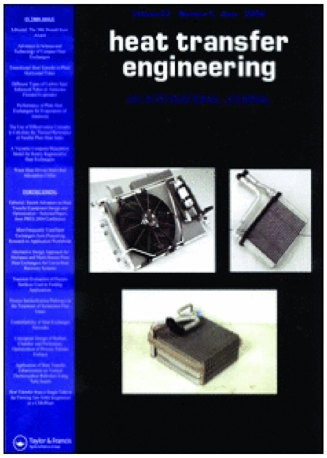

Heat Transfer in Confined Forced-Flow Boiling

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Remarkably different behaviors are found when comparing micro-scale flow boiling heat transfer data by distinct authors, even under similar experimental conditions. Such differences are almost certainly related to the complexity of confined forced-flow boiling. Certain aspects of the phenomenon, which are negligible in the macro-scale, become surprisingly relevant when the system size becomes small. From the results reported in the literature on the thermal-fluid features of evaporating flows in small channels, the following study presents a discussion concerning convective boiling heat transfer, highlighting the aspects that are characteristic to confined two-phase flows.

INTRODUCTION

Since the early 1980s, when the first heat transfer results for flow boiling in micro-channels were published, a growing number of investigations have addressed the subject. Many studies have presented measurements for both the single-channel configuration as well as for parallel multi-channels. The published heat transfer data, often reported as heat transfer coefficient (h) versus thermodynamic equilibrium vapor quality (x), show a variety of different trends. From the earliest results of Lazarek and Black [1], who showed values for the heat transfer coefficient that were unaffected by vapor quality but rather a function of heat flux, many others followed that confirmed this behavior. The explanation proposed by most authors was that the heat transfer process was dominated by nucleate boiling: bubble nucleation occurring at the channel wall being essentially unaffected by the bulk fluid flow. As the amount of experimentation in the sector increased, the range of reported trends extended to decreasing curves in the h-x plane, even at low vapor qualities. These new observations brought a shadow of uncertainty on the nature of flow boiling in small size channels. If indeed these systems had a strong nucleate boiling presence, another mechanism, triggered by the combination of fluid and operating conditions, was also to be accounted for in order to provide a broad explanation to the flow boiling behavior.

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A number of studies were also aimed at shedding light on the flow patterns that occur in two-phase micro-channel flows (e.g., [2,3]). Many of these were done on air-water flows and, other than for certain incongruities due to the subjectivity involved in flow pattern denominations, they were in general agreement as to the four main flow modes:

1. bubbly flow, at very low mass fractions of air,
2. slug flow (i.e., the passage of long bubbles separated by liquid slugs),
3. churn flow, a transition mode between slug flow and fully annular flow, and
4. annular flow, occurring at the highest air superficial velocities.

Slug flow was reportedly dominant for the very small channel diameters.

The need to give a better description to the boiling process in micro-channel flow, as well as the desire to include the influence of flow patterns, led some investigators to look at alternative explanations to the different behaviors in the heat transfer data. Cornwell and Kew [4], for example, argued that different flow modes presented different heat transfer mechanisms, varying from essentially nucleate boiling, to confined bubble boiling,

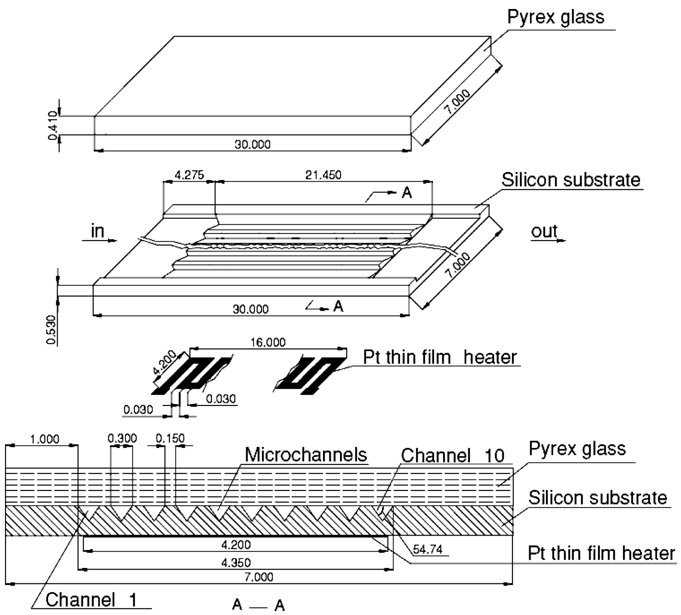

Figure 1 A sample multi-channel test-section (taken from [14]).

