**References For Flow Boiling in Microchannels**

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(<http://www.sciencedirect.com/science/article/pii/S0301932211001662>)  
Abstract: Experiments were conducted to analyze flow boiling characteristics of water in a single brass microchannel of 25&#xa0;mm length, 201&#xa0;μm width, and 266&#xa0;μm depth. Different heat flux conditions were tested for each of two different mass flow rates over three different values of inlet fluid temperature. Temporal and spatial surface temperature profiles were analyzed to show the relative effect of axial heat conduction on temperature rise along the channel length and the effect of flow regime transition on local surface temperature oscillation. Vapor bubble growth rate increased with increasing wall superheat. The slower a bubble grew, the further it was carried downstream by the moving liquid. Bubble growth was suppressed for increased mass flux while the vapor bubble was less than the channel diameter. The pressure spike of an elongating vapor bubble was shown to suppress the growth of a neighboring bubble by more than 50% of its volume. An upstream progression of the Onset of Bubble Elongation (OBE) was observed that began at the channel exit and progressed upstream. The effects of conjugate heat transfer were observed when different flow regime transitions produced different rates of progression for the elongation sequence. Instability was observed at lower heat fluxes for this single channel experiment than for similar studies with multiple channels.  
Keywords: Flow boiling; Microchannel; Flow regime transition; Onset of Bubble Elongation (OBE); Instability; Bubble growth

2. Jacqueline Barber, D. Brutin, K. Sefiane, J.L. Gardarein, L. Tadrist, Unsteady-state fluctuations analysis during bubble growth in a “rectangular” microchannel, International Journal of Heat and Mass Transfer, Volume 54, Issues 23-24, November 2011, Pages 4784-4795, ISSN 0017-9310, 10.1016/j.ijheatmasstransfer.2011.06.026.  
(<http://www.sciencedirect.com/science/article/pii/S0017931011003486>)  
Abstract: Boiling in microchannels shows great potential for cooling systems and compact heat removal applications. However for confidence in this cooling technique, it is essential that any excursions from typical flow boiling are understood and predicted. Confined bubble growth can cause pressure fluctuations which interfere with bubble nucleation and growth and can also lead to flow reversal and instances of temperature excursions. Boiling experiments are performed in a single rectangular microchannel of hydraulic diameter 771&#xa0;μm, using n-Pentane as the working fluid. A heating technique was incorporated on the exterior walls of the microchannel; a transparent, metallic, conductive deposit, which allows simultaneous uniform heating and visualisation to be achieved. In conjunction with obtaining high-speed imaging, an infrared camera is used to record the temperature profile at the microchannel wall, and sensitive pressure sensors are used to record the pressure drop across the microchannel over time. During flow boiling in the microchannel periodic and non-periodic fluctuations in both the channel pressure drop and channel temperature profile over time are apparent. In this paper we provide a full analysis of the temperature measurements and pressure data obtained during the growth of a vapour bubble in the microchannel. An augmentation of the heat transfer coefficient of over 216% has been achieved during periodic two-phase flow boiling in the microchannel. However overpressure (over 410% increase) in the microchannel occurs at corresponding instances to the heat transfer enhancement. The two time steps during the periodic bubble dynamics, namely the bubble expansion time period and the waiting time period in-between the bubble expansion fluctuations, are also investigated and modelled. It was determined that both the bubble dynamics and the channel wall heating time period are responsible for the pressure and temperature fluctuation time periods observed.  
Keywords: Flow boiling instabilities; Experimental; Microchannel; Pressure fluctuations; Infrared measurements

