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# Numerical and experimental investigation on the effects of diameter and length on high mass flux subcooled flow boiling in horizontal microtubes

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High mass flux subcooled flow boiling was investigated both numerically and experimentally in horizontal microtubes. Microtubes with inner diameters of ~600 and ~900 μm, and outer diameters of ~900 and ~1100 μm, and heated lengths of 6 and 12 cm were tested in order to investigate the effects of diameter and heated length on subcooled flow boiling at high mass and heat fluxes. In the experimental part, microtubes made of stainless steel were used, and deionized water was as the working fluid. In the numerical part, the two-phase Eulerian method was adopted using the finite volume approach. Numerical results showed a good agreement with experimental results. Heat transfer coefficients were higher in the microtubes with smaller diameters, while longer microtubes resulted in higher heat transfer coefficient. The results indicated that smaller pressure drops were achieved for shorter microchannels along with higher heat fluxes. Local heat transfer coefficients were presented along the microtube to provide an understanding on local flow boiling characteristics. As the vapor quality and void fraction increased, higher heat transfer coefficients were obtained. With the increase in mass flux, an enhancement in boiling heat transfer was observed implying convective heat transfer effects on flow boiling along with nucleate boiling. Furthermore, heat transfer coefficient increased with decreasing inlet subcooling.

## 1. Introduction

Micro and nano scale heat transfer has attracted much interest of the heat transfer community because of its potential in its use in various engineering fields such as rapid solidification [1], microfluidic applications [2], bio MEMS (Microelectromechanical Systems) [3], thermal management [4], nano optics [5], and pool boiling [6]. With recent requirements of heat exchangers, continuous improvements in heat removal from micro scale cooling systems have been taking place. Boiling in microchannels is considered as an effective method to obtain high heat removal rates. State of art technologies [7], high mass flux flow boiling [8], numerical approaches [9], and heat transfer enhancements with surface modifications [10–12] were recently included in the literature. Low critical heat flux and flow instabilities at particularly low mass fluxes and system pressures restrict thermal performance of such systems involving phase change in micro scale. Since scaling laws are not applicable to two-phase flow and flow boiling, there exists a lack of data and information about flow boiling under subcooled boiling and high flow rate conditions in micro scale.

During the last decade, fundamental differences between micro and macro scale boiling phenomena have been reported in some studies, which include analysis of experimental data [13], Critical Heat Flux (CHF) correlations [14], two-phase pressure drop modeling [15], flow patterns [16], and flow boiling heat transfer [17]. Recent investigations were focused on developing new models and correlations for micro scale flow boiling. Small scale dimensions limit experimental studies in obtaining local heat transfer and flow characteristics in micro scale. Mechanistic modeling is considered as a powerful tool to assess local thermal and hydrodynamic characteristics and can be utilized for design and optimization of micro devices [18–20].

High mass flux boiling is getting more and more popular, where instabilities become suppressed, and higher critical heat fluxes would be achieved. Increasing flow rate changes boiling mechanism from saturated boiling to subcooled low quality boiling inside micro systems. Experimental studies on heat transfer characteristics of low quality flow boiling are already present in the literature [21–30]. Due to the importance of high mass and heat flux flow boiling studies in micro scale, the availability of reliable results and models related to local heat transfer coefficient and pressure drop are vital for researchers and engineers.

One of the first experimental investigations in subcooled flow boiling was conducted by Pierre and Bankoff [21]. They measured

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## Nomenclature

| | |
|---|---|
| $A$ | area (m$^2$), constant number (–) |
| $d,\ D$ | diameter (m) |
| $C$ | constant number (–), dimensionless coefficient |
| $c_p$ | specific heat capacity (J kg$^{-1}$ K$^{-1}$) |
| $f$ | friction factor (–), frequency (s$^{-1}$), variable (units vary) |
| $F$ | body force (N m$^{-3}$), surface factor (–) |
| $G$ | mass flux (kg m$^{-2}$ s$^{-1}$), term in the turbulent kinetic energy equation (kg m$^{-1}$ s$^{-3}$) |
| $h$ | heat transfer coefficient (W m$^{-2}$ K$^{-1}$), specific enthalpy (J kg$^{-1}$) |
| $H$ | enthalpy (J) |
| $h_{fg}$ | latent heat of vaporization (kJ kg$^{-1}$) |
| $k$ | thermal conductivity (W m$^{-1}$ K$^{-1}$), turbulence kinetic energy (J kg$^{-1}$) |
| $K$ | projected area of bubbles (m$^2$) |
| $L$ | length (m), latent heat per unit mass (J kg$^{-1}$) |
| $\dot{m}$ | mass flow rate (kg s$^{-1}$), transferred mass per unit volume (kg m$^{-3}$ s$^{-1}$) |
| $M_t$ | number of data points |
| MAE | mean absolute error |
| $N_a$ | active nucleation site density (–) |
| $Nu$ | Nusselt number (–) |
| $Pr$ | Prandtl number (–) |
| $P$ | pressure (Pa), electrical power (W) |
| $Q,\ q$ | heat transfer rate (W), $q$th phase |
| $q'$ | volumetric heat generation (W m$^{-3}$) |
| $\dot{Q},\ \dot{q}$ | heat flux (W m$^{-2}$) |
| $r$ | radius (m) |
| $R$ | interaction force (N m$^{-3}$) |
| $Re$ | Reynolds number (–) |
| $S$ | source term (units vary), bubble induced |
| $St$ | Stanton number (–) |
| $T$ | temperature (K) |
| $t$ | time (s) |
| $u,\ v,\ w$ | velocity components (m s$^{-1}$) |
| $U$ | experimental parameter |
| $V$ | volume (m$^3$) |
| $\vec{V}$ | velocity vector (m s$^{-1}$), interface velocity (m s$^{-1}$) |
| $x$ | location along the microtube (m), vapor quality (–) |
| $y$ | Variable (units vary), distance (m) |