and finally to purely convective boiling for annular flows. On the other hand, Jacobi and Thome [5] postulated that in these channels, heat was transferred primarily by conduction through the thin evaporating film surrounding the elongated bubbles; a statement in contrast with prior opinions on the subject. Furthermore, some authors (e.g., [6–8]) suggested the presence of periodic dry-out of the channel wall, thus explaining the lower heat transfer performance with higher vapor qualities. This dry-out mechanism, however, was not entirely understood, and very few gave a clear opinion as to how and when it occurred. For example, extending the work presented in [5], Thome and coworkers [8] suggested the development of a dry-zone at the tail of an evaporating bubble.

In recent years, a number of studies introduced a characteristic behavior for micro-channel systems that had previously been neglected. By utilizing a transparent cover to the evaporator (see Figure 1), heated flow visualizations showed substantial fluctuating backflow (i.e., liquid and vapor were seen exiting from the evaporator inlet in periodic patterns, often coupled to oscillating pressure drop measurements [9–11]). Bergles and Kandlikar [12] classified this as a compressible volume instability, related to the presence of compressible volumes upstream of the heated channels. Many previous studies on micro-channels had not considered the possible presence of this particular behavior, as only visualizations or measurements by high-speed instrumentation could have actually described the channel-side mechanisms. Although several recent investigations (see [13]) have addressed the importance of these instabilities on the approach to critical conditions (critical heat flux, CHF), the possible effects obviously extend to non-critical flow-boiling heat transfer.

Further studies have provided additional interesting descriptions, revealing the eruptive nature of this boiling process. Visualizations by high-speed cameras, such as those recently presented by Xu et al. [14], have shown the process to unveil itself in different stages, each of which presents a different heat transfer mechanism. In particular, the results reported in [14] (ten parallel silicon channels with hydraulic diameters of 155.4 μm and using acetone as the working fluid) show the cyclical occurrence of five distinct stages:

1. single-phase liquid filling of the test-section;
2. bubble nucleation at the channel wall;
3. bubble growth and coalescence, leading to the formation of a vapor pouch over the channel cross-section;
4. a violent expansion of the vapor over the entire channel length, leaving a thin liquid film at the channel wall; and
5. evaporation of the quasi-static liquid film.

Different combinations of heat fluxes and mass velocities affected the extent of each of these five stages, thus changing the trends of the curves on the h-x plane. The stationary and decreasing trends in the heat transfer coefficients observed by numerous other authors were found respectively for medium and high values of the boiling number ($Bo = q/Gh_{lv}$). Periodic dry-out resulted when the liquid film at the channel wall completely vaporized.

The most recent efforts in the field of confined forced-flow boiling have therefore been oriented toward understanding the more intimate nature of the boiling process. The heat transfer characteristics associated to an oscillatory behavior, such as the one described above, may be detrimental for the application of such devices, as this may induce pressure waves in the loop that may lead to premature failure of the pumping system. Furthermore, the question remains as to the limit such a boiling process sets on the value of the critical heat flux, which for constant and high heat flux applications, such as the cooling of computer chips, is an issue of paramount importance. The discussion that follows gives a brief review of the main conclusions that may be drawn from the studies on the heat transfer mechanisms present in forced vaporization in small-diameter channels, illustrating some of the open issues that must be addressed for the successful application of micro-channel boiling in industrial technology.

EXPERIMENTAL HEAT TRANSFER IN CONFINED FORCED-FLOW BOILING

The work done on confined forced-flow boiling has been aimed at understanding its underlying physical mechanisms as well as evaluating its potential for cooling in industrial applications. From this perspective, the studies done on small channels have essentially covered two different systems: single- and parallel multi-channel arrangements.

Single-Channel Heat Transfer

Single-channel experiments have usually been done on electrically heated circular or rectangular channels. The small system sizes usually prevent any direct measurements of either fluid temperature or inner-wall temperature. In most studies, the fluid temperature is estimated through the measured values at the channel inlet and outlet, while the inner-wall temperature is back-calculated from thermocouple measurements at the outer-wall. Recently, infrared thermography has also been used for this purpose.

