calculated from the applied electrical power, \(q_{app}\), and accounting for heat losses by natural convection, \(q_{conv,air}\) and by radiation, \(q_{rad,air}\) from the outer surface of the InOx thin film to the environment \((q_s = q_{app} - q_{conv,air} - q_{rad,air})\) as found in Silvério and Moreira [1].

The temperature of the working fluid is measured at the entrance and exit of the test section with 1mm k-type thermocouples \((u_T < 1.4\%)\), as the instantaneous temperature along the outer wall of the channel is measured with twelve 25µm k-type thermocouples \((u_T < 2\%)\), eight of which are placed in the heated test section. The temperature along the outer surface of the channel is averaged, \(T_{w,avg}\), as well as the temperature of the fluid along the channel \(T_{f,avg}\) to find the average heat transfer coefficient, \(h\), given by

\[
h = \frac{q_{s}^{*}}{T_{w,avg} - T_{f,avg}}
\]  

(2)

In order to study the influence of surface average temperature on flow instabilities, the experiments are conducted by increasing the heat flux with a constant mass flux, for six mass fluxes, four different heat fluxes and two different fluids, methanol, \(\text{CH}_3\text{OH}\) (99.8%, BDH®) and ethanol \(\text{C}_2\text{H}_5\text{OH}\) (absolute, Emparta®) (Figure 2)

![Figure 2: Heat flux transferred to the fluid, \(q_s^{*}\), as a function of the mass flux, \(G\). Open symbols represent results for methanol while closed symbols are for ethanol.](image)

The mechanisms of both temperature and pressure fluctuations are interpreted from high speed images synchronized with the acquisition of temperature and pressure obtained at 4096 frames per second during 3.16s at a distance of 55mm from the start of the heated section of the channel, where the flow is fully hydrodynamic and thermally developed. The high-speed camera used is a Vision Research Phantom® V4.2 coupled to an inverted DMIL LED Leica® microscope with Hi-Plan 10x (scale factor 0.22) and C-mount 0.55x HC lenses. The field of view is \((1.69\times0.58)\text{mm}^2\).
3. Results and discussion

The two-phase flow in channels with circular section has been studied by numerous investigators, either with horizontal and vertical orientations, as well as inclined orientations. Flow patterns are identified and the transitions between flow patterns are defined, primarily from visual observations. In Table 1 examples of images of flow patterns obtained experimentally are presented according to generally accepted definitions adapted from Collier and Thome [8] and Carey [9]. The flow is from left to right. Capillary flow, or independent droplets moving across the annular flow, is not observed in methanol flow.

| Flow regime          | \( \text{CH}_3\text{OH} \) | \( \text{C}_2\text{H}_5\text{OH} \) |
|----------------------|-----------------|-----------------|
|                      | 9.2W.cm\(^{-2}\) 227kg.m\(^{-2}\).s\(^{-1}\) | 8.8W.cm\(^{-2}\) 228kg.m\(^{-2}\).s\(^{-1}\) |
|                      | \( Bo = 0.39 \times 10^{-3} \), \( \tilde{k} \sim 0.063 \) | \( Bo = 0.47 \times 10^{-3} \), \( \tilde{k} \sim 0.065 \) |
| bubbly               | ![Image]         | ![Image]         |
| plug                 | ![Image]         | ![Image]         |
| slug                 | ![Image]         | ![Image]         |
| annular              | ![Image]         | ![Image]         |
| wavy                 | ![Image]         | ![Image]         |
| capillary            | not observed     | ![Image]         |
| thin film nucleate   | ![Image]         | ![Image]         |
| boiling              | ![Image]         | ![Image]         |
| mist                 | ![Image]         | ![Image]         |

Pressure drop and temperature across the channel are found reasonably constant with increasing heat flux for single-phase liquid flow, but increase appreciably when boiling initiates inside the microchannel and vary with time. Figure 3 evidences this behavior in averaged temperature and pressure drop data for methanol (left) and ethanol (right) for the same conditions presented in Table 1. The semi-periodic variation depicted in the figure has been inferred from high speed images to occur simultaneously with variations of the flow pattern, associated with different boiling regimes. Longer time periods with higher amplitude in both temperature and pressure drop are found for ethanol (\( \tau \sim 0.33s \)) when compared with methanol (\( \tau \sim 0.14s \)).
Fig. 3 Temporal variation of averaged wall temperature temperature (black) and pressure drop (gray) for methanol $9.2 \text{W.cm}^{-2}$, $227 \text{kg.m}^{-2}.\text{s}^{-1}$ (left) and ethanol $8.8 \text{W.cm}^{-2}$, $228 \text{kg.m}^{-2}.\text{s}^{-1}$ (right).

The percentage of the period of fluctuations during which each boiling regime occurs is shown in Figure 4 for methanol (left) and ethanol (right). For the exception of wavy flow, all flow patterns have larger ratio for ethanol flow. Also, the residence time of each flow pattern is higher, namely for bubbly and plug flow, responsible for the higher heat transfer.

