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OPTICAL STUDIES OF EVAPORATION IN MICROCHANNEL ARRAYS

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ABSTRACT

Phase transition in microchannels has become an interesting filed of research within the last few years. Using arrays out of a multitude of parallel microchannels, it is possible to transfer a huge amount of thermal energy by taking advantage of the latent heat of evaporation. Another point of interest concerning this research field is the stable generation of steady vapor with homogeneous parameters such as vapor quality, mass flow, pressure or temperature.

Phase transition and accompanying phenomena during evaporation of water in microchannel arrays as well as influences of microstructure geometry were observed during these research studies. Optical investigations have been done using a digital high-speed camera for visualization of transient processes, e.g. explosively and confined bubble growing behavior or phase transition fluctuation.

Beside this, a novel test device for optical investigation is presented in this report. The test device enables to vary several variables like temperature, microstructure or pressure drop, to name but a few. Furthermore, results and influences of different microstructure geometries on phase transition as well as different shapes of phase transition fronts in microchannel arrays are presented. Additionally, the visualization of complete and stable phase transition in microchannel arrays with steam superheating is shown.

INTRODUCTION

Research activities in phase transition and resulting multiphase flow in microchannels have been drastically increased in the last decade. An overview of evolution, manufacturing methods and thermal performances of microstructured devices is given in [1] and especially for fabrication in metals in [2]. Since the pioneering work of Tuckerman and Pease [3] at the beginning of the 1980s, microstructure devices became more and more important in heat exchange applications like cooling of electronic devices, e.g. computer chips or high performance laser diodes [4]. Extremely large inner surfaces lead to extraordinary heat exchange efficiencies of microstructure heat exchangers. Thus, these devices are predestined for removing huge amounts of thermal energy by keeping compact dimensions [5], [6]. Increasing performances of computer chips leads to increasing requirements in heat exchange, which are accessible by using latent heat of evaporation [7], [8]. Microstructured heat exchangers enable nearly uniform temperature distributions during cooling of integrated circuits [9]. Thus, microstructured devices provide several advantages in transferring huge amounts of thermal energy, leading to high heat transfer coefficients in microchannels. An overview on recent research activities as well as high resulting heat transfer coefficients in microchannels is given in [10].

Other areas of application of microstructured devices are generation of multiphase flow or evaporation for steam generation. Electrically powered evaporators, which consist of microstructured metal foils, are particularly suitable to act as evaporators due to the easy applicability of thermal energy [11]. Therefore, many research activities and articles cover this interesting topic, e.g. the articles of Kandlikar [12], [13] and Thome [14] present an overview about boiling and related multiphase flow in microchannels, while [15], [16] deal with evaporation in microchannels.

Phase transition and multiphase flow in microchannels has not been investigated in all details yet. Hence, there is a lack of understanding which prevents a comprehensive description of these processes. Instabilities like pressure, temperature and mass flow fluctuations, such as the well known Ledinegg instability, occur during phase transition in microchannels. Confined and explosively bubble growing behavior lead to phenomena like vapor plugging, vapor slugging or diverting flow direction which cannot be found in macrochannels to a major extent. Intermittent fluid flow behavior was investigated by Brutin et al. [17], as well as diverting fluid flow direction by Qu and Mudawar [18]. Hetsroni et al. observed explosive bubble growing behavior [19] as well as fluctuations during boiling in microchannels [20]. These phenomena affect evaporation in microchannels negatively by producing inhomogeneous vapor with varying liquid droplet sizes and fluctuations such as pressure, temperature and mass flow oscillations at the device outlet.

OBJECTIVE

The main topic of these research activities is the investigation of phase transition and accompanying phenomena during evaporation in microchannel arrays, as well as the investigation of dependencies on the microstructure geometry on phase transition and related phenomena. For this purpose, a special device was designed which enables the optical investigation of phase transition in microchannels and related transient processes. Additionally, several investigations on phase transition have been done.

EXPERIMENTAL SETUP

The test device is designed as an evaporator with a glass window for optical inspection of processes in microchannels. A picture of this test device is presented in Fig. 1 and a detailed comprehensive description is presented in [21] – therefore, it will only be briefly introduced.

The device consists of a microstructured metal foil, which includes the microchannels or the microchannel array itself, as well as fluid inlet and outlet distribution systems. Exchangeable metal foils enable to investigate different microstructure geometries and their influences on phase transition and accompanying phenomena. The microstructure (microchannel array as well as fluid inlet and outlet) is covered by a glass lid for optical investigations which is sealed by standard gaskets to the test device. An HPLC-pump delivers water with constant mass flow rate and negligible mass flow pulsation ($\dot{V} \sim 1.7 \cdot 10^{-6}\ m^{-3} \cdot s^{-1}$ at maximum). The microchannels, or more precisely, the microstructured metal foils are heated by three thermally insulated copper heating blocks which are powered by up to three electrical resistor heater cartridges in each block. The heating blocks lead to a nearly homogeneous temperature distribution perpendicular to the fluid flow direction (±3 K at T ~ 450 K), due to the high thermal conductivity of copper. The thermal insulation, e.g. by air or ceramics, provides very sharp temperature profiles at the microchannel array, as witnessed by a temperature increase of 300 K from one block to the adjacent one. Besides this, cooling of one or more copper blocks is also possible to enhance temperature profiles or to investigate condensation.

