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NUMERICAL INVESTIGATION OF OSCILLATING VAPOUR SLUGS WITHIN HEATED MICROCHANNELS IN SATURATED FLOW BOILING CONDITIONS

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KEY WORDS

Volume of Fluid method, saturated flow boiling, oscillating vapour slugs, conjugate heat transfer, capillary ridges

SHORT SUMMARY

An enhanced Volume Of Fluid (VOF) based numerical simulation framework that accounts for conjugate heat transfer between a solid region and a two-phase flow region with phase-change due to evaporation and/or condensation, is applied in order to investigate the effect of global flow oscillation frequency and amplitude in generated instabilities in the liquid film around isolated, elongated vapour slugs within a heated micro-channel, in saturated flow boiling conditions. A series of numerical simulations were performed, for different values of flow oscillation amplitude and frequency. The oscillations were generated applying an oscillating pressure boundary condition at the inlet of the channel, keeping the pressure constant at the outlet after an initial period of constant pressure drop between the inlet and the outlet of the channel. R245fa was used as the working fluid. Capillary ridges initiated at the liquid film surrounding in the vicinity of the leading edge of the considered vapour slug, are identified as a result of the imposed oscillations. It is shown that the generation frequency as well as the height of the proposed ridges are directly related to the corresponding frequency and amplitude of the induced pressure oscillations at the inlet of the channel.

EXTENDED ABSTRACT

The demand for increasingly higher performances of electronic equipment, has pushed researchers and engineers to develop a new generation of heat dissipation systems based on the local phase-change of a working fluid. Efficient thermal control, of densely packed electronic components, has become of crucial importance. Flow boiling within micro-channels, constitute one of the most promising cooling technologies to dissipate high heat fluxes from micro-scale electronic components (e.g. micro-processors). Two-phase cooling devices utilizing evaporators consisting of micro-channels that are in direct contact with a micro-chip, can remove heat fluxes up to 300 W/cm^2 [1]. However, the flow complexity in cases of multi-

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microchannel two-phase flow evaporators, can lead to high-amplitude and high-frequency temperature and pressure oscillations [2]. Such oscillations, in the slug flow regime, may generate significant instabilities in the liquid film that surrounds elongated vapour slugs. Similar instabilities are also generated in the case of oscillating closed loop two-phase cooling devices such as Pulsating Heat Pipes that might consist of micro- (e.g. [3]) or mini-channels (e.g. [4]).

In the present investigation, an enhanced Volume Of Fluid (VOF) based numerical simulation framework that accounts for conjugate heat transfer between a solid region and a two-phase flow region with phase-change due to boiling and/or condensation, is applied for the conduction of a series of numerical simulations aiming to identify the effect of global flow oscillation frequency and amplitude in the generated liquid film instabilities, for isolated, elongated vapour slugs within a micro-channel, in saturated flow boiling conditions.

More details about the development and validation of the proposed enhanced VOF-based numerical simulation framework can be found in previous investigations by the authors ([5-7]). The proposed model is applied for a series of numerical experiments, for a specific value of applied heat flux ($q=5000 W/m^2$) in the heated section of the considered circular micro-channel (D_o = 0.69 mm, D_i=0.5 mm) and for different values of oscillation amplitude and frequency. The flow oscillations were generated inducing an oscillating pressure boundary condition at the inlet of the channel while keeping the pressure constant at the outlet. In all simulations, R245fa refrigerant is used as the working fluid. Each simulation is conducted in three stages. At the first stage a single phase simulation is run with only liquid flowing into the channel, applying a constant pressure drop of ΔP = 500 Pa and a constant heat flux of $q= 5000 W/m^2$ at the heated part of the considered micro-channel heated wall. In the second stage, after the single phase flow has reached a steady state and the hydrodynamic and thermal boundary layers have been developed (t=0.2 s), a vapour slug is patched upstream of the heated section of the microchannel at a certain distance from the channel inlet, having a, initial length of $3xD_i$ and an initial liquid film thickness of $h_{film(init)}$ = 20μm. This initial vapor slug is then left to be carried away downstream by the previously developed liquid cross-flow, towards the heated section on the circular micro-channel. At the third and final stage, after 0.017 s that the vapour slug front has reached approximately the middle of the channel in each case (ensuring that it is completely contained within the heated region), an oscillating relative pressure boundary condition is imposed at the inlet of the channel, keeping the relative pressure at the outlet constant at 0 Pa. The resulting pressure value for the inlet with respect to time, can be described by the following equation.

$$P(t)=(1+\alpha \sin(\pi f t)\,)\,P_{ref}+P_0 \tag{1}$$

where α and f are the amplitude and frequency of the oscillation, while P_0 and P_{ref} are the initial pressure and a reference pressure, respectively. An axisymmetric computational domain is constructed with the axis of symmetry coinciding with the central/longitudinal axis of the considered circular micro-channel. The computational domain, mesh and the applied boundary conditions as well as the initial condition for the oscillating part of the simulations, are illustrated in Fig. 1. Tab. 1 summarizes the imposed oscillation characteristics for each of the examined cases in the present numerical investigation.