3. A. Mukherjee, S.G. Kandlikar, The effect of inlet constriction on bubble growth during flow boiling in microchannels, International Journal of Heat and Mass Transfer, Volume 52, Issues 21-22, October 2009, Pages 5204-5212, ISSN 0017-9310, 10.1016/j.ijheatmasstransfer.2009.04.025.  
(<http://www.sciencedirect.com/science/article/pii/S0017931009002981>)  
Abstract: Flow boiling through microchannels is characterized by nucleation of vapor bubbles on the channel walls. In parallel microchannels connected through a common header, formation of vapor bubbles often results in flow mal-distribution that leads to reversed flow in certain channels. One way of eliminating the reversed flow is to incorporate flow restrictions at the channel inlet. In the present study, a nucleating vapor bubble placed near the restricted end of a single microchannel is numerically simulated. Placing restrictions at channel inlet increased the incoming liquid velocity for the same flow rate that prevented explosive bubble growth and reversed flow. It is proposed that channels with increasing cross-sectional area may be used to promote unidirectional growth of the vapor plugs and prevent reversed flow.  
Keywords: Flow boiling; Bubble; Microchannel

4. Jacqueline Barber, David Brutin, Khellil Sefiane, Lounes Tadrist, Bubble confinement in flow boiling of FC-72 in a “rectangular” microchannel of high aspect ratio, Experimental Thermal and Fluid Science, Volume 34, Issue 8, November 2010, Pages 1375-1388, ISSN 0894-1777, 10.1016/j.expthermflusci.2010.06.011.  
(<http://www.sciencedirect.com/science/article/pii/S0894177710001238>)  
Abstract: Boiling in microchannels remains elusive due to the lack of full understanding of the mechanisms involved. A powerful tool in achieving better comprehension of the mechanisms is detailed imaging and analysis of the two-phase flow at a fundamental level. Boiling is induced in a single microchannel geometry (hydraulic diameter 727&#xa0;μm), using a refrigerant FC-72, to investigate the effect of channel confinement on bubble growth. A transparent, metallic, conductive deposit has been developed on the exterior of the rectangular microchannel, allowing simultaneous uniform heating and visualisation to be achieved. The data presented in this paper is for a particular case with a uniform heat flux applied to the microchannel and inlet liquid mass flowrate held constant. In conjunction with obtaining high-speed images and videos, sensitive pressure sensors are used to record the pressure drop across the microchannel over time. Bubble nucleation and growth, as well as periodic slug flow, are observed in the microchannel test section. The periodic pressure fluctuations evidenced across the microchannel are caused by the bubble dynamics and instances of vapour blockage during confined bubble growth in the channel. The variation of the aspect ratio and the interface velocities of the growing vapour slug over time, are all observed and analysed. We follow visually the nucleation and subsequent both ‘free’ and ‘confined’ growth of a vapour bubble during flow boiling of FC-72 in a microchannel, from analysis of our results, images and video sequences with the corresponding pressure data obtained.  
Keywords: Confined bubble; Flow boiling; Experimental; High aspect ratio microchannel; Two-phase flow instabilities

5. A. Mukherjee, Contribution of thin-film evaporation during flow boiling inside microchannels, International Journal of Thermal Sciences, Volume 48, Issue 11, November 2009, Pages 2025-2035, ISSN 1290-0729, 10.1016/j.ijthermalsci.2009.03.006.  
(<http://www.sciencedirect.com/science/article/pii/S1290072909000763>)  
Abstract: Flow boiling through microchannels is characterized by nucleation and growth of vapor bubbles that fill the entire channel cross-sectional area. As the bubbles nucleate and grow inside the microchannel, a thin film of liquid or a microlayer gets trapped between the bubbles and the channel walls. The heat transfer mechanism present at the channel walls during flow boiling is studied numerically. It is then compared to the heat transfer mechanisms present during nucleate pool boiling and in a moving evaporating meniscus. Increasing contact angle improved wall heat transfer in case of nucleate boiling and moving evaporating meniscus but not in the case of flow boiling inside a microchannel. It is shown that the thermal and the flow fields present inside the microchannel around a bubble are fundamentally different as compared to nucleate pool boiling or in a moving evaporating meniscus. It is explained why thin-film evaporation is the dominant heat transfer mechanism and is responsible for creating an apparent nucleate boiling effect inside a microchannel.  
Keywords: Bubble; Flow boiling; Thin-film evaporation

6. Jacqueline Barber, Khellil Sefiane, David Brutin, Lounes Tadrist, Hydrodynamics and heat transfer during flow boiling instabilities in a single microchannel, Applied Thermal Engineering, Volume 29, Issue 7, May 2009, Pages 1299-1308, ISSN 1359-4311, 10.1016/j.applthermaleng.2008.07.004.  
(<http://www.sciencedirect.com/science/article/pii/S1359431108003025>)  
Abstract: Boiling in microchannels is widely considered as one of the front runners in process intensification heat removal. Flow boiling heat transfer in microchannel geometry and the associated flow instabilities are not well understood, further research is necessary into the flow instabilities adverse effect on heat transfer.  
  