The time averaged pressure drop is further analysed and plotted against the Boiling number, $Bo$, in Figure 5a. In general the results show that, for small values of $Bo$, the pressure drop decreases steeply down to a characteristic minimum associated with incipient boiling in the stable flow regime, more pronounced in the flow of methanol. This is consistent with the criterion for static instability in Zhang et al. [10]. The stable flow regime ($Bo < 0.13 \times 10^{-3}$ or $q \cdot J / G < 0.17 \text{kJ.kg}^{-1}$ for methanol and $Bo < 0.17 \times 10^{-3}$ or $q \cdot J / G < 0.20 \text{kJ.kg}^{-1}$ for ethanol) characterized by small oscillations of pressure drop, includes single-phase flow and incipient boiling when small isolated bubbles flow inside microchannels in a pattern which can be described as the bubbly flow regime. Additional increase in $Bo$ results in high oscillations, characteristic of slow transitions between small slugs and elongated plugs that fill the entire channel. The posterior decrease of magnitude of flow oscillations for higher $Bo$ is attributed to the lower residence time of elongated bubbles inside the microchannel. The transition between flow regimes becomes faster, hence diminishing the magnitude of oscillations. The same trends are observed for different values of wall heat flux, though with values of the pressure drop increasing with $q \cdot J$.

Fig 4 Ratio of flow pattern in a period oscillation for methanol $9.2 \text{W.cm}^{-2}$, $227 \text{kg.m}^{-2}.\text{s}^{-1}$ (left) and ethanol $8.8 \text{W.cm}^{-2}$, $228 \text{kg.m}^{-2}.\text{s}^{-1}$ (right).

Fast Fourier Transform (FFT) analysis was performed on pressure drop data to obtain the frequency distribution (Fig. 5b). For stable flow conditions, no significant differences in pressure and
temperature oscillations are observed. For unstable conditions, the pressure drop has dominant frequency of phase alternation that varies with the relation $q' \sqrt{G}$ for both fluids. The decrease in the period of phase alternations results in a higher frequency of pressure and temperature oscillations for increasing $q' \sqrt{G}$, meaning that the cycle - formation, growth and dryout of bubbles - becomes more rapid and more frequent. As the dryout occurs, the channel is clear for new liquid refill, giving rise to a new cycle.

**Fig 5**  
(a) time-averaged pressure drop, (b) FFT dominant frequency and (c) FFT power spectral density as a function of the Boiling Number for methanol (left) and ethanol (right)
Analysing the power spectral density of the FFT applied to the pressure drop, presented in Figure 5c, for conditions close of those for the incipience of boiling, oscillations become more pronounced, progressively decreasing for higher $q_s/G$. The high amplitude, low dominant frequency oscillations in the signals of both temperature and pressure are characteristic of cycles as seen in Figure 3.

Averaged heat transfer coefficients are obtained from the time averaged outer wall temperatures collected over 20s. For the conditions presented in Table 1, $\bar{\varphi}$ ~0.06, heat transfer coefficients have larger values for ethanol, $\bar{h} = 6682\text{W.m}^{-2}\text{.K}^{-1}$, than for methanol, $\bar{h} = 2195\text{W.m}^{-2}\text{.K}^{-1}$. As seen, the ratio of flow patterns in Figure 4 clearly shows the difference between the residence times of each flow pattern in one period. For ethanol, longer time periods are recorded ($\tau$ ~0.33s), with larger flow pattern ratios for one period, with exception for wavy flow. This is mainly attributed to the difference in thermophysical properties for both fluids.

It is worth noting that the increase in the heat transfer is coincident with the lower pressure drops, but higher magnitude of pressure oscillations. The equilibrium between the applied heat and mass flux is preponderant in the efficiency of the heat removal and the consequent oscillations generated in both pressure and temperature measurements.

The experimental values where compared with correlations available in the literature and showed good agreement with the predictions of the Haynes and Fletcher [11] correlation (Figure 7).
4. Summary
Experiments were performed in a circular section borosilicate glass channel with $D_h=542\mu\text{m}$ with uniform, constant heat flux, cooled by a constant fluid flow (methanol or ethanol) at atmospheric pressure. Time-averaged measurements were obtained of the inlet and outlet pressures and external wall temperature at 12 locations, with synchronized high speed video recordings of flow events.

Depending on operating conditions, two types of behavior can be observed; a steady state characterized by fluctuations in pressure drop with low amplitude and a multiphase flow in non-stationary regime, without characteristic frequency or with higher amplitude. Liquid flow - phase change - vapor flow cycles are in the basis of high amplitude and low frequency oscillations for low $q_s/G$. With increasing $q_s/G$, the progressive change to low amplitude-high oscillation frequencies is observed. At low heat fluxes, the bubbles nucleate near the walls, grow downstream and leave the channel. For higher heat fluxes, instabilities are observed. Subsequently to the onset of boiling, bubbles rapidly coalesce or grow into oblong bubbles typical of slug flow and extend to occupy the cross section of the channel. The increase in heat flux results in subsequent increase in frequency and decrease in amplitude of pressure and temperature oscillations, phenomena resultant of the quasi-periodical change of bubbly to slug to annular flow, dryout, rewet and refilling of the channel. Increasing even further the heat flux, explosive bubble behavior is observed, usually followed by the channel complete dryout.

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