Among the first studies on evaporative heat transfer in a single channel was the one by Lazarek and Black [1], who reported experimental heat transfer coefficients for flow boiling of R-113 in a vertical tube with an inner diameter of 3.1 mm. Their heat transfer coefficients had a strong dependency on the applied heat flux, but were essentially independent of vapor quality. Similar results were obtained by Tran et al. [15] and Bao et al. [16]. Tran and coworkers performed experiments on R-12 in circular and rectangular channels with sizes ranging from 2.40 to 2.92 mm. Their data showed that for a sufficiently high wall superheat, the values of the heat transfer coefficient were unaffected by vapor quality and mass velocity but increased significantly with heat flux. The flow boiling experiments of Bao et al. again confirmed the heat transfer coefficient as only a function of heat flux and saturation pressure.

A new set of trends in the heat transfer data for confined force-flow boiling was introduced in the investigation performed by Lin et al. [17]. In their study on R-141b (1.1 mm internal diameter tube), the heat transfer coefficient versus vapor quality curves were increasing, invariant, or decreasing with increasing heat flux. More recent studies in single channels have also shown similar trends for several different fluids. For example, Sumith et al. [18] presented flow boiling results for water in a 1.45 mm vertical tube with positive sloping curves in the h-x plane at low and medium-high heat fluxes, and invariant values of the heat transfer coefficient at the highest values for q. Lihong et al. [19] presented experimental results for R-134a in a 1.3 mm circular channel, showing substantial agreement with [17], and furthermore suggesting a dependence of heat transfer on mass velocity at lower values of heat flux. (This had also been noticed by [15] for wall superheats below 2.75°C and by [18].) Lihong and coworkers also noticed the positive effect of a higher saturation pressure on heat transfer that had been previously observed in [16]. Cortina Díaz and Schmidt [20] reported decreasing and increasing heat transfer coefficients with vapor quality for flow boiling of water and ethanol in a 0.3×12.7 mm^2 ($d_h = 0.59$ mm) rectangular channel.

On a final note, among the above-mentioned studies, several ([1,17,18, and 20]) reported oscillations in the wall temperature measurements at medium and high heat fluxes, the amplitudes of which were shown to increase with heating intensity.

Multi-Channel Heat Transfer

Multi-channel arrangements (see Figure 1) are usually comprised of a parallel sequence of channels in either a closed system configuration, or manufactured on the upper face of a copper or silicon block with a transparent cover to allow for flow visualization. Although some studies have utilized direct electrical heating, a number of experiments have relied on cartridge or film heating, exposing only one side of the system to the heat source (which is representative of what would occur in the case of computer chip cooling). The shapes of the channel cross-sections have been several, including circular, rectangular, triangular, and trapezoidal geometries. Again, the wall temperatures are obtained through local measurements of embedded thermocouples, or, in the case of heating by a thin electrically conductive film, by infrared thermography. Although multi-channel systems may allow for higher flow and heating rates (i.e., improved energy balances and lower uncertainties on the heat input), the analysis of a multi-channel system is generally more complicated with respect to the single-channel setup, as the boiling process is coupled to the quality of the flow distribution, as well as to conjugate heat transfer effects. While a single-channel experiment removes any uncertainty in the results related to these issues, it is essential to assess their importance in view of the real application.

The experimental data for heat transfer in multi-channel systems present the same variety of behaviors reported for single channels. Yan and Lin [21] (R-134a in 2 mm circular channels) showed heat transfer coefficients that increased, remained constant, or decreased with vapor quality depending on the value of the applied heat flux and the mass velocity. Heat transfer was shown to benefit from higher saturation temperatures and, for vapor qualities up to 0.7, also from higher heat fluxes. Pettersen [22] presented heat transfer coefficients for flow boiling of CO_2 that were essentially independent of vapor quality and mass velocity but increased with saturation temperature and heat flux. More recently, Qu and Mudawar [13], Lee and Mudawar [23], Hetsroni et al. [24], and Xu et al. [14] have coupled heat transfer measurements to flow visualizations. These investigations confirmed the trends in the heat transfer coefficients reported in previous investigations (i.e., an increase in the heat transfer performance with heat flux and saturation temperature, and a variable dependence on vapor quality and mass velocity), combining them to the physical development of the flow-boiling process. Figure 2 shows an extract of the data from the experimental work in [14].