Boiling is induced in microchannel geometry (hydraulic diameter 727&#xa0;μm) to investigate several flow instabilities. A transparent, metallic, conductive deposit has been developed on the exterior of rectangular microchannels, allowing simultaneous heating and visualisation.  
  
Presented in this paper is data for a particular case with a uniform heat flux of 4.26&#xa0;kW/m2 applied to the microchannel and inlet liquid mass flowrate, held constant at 1.13&#xa0;×&#xa0;10−5&#xa0;kg/s. In conjunction with obtaining high-speed images, a sensitive infrared camera is used to record the temperature profiles on the exterior wall of the microchannel, and a data acquisition system is used to record the pressure fluctuations over time. Various phenomena are apparent during the flow instabilities; these can be characterised into timescales occurring at 100’s seconds, 10’s seconds, several seconds and finally milliseconds. Correlation of pressure oscillations with temperature fluctuations as a function of the heat flux applied to the microchannel is possible.  
  
From analysis of our results, images and video sequences with the corresponding physical data obtained, it is possible to follow simultaneously particular flow, pressure and temperature conditions leading to nucleate boiling, flow instabilities and transition regimes during flow boiling in a microchannel. The investigation allowed us to quantify and characterise the timescales of various observed instabilities during flow boiling in a microchannel. High speed imaging revealed some of the controlling physical mechanisms responsible for the observed instabilities.  
Keywords: Boiling; Microchannels; Visualisation; Flow boiling instabilities; Heat transfer

7. Jae Yong Lee, Moo-Hwan Kim, Massoud Kaviany, Sang Young Son, Bubble nucleation in microchannel flow boiling using single artificial cavity, International Journal of Heat and Mass Transfer, Volume 54, Issues 25-26, December 2011, Pages 5139-5148, ISSN 0017-9310, 10.1016/j.ijheatmasstransfer.2011.08.042.  
(<http://www.sciencedirect.com/science/article/pii/S001793101100487X>)  
Abstract: Microchannel (Dh&#xa0;⩽&#xa0;100&#xa0;μm) water flow boiling under low mass flux (G&#xa0;⩽&#xa0;138.9&#xa0;kg/(m2&#xa0;s)) is presented to investigate the local phenomena of flow regime development and nucleating bubble growth rate. During horizontal flow, onset of nucleation, flow regime, and isolated single bubble growth and detachment from a single artificial cavity were observed and analyzed by microscopic high-speed visualization under various flow rates and wall superheat conditions. Results showed that while the predictions pertaining to inception by bubble nucleation theory match well, bubble growth rate, detachment and expansion in a microchannel differs dramatically from a macrochannel.  
Keywords: Visualization; Flow boiling; Bubble incipience; Bubble detachment; Bubble growth rate; Microchannel

8. Satish G. Kandlikar, Scale effects on flow boiling heat transfer in microchannels: A fundamental perspective, International Journal of Thermal Sciences, Volume 49, Issue 7, July 2010, Pages 1073-1085, ISSN 1290-0729, 10.1016/j.ijthermalsci.2009.12.016.  
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Abstract: Flow boiling in microchannels has received considerable attention from researchers worldwide in the last decade. A scaling analysis is presented to identify the relative effects of different forces on the boiling process at microscale. Based on this scaling analysis, the flow pattern transitions and stability for flow boiling of water and FC-77 are evaluated. From the insight gained through the careful visualization and thermal measurements by previous investigators, similarities between heat transfer around a nucleating bubble in pool boiling and in the elongated bubble/slug flow pattern in flow boiling are brought out. The roles of microlayer evaporation and transient conduction/microconvection are discussed. Furthermore, it is pointed out that the convective contribution cannot be ruled out on the basis of experimental data which shows no dependence of heat transfer coefficient on mass flow rate, since the low liquid flow rate during flow boiling in microchannels at low qualities leads to laminar flow, where heat transfer coefficient is essentially independent of the mass flow rate. Specific suggestions for future research to enhance the boiling heat transfer in microchannels are also provided.  
Keywords: Flow boiling; Boiling; Microchannels; Mechanisms; Scale; Scaling

