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Heat Transfer and Pressure Drops in Micro-Tubes for ground and Space applications

Abstract:

The aim of the research is to compare and understand the bubble dynamics, heat transfer mechanism and pressure drops in subcooled flow boiling, at both, microgravity and normal gravity conditions. Nowadays, there are few studies on this topic, nevertheless the possible applications are many, from the spatial usage to microelectronics cooling. Micro-exchangers are the next generation of cooling systems useful for both terrestrial and space applications where weight and dimensions are important. Flow boiling is the best way to reach high heat fluxes. Micro-tubes, thanks to their dimension, can be used in a wide range of microgravity systems i.e. satellites for communications, thermal management for the International Space Station, cooling of hi-power electronic devices, nuclear space reactors, etc. To develop and design thermal systems for small applications, it is necessary to achieve a detailed understanding of all flow boiling aspects, also under low gravity conditions, at low pressure and at high thermal fluxes. A deepen analysis of available correlations in the literature has been performed and a comprehensive comparison with experimental data provided by two ENEA facilities (MICROBO and BOEMIA) has been carried out. The analysis considers 17 micro-channel correlations, 5 macro-channels and 2 models to calculate heat transfer. Instead, 5 correlations were chosen to calculate saturated boiling pressure drops and 3 for subcooled boiling. As most of data are in subcooled boiling, its effect on prediction is discussed and a model is proposed to calculate vapor quality in the channel. Moreover, a new methodology to calculate pressure drops has been developed and discussed.

State of the art:

Many studies about flow boiling are available in the literature, not only related to mini or micro channels or to subcooled boiling, but regarding different approaches to predict pressure drops and heat transfer coefficients. Most of the studies, like those for heat transfer from Chen, Kandlikar, Gungor and Winterton, focus on macro scale channels. There are less studies about micro-scale heat transfer, some examples are: Lazarek and Black., Bertsch et al., Zhang et al., or also Kew and Cornwell. And more less about subcooled boiling in micro-channels. There are also multi-correlations able to work with different scales, for example the work of Mikielewicz for both micro and macro-channal heat transfer coefficient prediction. Moreover, recently an innovative approach has born, and some models were developed considering the physical phenomenon involved in heat transfer (Thome and Consolini models). However, those models were developed for flow boiling and are unemployable in subcooling, so that one of the issue rose during the research was the employing of vapour qualities in substitution of negative thermodynamic qualities, as introduced by the work of Delhaye et al. The difference with this modification in the prediction capability and phenomenon analysis is necessary to identify the main physical groups that characterize boiling phenomenon and its transition. Is important to underline that subcooled boiling is a common phenomenon that occurs in many facilities. In fact, if the incoming fluid is supplied below saturation temperature at inlet, both subcooled and saturated boiling occurs. At high void fractions, when the fluid is in saturated boiling, the wall-bubbling is replaced by evaporation of the residual liquid film at the heated wall. It is associated with churn, slug and annular flow. It is interesting that in sub-cooled region, flow boiling can occur at higher heat fluxes than in saturated, also the critical heat flux is greater in sub-cooled boiling. Furthermore, there are drastic differences in CHF mechanism between the two regimes. High-flux applications can take advantage from sub-cooled boiling. This regime can be achieved mainly by two ways: (1) increasing mass velocity (2) increasing liquid subcooled at the inlet. Channel geometry can also have a strong effect on the extent of the subcooled boiling region. For example, channels with small length-to-diameter ratio are more likely to maintain subcooled boiling. Bertsh et al. performed an extensive assessment for saturated flow boiling in micro tubes with 25 correlations and 1847 data points collected from 10 different laboratories. Instead, Mohamed and Karayannis performed an assessment with the most common 21 correlations and models with a database of 5152 data points with diameters of 4.26, 2.88, 2.01 mm. and R134a as refrigerant in stainless steel micro tubes. A recently deep review of phenomena that occurs in microchannels and in microgravity was made by Konishi and Mudawa. Their study shows a severe shortage of useful correlations, mechanistic models and computational models, which compromises reliability of the actual correlations to adopt in microgravity flow boiling. Agostini et al. presented a comprehensive state of the art for high heat flux cooling technology. Furthermore Xu et al., Harirchian et al. and Thome contributed broadly to the field of two phase flow boiling. Almost all the experimental work present in literature have shown a dominant effect of heat flux on the heat transfer coefficient. Besides the influence of forced convective boiling on heat transfer is insignificant. The increasing of heat transfer in the annular flow regime suggests that convective evaporation is the dominant mechanism in confined channels. The experimental data under stable two-phase micro-channel flows indicated the importance of the fluid properties on the flow boiling heat transfer process in confined micro-scale channels. Thome, Consolini and more recently Kim and Mudawar have developed flow boiling models to predict, with a physical and phenomenological approach, the heat transfer in micro channels. An important work was made by Kim and Mudawar whom developed a new correlation for subcooled flow boiling accounting pressure drops, inlet subcooling, micro-channel aspect ratio, and length-to-diameter ratio. Lee and Mudawar studied the performance of a new cooling system that works in subcooled boiling condition. Levy, Kroeger and Zuber, Saha and Zuber and Lahey and Moody proposed different methods to calculate the void fraction in subcooled boiling based on the Zuber and Findlay drift flux model, calculation the void fraction in the fully developed boiling region and assume a zero void fraction before. Garnier et al. analyzed the subcooled models and found how they mainly differ for: (1) the relation between the actual and equilibrium quality, (2) the distribution parameter, and (3) the weighted drift velocity. Levy and Griffith et al. proposed correlations for the void fraction at the OSV.