FLOW BOILING IN SMALL CHANNELS

Nucleate Versus Convective Boiling

The initial heat transfer measurements [1,15,16] for confined forced flow boiling, which presented the heat transfer coefficient essentially as a function of heat flux and saturation conditions, lead to some debate as to the nature of the boiling/heat transfer mechanism in these systems. Numerous authors, supported by the superposition model of Chen [25], suggested nucleate boiling to be dominant, with bubble nucleation occurring at the channel wall being almost unaffected by the bulk fluid flow.

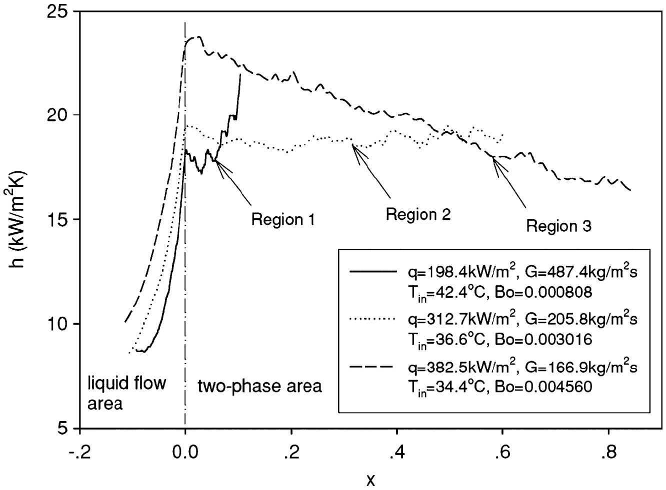

Figure 2 Heat transfer coefficient versus vapor quality, as presented in [14]. Region 1: low Bo; region 2: medium Bo; region 3: high Bo.

Chen's method for flow boiling separates the nucleate boiling contribution (h_{nb}) to the heat transfer coefficient from that of convection (h_{cv}), i.e.,

$$h = h_{nb} + h_{cv} \tag{1}$$

with only the nucleate boiling term (first term on the right hand side of the equation) a function of heat flux. In contrast, Jacobi and Thome [5] argued that a different mechanism could yield the same heat transfer behavior by modeling the two-phase flow as a cyclical passage of elongated bubbles and liquid slugs. The high heat transfer rates achieved by thin film evaporation were balanced by the lower values associated to the passage of liquid slugs.

Compressible Volume-Oscillatory Flow Instability

Much of this debate was based more on heat transfer coefficient measurements than on actual flow visualizations, due to the limited amount of studies that actually "looked" into the flow. In order to satisfy the need for more visual information, a number of authors exploited multi-channel systems to obtain a flow visualization database, while continuing to collect heat transfer measurements (e.g., [13,14,23,24]). The results of these studies were of utmost interest and have shed substantial light on the boiling process.

For medium to high heat fluxes, these authors reported an eruptive boiling phenomenon (at times also referred to as "explosive boiling," see [24]) that involved most if not all the channel length and that created substantial backflow. The nature of this behavior is that of an oscillatory instability, which occurs when a small amount of compressibility is present upstream of the evaporator. Xu et al. [14] described it as the periodic development of five distinct stages:

1. single-phase liquid filling of the channel,
2. bubble nucleation over the channel length,