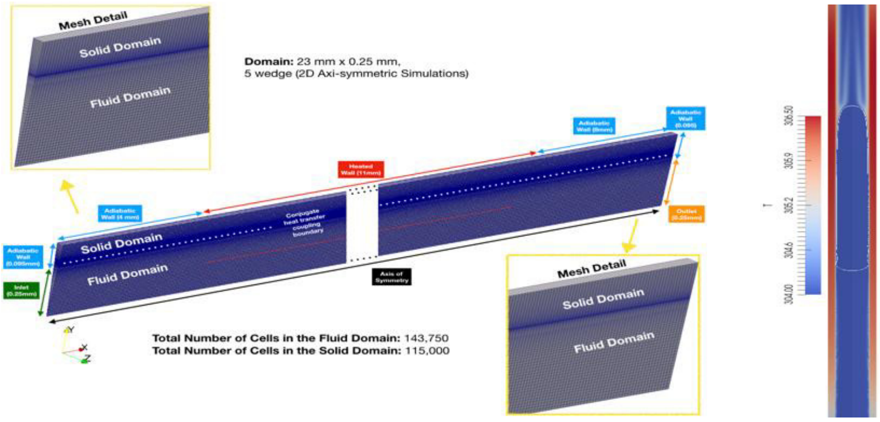

Figure 1: Geometry, Mesh and Boundary conditions (left), initial state before imposed flow oscillations (right).

The computational domain consists of a solid and a fluid region that are coupled at their interface through a specifically developed conjugate boundary condition (see [7] for more details). The fluid and solid domains consist of a total number of 143,750 and 115,00 computational cells, respectively. The mesh density was selected after a mesh independency study. A structured mesh, consisting of hexahedral and prismatic elements is used , with a grid clustering towards the coupling interface between the solid and fluid regions. The overall computation domain constitutes a 5^0 wedge of the circular micro-channel under consideration, since this is the way that 2D axisymmetric simulations are conducted in OpenFOAM, the open-source CFD platform that is utilized for the overall computations.

Table 1: Inlet pressure oscillation characteristics for the considered cases.

Experiment	Pressure Oscillation Amplitude [Pa]	Pressure Oscillation Frequency [Hz]	Initial Pressure [Pa]	Reference Pressure [Pa]
Case 1	100,000	500	0	1
Case 2	100,000	750	0	1
Case 3	100,000	1000	0	1
Case 4	50,000	500	0	1
Case 5	75,000	500	0	1

The spatial and temporal evolution of the considered vapour slug, under different pressure oscillation frequencies at the inlet of the considered micro-channel, is depicted in Fig. 2 were the numerical simulation results for cases 1, 2 and 3 from Tab. 1 are presented (increasing induced flow oscillation frequency) .

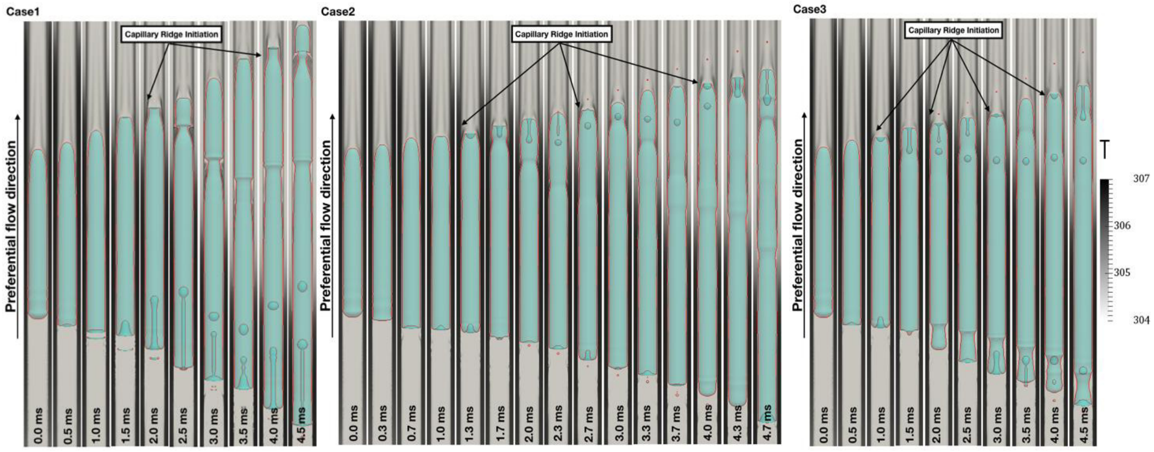

Figure 2: Spatial and temporal evolution of vapour slug after the initiation of the oscillating pressure boundary condition at the inlet. Case 1 (left), case 2 (middle) and case 3 (right), from Tab. 1. The camera view is moving along with the vapour slug, as it progresses downstream the considered micro-channel (effect of flow oscillation frequency).