Methodology

Two different experimental setups have been used with a different layout and experimental section. The tubes diameter varies from 1mm up to 4mm. The data base used to calculate pressure drops have been obtained in the experimental facility BO.E.MI.A. (Boiling Experiments in MIcrochannel Apparatus), built and operated in the ENEA Laboratory of Thermo-Fluid Dynamics. The facility aim is to perform, at different regimes, heat transfer tests on mini and micro channels, with inner diameter in the range from 0.25 up to 2 mm. A simplified layout of the experimental loop is shown in figure 88. FC-72 (perfluorohexane C6F14), a fluorine liquid manufactured by 3M, was used as working fluid; it is thermally and chemically stable, compatible with sensitive materials, nonflammable, leaves essentially no residue upon evaporation and has no ozone depletion potential, properties that make it ideal for electronics. The second section is called MicroBo (Microgravity Boiling) and was developed to be used in parabolic flight at near 0 g acceleration. The section can use tube from 1 mm up to 8mm and was equipped with tubes of 2 and 4 mm. The facility was designed at the ENEA laboratories to perform flow-boiling experiments at microgravity and normal gravity conditions to obtain heat transfer coefficients. The experiments that are made in flow boiling with 2.0 mm and 4.0 mm tubes. The working fluid is FC-72, perfluorohexane, C6F14, a liquid manufactured by 3M. It was projected to be employed in electronic cooling and to be used for boiling experiments. A deepen analysis of available correlations in the literature has been performed and a comprehensive comparison with experimental data provided by the ENEA's facilities (MICROBO and BOEMIA) has been carried out. The analysis considers 12 micro-channel correlations, 5 macro-channels and 2 models to calculate heat transfer. Macro-Scale correlations: (1) Chen, (2) Shah, (3) Gungor and Winterton, (4) Kandlikar, (5) Liu and Winterton. Micro-Scale correlations: (1) Lazarek and Black, (2) Tran et al., (3) Kew and Cornwell, (4) Warrier et al., (5) Kandlikar and Balasubramanian, (6) Zhang et al., (7) Lee and Mudawar, (8) Saitoh et al., (9) Bertsch et al., (10) Mikielewicz, (11) Li and Wu, (12) Mohamed and Karayiannis. Models: (1) Three-Zone Model proposed by Thome, Dupont and Jacobi and (2) Slug Coalescence Model prosed by Thome and Consolini. Instead, 5 correlations were chosen to calculate saturated boiling pressure drops and 3 for subcooled boiling. Developed boiling: (1) Friedel, (2) Chisholm, (3) Lockhart-Martinelli, (4) Chawla and, (5) Müller-Steinhagen and Heck. Subcooled boiling: (1) Owens-Schrock, (2) Kim-Mudawar and (3) Tong. The model used to calculate vapor quality used in the different models and correlations is developed by Delhaye.

Conclusions:

The assessment has been conducted using local heat transfer coefficients calculated along the experimental section on the thermocouples position and with the pressure drops between the entrance and the end of experimental sections. The comparison of heat transfer coefficients demonstrated that all examined correlations are not general enough and/or could not predict the current experimental data with a reasonable accuracy. A depth remark for MICROBO is necessary, due to microgravity application, for every correlation to understand the plausible causes of a bad prediction or the insufficient accuracy of the model/correlation. As expected, micro-scale models work better for the 2mm channel. The most effective correlations are Chen's for the macro scale and Zhang's for the micro scale, they can predict up to 70% of the data. Consolini and Thome model does not return valid results. However, no one of the correlation is expected to work with FC-72 as refrigerant fluid. The same study was made for BOEMIA on 1 mm tubes, 100 mm and 200 mm long. Only saturated boiling points have been considered. Macro scale correlations provide quite better results than expected, especially for the Chen's correlation. However, the micro scale correlations provide a better agreement than the macro scale ones. The correlations of Zhang et al. and Li and Wu give more than 83% of data within ±30% error band, with a MAPE lower than 27%. This behavior is due to the dimension of the 1 mm channel that is close to the micro scale. The mechanistic "Three-zone model" provides a better agreement than the "Slug-Coalescence model" with more experimental points.

The developed methodology can be used in transition flow and with non-equilibrium vapor quality (instead of the equilibrium thermodynamic quality). The methodology includes single phase, subcooled and saturated boiling conditions, identifying their boundaries. Employing a third order interpolation curve, the pressure drop for subcooled liquid in transition flow can be calculated. The model considers the fluid proprieties, the energy, mass and momentum conservation to predict the ONB, OSV points and a hyperbolic function is adopted to calculate the non-equilibrium vapor quality in the subcooled boiling region. The best agreement with the ENEA experimental data has been obtained using a transient model for the Single-Phase flow region, the Chisholm model for the subcooled flow boiling region followed by Lockhart-Martinelli for the saturated flow boiling region. The resulting MAPE is of 18,54%, a MPE of -5,88% and 82,45% of the predicted points with an error lower than 30%. The results are very encouraging because none of the employed correlation was developed specifically for the ENEA database or adapted on it. Further pressure drop correlations that can be used with the proposed methodology are available in the literature. Moreover, all the methodology steps have been checked with an "applicability model", used to analyze "equivalent" correlation rages with other fluids or setups, to assure the compatibility with the fluid and ranges used in the experimental facility.

Keywords:

Micro-Gravity; Micro-Tubes; Macro-Tubes; Pressure Drops, Subcooled Boiling.