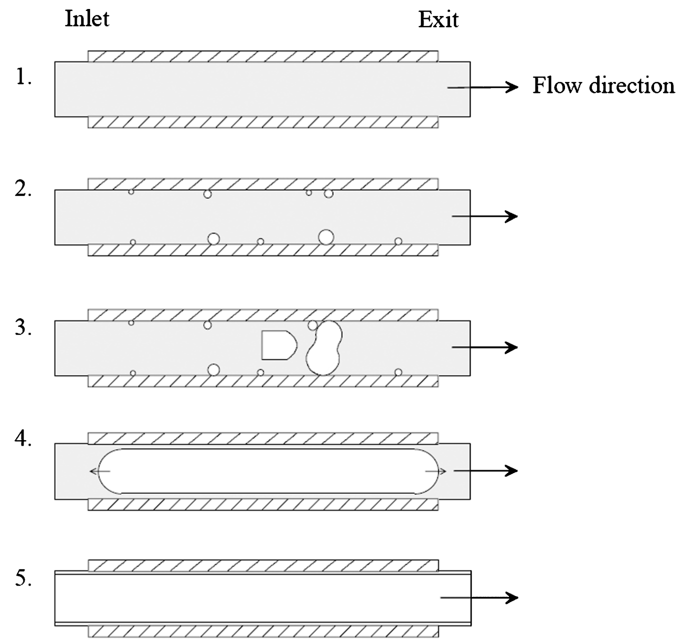

Figure 3 Schematic representation of the boiling features occurring during one cycle of an oscillatory instability.

3. growth and coalescence of bubbles at certain axial locations to form a vapor pouch over almost the entire cross-section,
4. a violent expansion of the vapor toward the channel inlet and outlet, and
5. evaporation of the quasi-static liquid film left at the channel wall after the bubble expansion.

Figure 3 shows a schematic representation of the process. In [14] and [24], it is shown that for sufficiently high heat fluxes, the liquid film left by the expanding bubble may dry-out, thus leaving the channel wall periodically in contact with only vapor. At the medium heat fluxes, bubble nucleation has a stronger impact on heat transfer than the convective boiling process induced by the bubble explosions. The five-part sequence essentially reduces to the growth of the bubbles at the wall followed by liquid refilling of the channel, yielding heat transfer coefficients that are independent of vapor quality and that present the typical nucleate boiling characteristics. At higher heat fluxes and lower mass velocities, the onset of nucleation shifts toward the channel inlet, and substantial convective boiling results from the eruptive mechanism. The probability of dry-out of the liquid film increases in the flow direction, thus explaining the decreasing heat transfer coefficients with increasing vapor quality. This was also suggested in the study of Agostini and Bontemps [26] (R134a flowing in 11 parallel rectangular channels, $d_h = 2.03$ mm), where the authors observed how the statistical uncertainty on the measured wall temperatures increased at vapor qualities above 0.4, suggesting the presence of partial dry-out.

The periodic development of substantial dry-zones, along with possible fluctuations in the saturation temperature (coupled to the propagation of pressure pulses in the fluid), may also explain the wall temperature oscillations reported in several

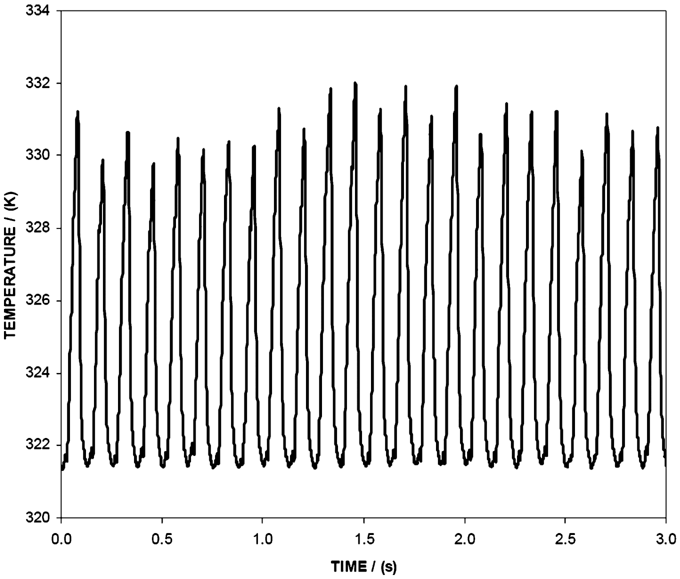

Figure 4 Outer wall temperature fluctuations for flow boiling of R-134a in a single 0.8 mm circular channel, taken at half the channel length (heat flux: 140 kW/m^2, mass velocity: 300 kg/m^{2}s, saturation temperature: 31°C, channel length: 70 mm).