9. Y.Q. Zu, Y.Y. Yan, S. Gedupudi, T.G. Karayiannis, D.B.R. Kenning, Confined bubble growth during flow boiling in a mini-/micro-channel of rectangular cross-section part II: Approximate 3-D numerical simulation, International Journal of Thermal Sciences, Volume 50, Issue 3, March 2011, Pages 267-273, ISSN 1290-0729, 10.1016/j.ijthermalsci.2010.09.004.  
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Abstract: This Part II of the paper reports the three-dimensional (3-D) numerical modelling on bubbly flow in confined mini-/micro-channels using the volume of fluid (VOF) method in commercial CFD code FLUENT. The numerical simulation aims to provide detailed information of the fields of velocity, temperature and pressure so as to further understand the effect of bubble growth on the flow field and heat transfer from the channel wall.  
  
In Part I, the experiment of flow boiling in a mini-/micro-channel of rectangular cross-section was carried out and a simple one-dimensional (1-D) model for the interaction of the pressure fluctuations during the growth of a confined bubble with various kinds of upstream compressibility was developed as an aid to the rational specification of inlet resistance. In Part II, the experimental observers and the theoretical model developed in Part I are tested by performing the 3-D numerical simulation of bubble growth from nucleation to full confinement. The simulation involves some approximations based on a concept of pseudo-boiling to avoid the well-known difficulties of modelling bubble generation and growth. During the simulation, the volumetric growth rate of the bubble is defined to match the experimental observations. At small times prior to bubble detachment, a vapour flow was injected through a small hole in the wall to simulate nucleation. Following partial confinement, vapour injection was stopped and growth was driven by the generation of vapour at a defined rate at the contact area between the bubble and the superheated wall. The 3-D simulation reproduces the experimental observations of the distorted profile of the bubble and its trajectory during partially confined growth and provides information about flow and heat transfer in the bulk liquid outside the thin film region. The 3-D and 1-D predictions of the development of axial pressure distributions during partially and fully confined growth are in satisfactory agreement.  
Keywords: Confined bubble; CFD; Flow boiling; Rectangular micro-channel

10. Gian Piero Celata, Sujoy Kumar Saha, Giuseppe Zummo, Denam Dossevi, Heat transfer characteristics of flow boiling in a single horizontal microchannel, International Journal of Thermal Sciences, Volume 49, Issue 7, July 2010, Pages 1086-1094, ISSN 1290-0729, 10.1016/j.ijthermalsci.2010.01.019.  
(<http://www.sciencedirect.com/science/article/pii/S129007291000044X>)  
Abstract: Heat transfer characteristics of subcooled flow boiling of FC-72 in a single horizontal circular cross-section microchannel (480 μm i.d., 800 μm o.d., 102 mm long) are presented. Different flow patterns, both in the stable and unstable flow boiling regimes, have been captured using high speed video camera. Data in small, medium, high and very high heat flux cases under small, medium and high mass flux has been presented. Convective heat transfer coefficients in each flow boiling situation have been calculated and presented. Stable flow boiling with alternating bubbly/slug flow, slug/annular flow and annular/mist flow have been observed for heat flux of 150 kW/m2 or higher and mass flux of 1500 kg/m2 s or higher. Back and forth oscillations with flow instabilities have been observed in cases of lower heat and mass fluxes. However, no complete reverse flow in upstream direction has been observed.  
Keywords: Heat transfer; Subcooled flow boiling; Microchannel; Instability; Flow pattern