*Greek*

| | |
|---|---|
| $\alpha$ | volume fraction (–) |
| $\beta$ | angle (°), contact angle (°) |
| $\Delta$ | difference (e.g. $\Delta P$ is pressure drop) |
| $\varepsilon$ | turbulence dissipation rate (J Kg$^{-1}$ s$^{-1}$), surface porosity |
| $\kappa a$ | Von Karman constant (–) |
| $\tau$ | shear tensor (Pa) |
| $\lambda$ | bulk viscosity (kg m$^{-1}$ s$^{-1}$) |
| $\mu$ | shear viscosity (kg m$^{-1}$ s$^{-1}$) |
| $\nu$ | specific volume (m$^3$ kg$^{-1}$) |
| $\rho$ | density (kg m$^{-3}$) |
| $\sigma$ | surface tension (N m$^{-1}$) |
| $\Omega$ | portion of wall that is that is covered by vapor (–) |
| $\nabla$ | Nabla (vector differential operator) |

*Subscripts*

| | |
|---|---|
| $b$ | bubble |
| $c$ | cross sectional |
| $D$ | drag coefficient |
| $E$ | evaporation heat flux |
| $eff$ | effective |
| $f$ | fluid |
| $FC$ | forced convection |
| $g$ | gas |
| $h$ | heated |
| $i$ | inner, inlet, interfacial |
| $k$ | related to turbulence kinetic |
| $l$ | liquid, lift coefficient, liquid convective heat flux |
| $lift$ | lift force |
| $LO$ | entire flow as liquid |
| $loss$ | loss |
| $ls$ | liquid side |
| $m$ | mean, mixture |
| $o$ | outer, outlet |
| $ONB$ | onset of nucleate boiling |
| $p$ | wall-adjacent cell |
| $pq$ | between phase $p$ and $q$ |
| $Q$ | quenching heat flux |
| $sp$ | single phase |
| $sat,\ s$ | saturation, inner surface |
| $SB$ | subcooled |
| $t$ | turbulence |
| $tc$ | fraction that is in contact with the liquid |
| $td$ | turbulence dissipation |
| $tp$ | two-phase |
| $\mathrm{v}$ | vapor |
| $vs$ | vapor side |
| $vm$ | virtual mass |
| $vw$ | vapor and close to wall |
| $vl$ | wall lubrication |
| $w$ | wall |
| $x$ | location, vapor quality |
| $\varepsilon$ | related to turbulence dissipation |
| $v$ | related to bubble shear |

void fraction at different cross sections in a vertical rectangular channel. Their experiments showed no evidence of void peak near the walls. This is important because implementing the wall lubrication force for adiabatic two-phase flow resulted in the void fraction peak near the wall boundaries. This was proven to be advantageous for air/water two-phase flows as well as for water flow boiling [31–33].

Bartel and Lee et al. [25,27] studied radial flow characteristics in vertical tubes. They observed that the liquid velocity profiles generally deviated from the profiles of single-phase flow due to the non-uniform void fraction and vapor velocity distributions. Lie and Lin [34] experimentally investigated channel size effects on subcooled flow boiling heat transfer of refrigerant R-134a in a horizontal narrow annular duct. They found that subcooled flow boiling heat transfer coefficient increased with a reduction in the gap size, but decreased with an increase in the inlet liquid subcooling for subcooled boiling of R-134a. Wang and Cheng [30] investigated subcooled flow boiling and microbubble emission boiling (MEB) phenomena of deionized water in a partially heated Pyrex glass microchannel. Their results indicated that a vapor bubble in contact with a highly subcooled liquid could break up into many microbubbles due to condensation and instability of bubble interface between vapor and subcooled water.

Martín-Callizo et al. [35] investigated subcooled flow boiling heat transfer of refrigerant R-134a in vertical cylindrical micro- and mini-tubes. They concluded that an increase in mass flux lead to early subcooled boiling, which resulted in an increase in heat transfer coefficient, whereas an increase in mass flux only resulted