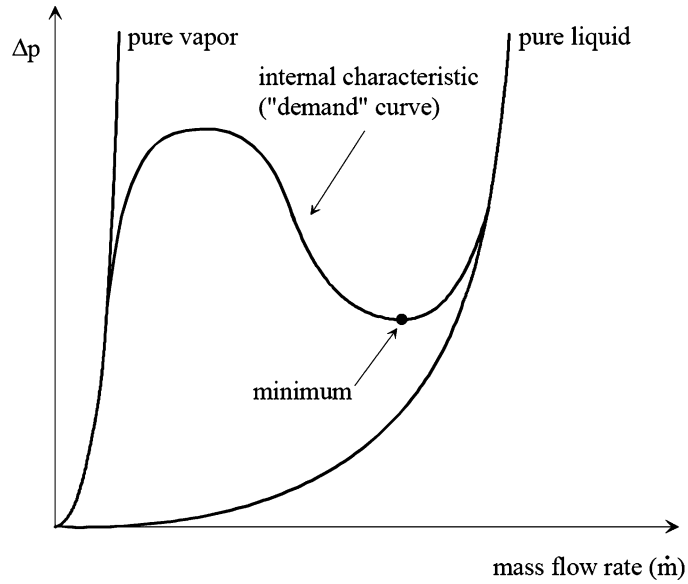

Figure 5 The internal characteristic for an evaporating flow at constant heat flux.

investigations. Figure 4 presents some preliminary results of outer wall temperature measurements for flow boiling of R-134a in a 0.8 mm circular channel with a 0.1 mm wall, which were performed using an infrared camera (900 images per second). The temperature is shown to exhibit cyclical excursions of frequency around 9 Hz and amplitude of approximately 8–9°C, which are possibly related to this type of boiling process.

The physical mechanism behind eruptive boiling has not been entirely understood; however, it may be associated to the high two-phase pressure drop in these small channels. Beyond the onset of nucleate boiling (ONB), the pressure of the flow reduces drastically due to the presence of vapor bubbles at the wall, with the liquid temperature remaining substantially high. The vapor bubbles downstream of the ONB location may thus find themselves surrounded by a highly superheated liquid that may therefore lead to violent flashing. The extent of superheat required to start nucleation is also related to the degree of surface roughness (i.e., smoother channels will exhibit higher liquid superheating, thus increasing the likeliness of eruptive boiling). Kandlikar [27] mentions interface velocities as high as 3.5 m/s. The expansion towards the inlet is made possible by the presence of a compressible volume, such as vapor in the header of a multiple channel system, upstream of the boiling location (cfr. [12]).

Bergles and Kandlikar [12] observed that the occurrence of the oscillatory instability coincides with a minimum in the "demand" curve on the pressure drop versus flow rate diagram, as shown in Figure 5. Kenning and Yan [28] reported oscillations in local pressure and wall temperature for experiments with different degrees of inlet compressibility. Their power spectrum analysis on both pressure and temperature signals gave peak values at frequencies around 6 Hz. Brutin et al. [10] reported a stability diagram for their experiments on n-pentane flowing in a single rectangular channel with hydraulic diameter $d_h = 889$ μm. From their flow visualizations, they observed the instability and associated it with significant oscillations in pressure drop (with frequencies of about 4 Hz). Using the onset of these fluctuations as a threshold between a stable and an unstable flow, Brutin and coworkers presented transition lines in terms of heat flux and mass flow rate. Xu et al. [14] argued that the extent of these flow oscillations determined three different behaviors in the heat transfer coefficient (see Figure 2), and associated each of the three to an interval in the boiling number (Bo). For their experiments on flow boiling of acetone in ten triangular microchannels ($d_h = 155.4$ μm), the heat transfer coefficients were shown to increase with vapor quality for $0.69 < Bo \times 10^3 < 1.184$ (region 1), remain stationary for $1.574 < Bo \times 10^3 < 3.219$ (region 2), and decrease for $3.562 < Bo \times 10^3 < 5.046$ (region 3). Figure 6

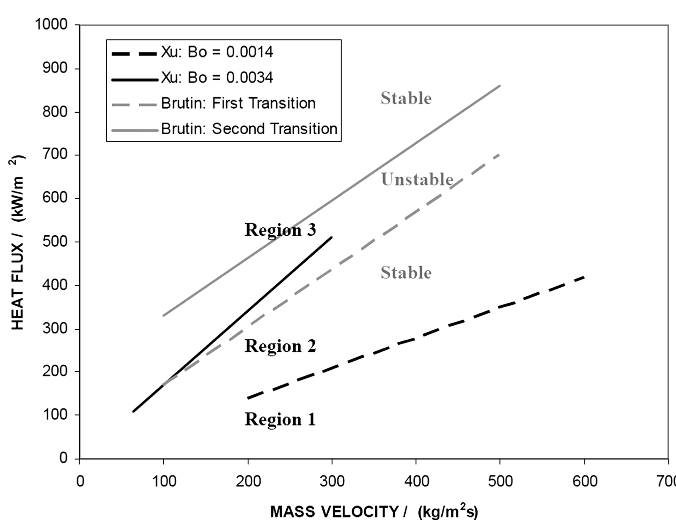

Figure 6 Stable-unstable transition lines (gray) as presented in [10], compared to the different heat transfer zones (black), as described in [14].