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Abstract: The heat transfer coefficients of the evaporative water flow in mini/microchannels are studied experimentally to explore the novel heat dissipation for high power electronics. Two sets of parallel channels which are 61 channels with hydraulic diameter of 0.293&#xa0;mm and 20 channels with hydraulic diameter of 1.2&#xa0;mm are investigated respectively. The inlet and outlet temperatures of fluids, and the temperatures beneath the channels are measured to calculate the heat dissipation of the evaporative water in channels. The experiments are carried out with the mass flow rates range from 11.09&#xa0;kg/(m2&#xa0;s) to 44.36&#xa0;kg/(m2&#xa0;s) for minichannels and 49.59&#xa0;kg/(m2&#xa0;s) to 198.37&#xa0;kg/(m2&#xa0;s) for microchannels. The effective heat flux range from 5&#xa0;W/cm2 to 50&#xa0;W/cm2, and the resulted outlet vapor qualities range from 0 to 0.8. The relations of the heat transfer coefficient with heat flux and vapor quality are analyzed according to the results. The experimental heat transfer coefficients are compared with the prediction of latest developed correlations. A new correlation takes the effect of Bond number is proposed, and be verified that it is effective to predict the heat transfer coefficient of both minichannels and microchannels in a large range of vapor qualities.

Keywords: Minichannel; Microchannels; Evaporation flow; Heat transfer coefficient; Correlations; Experimental study

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Abstract: This study provides an experimental investigation on forced convective heat transfer performance of water flowing through six microtubes with inner diameters ranging from 123 to 962&#xa0;μm. A non-contacted liquid crystal thermography (LCT) temperature measurement method that proposed by Lin and Yang [T.-Y. Lin, C.-Y. Yang, An experimental investigation on forced convection heat transfer performance in microtubes by the method of liquid crystal thermography, International Journal of Heat and Mass Transfer (2007), doi:10.1016/j.ijheatmasstransfer.2007.03.038] was used in this study to measure the surface temperature of microtubes. The test results show that the conventional heat transfer correlations for laminar and turbulent flow can be well applied for predicting the fully developed heat transfer performance in microtubes. The transition occurs at Reynolds number from 2300 to 3000. This is also the same range as that for conventional tubes. There is no significant size effect for water flow in tubes within this diameter range. The laminar thermal entrance length for microtubes is longer than that estimated by the conventional correlation. The developing Nusselt numbers for 962&#xa0;μm tube agree well with those predicted by the Shah and Bhatti [R.K. Shah, M.S. Bhatti, Laminar convective heat transfer in ducts, in: S. Kakac, R.K. Shah, W. Aung, (Eds.), Handbook of Single-Phase Convective Heat Transfer, Willy, New York, 1987] correlations. However, as the tube size decreases, the discrepancy between the test results and the predicting value increases.

Keywords: Forced convective heat transfer; Microtubes; Liquid crystal thermography (LCT); Thermally developing heat transfer

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Abstract: The numerical modeling of the conjugate heat transfer and fluid flow of Al2O3/water nanofluid through the microchannel heat sink is presented in the paper. The laminar flow regime was considered along with viscous dissipation effect. The microchannel heat sink with square microchannels and Dh&#xa0;=&#xa0;50&#xa0;μm is considered. The heat flux was fixed to q&#xa0;=&#xa0;35&#xa0;W/m2 with heating and cooling cases. The water based Al2O3 nanofluid was encountered with various volume concentrations of Al2O3 particles ϕ = 1 – 9 % and three diameters of the particle dp&#xa0;=&#xa0;13, 28 and 47&#xa0;nm. The analysis is performed on the results obtained for the local heat transfer coefficients based on a fixed pumping power. The results reveal a different local heat transfer behavior compared to the analysis made on a basis of the constant Re.