As it can observed in all three cases apart from the capillary waves that are present in the trailing edge of the slug at the beginning of the oscillation period (formed during the constant pressure drop stage), the imposed pressure oscillations at the inlet are responsible for the periodic generation of a capillary ridge in the vicinity of the leading edge of the evaporating vapour slug, that is then traveling downstream towards its trailing edge, gradually attenuating, reducing its maximum height and increasing its overall length. It is worth noticing that in all three cases the period of the capillary ridge generation, coincides with the period of a complete pressure oscillation at the inlet of the considered microchannel (i.e. every 2, 1.33 and 1 ms, for cases 1, 2 and 3, respectively). It is also evident that the increase in the pressure oscillation frequency at the inlet of the considered micro-channel, is accompanied by a reduction in the maximum height of the periodically generated capillary ridge, in each case. Some interesting inertial phenomena are also evident in all three cases, that result in the encapsulation of small liquid droplets within the elongated vapour bubble and/or in the detachment of small satellite bubbles from its leading and/or its trailing edge. The proposed phenomena are enhanced with the frequency increase of the imposed pressure oscillations at the inlet of the considered microchannel. Finally, it is also evident that as the pressure oscillation frequency at the inlet is increased, the final volume of the elongated vapour slug for the considered time period after the application of the oscillations (approximately at t = 4.5 ms), gradually decreases. This indicates that the liquid film evaporation rate is reduced with the increase of the induced flow oscillation frequency.

Accordingly, the effect of the oscillation amplitude in illustrated in Fig. 3, where the numerical simulation results from cases 4, 5 and 1 from Tab. 1, are presented. As it can be observed, the increase in amplitude of the imposed pressure oscillations at the inlet of the considered micro-channel, causes a corresponding increase in the maximum height of the periodically developed capillary ridge in the vicinity of the leading edge of the evaporating vapour slug. In this case, the final volume of the elongated vapour slug for the considered time after the application of the oscillations (at t = 4.5 ms), gradually increases with the corresponding increase in the amplitude of the induced pressure oscillations at the inlet of the considered micro-channel. This indicates that the liquid film evaporation rate is increased with the corresponding increase of the induced flow oscillation amplitude.

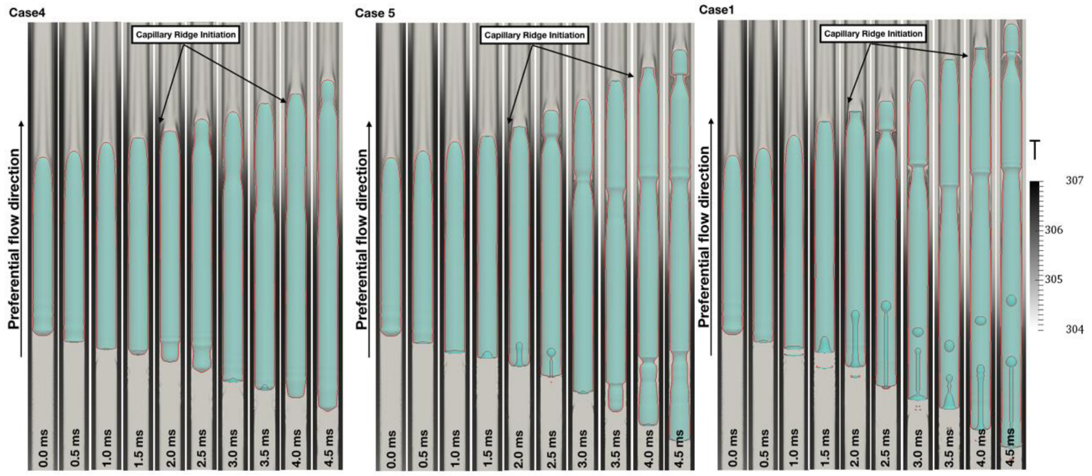

Figure 3: Spatial and temporal evolution of vapour slug after the initiation of the oscillating pressure boundary condition at the inlet. Case 4 (left), case 5 (middle) and case 1 (right), from Tab. 1. The camera view is moving along with the vapour slug, as it progresses downstream the considered micro-channel (effect of flow oscillation amplitude).

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