compares the two criteria. Although much caution should be used in comparing the transition lines, as they were developed for different systems and flow conditions, the change from region 2 to region 3 (black solid line in Figure 6) is seen to occur near the first stable-unstable transition proposed in [10].

Compressible Volume Instability: Drawbacks and Solutions

The inception of a compressible volume instability results from a perturbation in the system flow rate which, according to the location of the operating point on the pressure drop versus flow rate curve (demand curve in Figure 5), may give rise to an oscillating flow with corresponding fluctuations in the local pressure [29]. Both of these effects are undesirable in a cooling loop, as the pumping device would be exposed to periodic transients in both pressure and mass flow. These instabilities may be also associated to premature CHF because the evaporating liquid film left by the expanding bubble may not be replenished by incoming liquid.

Throttling the inlet of a multi-channel heat sink will localize the effect of any fluctuations occurring in the individual channels and prevent the development of excursive instabilities (Ledinegg instability). However, in the heat sink itself, the different channels, connected by a header, will interact through a "pumping" effect, where any liquid expelled from one channel will produce a flow into one or more of its neighbors. Throttling the entrance to individual channels (cfr. [12]) will create a resistance to any backflow, separating the flow from any compressible volume present in the header. In this case, the eruptive boiling process may still occur, but will develop toward the exit of the channel, with the incoming liquid acting to refill the evaporating film at the channel wall. The price to pay for either of the two solutions is a higher pressure drop over the evaporator.

CONCLUSIONS

Recent work on forced-flow vaporization in confined spaces has unveiled typical flow-boiling mechanisms characteristic to channels of reduced sizes. Flow visualizations in multi-channel experiments have often shown the process to develop in a cycle associated with a compressible volume instability, in which nucleate boiling, thin film evaporation, and single-phase heat transfer all play a role. The bubble nuclei at the channel wall have been shown to grow, coalesce, and exhibit a violent expansion in both the inlet and the outlet directions, leaving a liquid film at the wall. Periodic dry-out of the film may occur at sufficiently high heat fluxes, leaving a large portion of the channel wall in contact with vapor, thus lowering the local heat transfer rate, leading even to large excursions in the channel wall temperature. The cyclical eruptive boiling process, inclusive of its different stages, as well as the possibility of periodic dry-out may explain the trends in the heat transfer data reported in the literature for both single- and multi-channel experiments.

The presence of an oscillatory instability within a micro-channel heat sink has several drawbacks that must be assessed before implementing this cooling technique in industrial applications. In particular, backflow and the propagation of pressure waves, other than premature CHF, are important problems related to this mechanism. At the price of a higher pressure drop through the evaporator, throttling the entrance to individual channels may extinguish the bubble expansion towards the inlet, isolating the channels from upstream compressible volumes. In this case, the flow would be expected to be continuous from inlet to exit, which would limit the occurrence of the above-mentioned drawbacks. Nonetheless, substantial experimentation should take place in order to develop a comprehensive knowledge of the boiling process under fully stable conditions.

NOMENCLATURE

Bo	boiling number, q/Gh_{lv}
d	diameter, m
G	mass velocity, kg/(m^{2}s)
h	heat transfer coefficient, W/(m^{2}K)
h_{lv}	latent heat, J/kg
$\dot{m}$	mass flow rate, kg/s
p	pressure, Pa
q	heat flux, W/m^2
x	equilibrium vapor quality

Subscripts

cv	convection
nb	nucleate boiling
h	hydraulic

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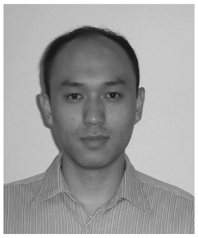

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