Keywords: Microchannels; Nanofluid; Viscous heating; Heat transfer coefficient

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(http://www.sciencedirect.com/science/article/pii/S0017931006006375)

Abstract: The present study explores experimentally the two-phase flow instability in a microchannel heat sink with 15 parallel microchannels. The hydraulic diameter for each channel is 86.3&#xa0;μm. Flow boiling in the present microchannel heat sink demonstrates significantly different two-phase flow patterns under stable or unstable conditions. For the stable cases bubble nucleation, slug flow and slug or annular flows appear sequentially in the flow direction. On the other hand, forward or reversed slug/annular flows appear alternatively in every channel. Moreover, the length of bubble slug may oscillate for unstable cases with reversed flow demonstrating the suppressing effect of pressure field for bubble growth. It is found that the magnitude of pressure drop oscillations may be used as an index for the appearance of reversed flow. A stability map on the plane of inlet subcooling number versus phase change number is established. A very narrow region for stable two-phase flow or mild two-phase flow oscillations is present near the line of zero exit quality.

Keywords: Microchannel; Flow boiling; Two-phase flow; Two-phase flow instability

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Abstract: A simultaneous visualization and measurement study have been carried out to investigate flow boiling instabilities of water in microchannels at various heat fluxes and mass fluxes. Two separate flow boiling experiments were conducted in eight parallel silicon microchannels (with flow interaction from neighboring channels at headers) and in a single microchannel (without flow interaction), respectively. These microchannels, at a length of 30&#xa0;mm, had an identical trapezoidal cross-section with a hydraulic diameter of 186&#xa0;μm. At a given heat flux and inlet water temperature, it was found that stable and unstable flow boiling regimes existed, depending on the mass flux. A flow boiling map, in terms of heat flux vs mass flux, showing stable flow boiling regime and unstable flow boiling regime is presented for parallel microchannels as well as for a single microchannel, respectively, at an inlet water temperature of 35&#xa0;°C. In the stable flow boiling regime, isolated bubbles were generated and were pushed away by the incoming subcooled liquid. Two unstable flow boiling regimes, with long-period oscillation (more than 1&#xa0;s) and short-period oscillation (less than 0.1&#xa0;s) in temperature and pressure, were identified. The former was due to the expansion of vapor bubble from downstream while the latter was owing to the flow pattern transition from annular to mist flow. A comparison of results of flow boiling in parallel microchannels and in a single microchannel shows that flow interaction effects from neighboring channels at the headers are significant.

Keywords: Boiling instability; Heat transfer; Microchannels; Instability; Reversed flow

16. Fabian Krause, Sven Schüttenberg, & Udo Fritsching. (2010). Modelling and simulation of flow boiling heat transfer. International Journal of Numerical Methods for Heat & Fluid Flow, 20(3), 312-331.

Abstract : The purpose of this paper is to describe the development and application of a numerical model for analysis of flow boiling phenomena and heat transfer. For flow boiling processes, the fluid and vapour flow regimes in connection with the conjugate heat and mass transfer problem for specimen quenching through the entire boiling curve is modelled. Vaporisation and recondensation, the vapour fraction distribution and vapour movement with respect to the liquid are considered in the calculation of the two-phase flow and heat transfer process. The derived flow boiling model is based on a mixture model and bubble crowding model approach for two-phase flow. In addition to the conventional mixture model formulation, here special model implementations have been incorporated that describe: the vapour formation at the superheated solid-liquid interface, the recondensation process of vapour at the subcooled vapour-liquid interface, the mass transfer rate in the different boiling phases and the microconvection effect in the nucleate boiling phase resulting from bubble growth and detachment. The model prediction results are compared with experimental data for quenching of a circular cylinder, showing good agreement in boiling state and heat transfer coefficient distribution. Simulation and experiments lead to a better understanding of the interaction of incident flow in the boiling state and the resulting heat transfer. Fluid temperatures in the range of 300-353 K and specimen wall temperatures up to 1,000 K are considered. Flow boiling is an efficient heat transfer process occurring in several technical applications. Application background of the model development is in quenching of complex metallic specimen geometries in liquids subject to fast changing heat fluxes. A general model for the complex two-phase boiling heat transfer at high wall temperatures and fast flow conditions that can be used in engineering applications does not yet exist. The results provide detailed information describing the non-uniform phase change during the complete quenching process from film boiling to pure convection.