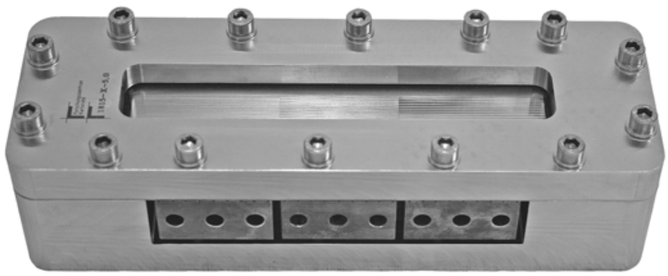

Figure 1: Test device; electrically powered evaporator with a glass window for optical investigation and exchangeable microstructured metal foils.

The device design permits the variation of several settings, such as fluid flow rate, pressure drop, temperature distribution or the microstructure itself. Exchangeable microstructures allow to investigate influences of several microstructure geometries, like fluid distribution systems or different channel shapes on phase transition. An example of a microstructured foil made out of stainless steel is presented in Fig. 2. The microchannel array consists of a multitude of parallel microchannels, which are connected to a collective inlet distribution system (left hand side in Fig. 2) as well as a collective fluid outlet (right hand side in Fig. 2). All microchannels are manufactured in-house at the IMVT by using e.g. micro-drilling and micro-sawing. These microstructure technologies enable to create rectangular shaped microchannels.

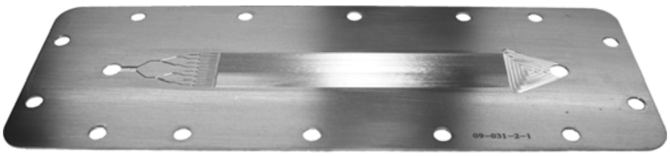

Figure 2: Microstructured metal foil made of stainless steel; array: parallel arranged and straight microchannels; cross-sectional area: 100 µm × 200 µm.

INVESTIGATIONS

A suitable and established technique for optical investigation of transient processes like multiphase flow or phase transition in microchannels is high-speed videography [15], [22-24].

In this study, investigations are performed by using a digital high-speed camera mounted to an optical stereo microscope. The camera is able to record picture sequences with frequencies of up to 200,000 pictures per second and exposure times of 0.5 µs at minimum, which lead to high-contrast pictures with reduced motion blur.

Computer-based batch processing is the preferred method to analyse the recorded picture sequences, each with several thousands up to a few million pictures. Analysis methods, e.g. automatic tracking analysis, enable to gain information on bubble growing behaviour or on phase transition boundary layer fluctuations. Furthermore, void fraction or liquid fraction is accessible by pixel intensity analysis [24].

RESULTS

Investigations were performed by using different inlet fluid flow distribution systems. Examples of such inlet fluid flow distribution systems are presented in Fig. 3. A special V-shaped distribution system is presented in Fig. 3-A, while an unstructured distribution system is presented in Fig. 3-B. A special treelike inlet fluid flow distribution system is shown in Fig. 3-C. The branches as well as the cross sectional areas of the distribution systems have been designed by using the bifurcation law [25], [26] to achieve a homogeneous fluid flow distribution at the microchannel array with low pressure drop.

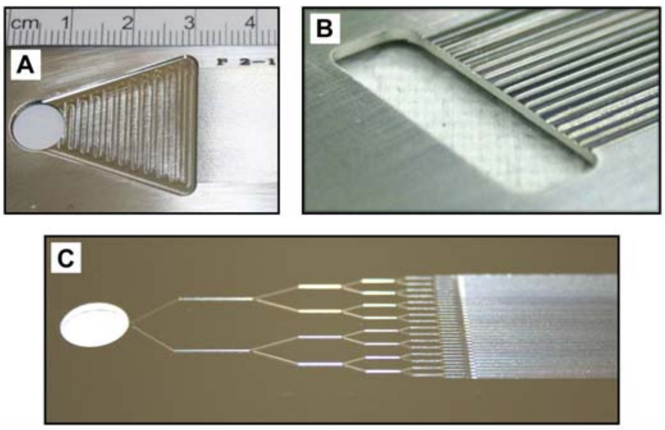

Figure 3: Different fluid inlet distribution systems; A: V-shaped, B: unstructured, C: treelike.

Fig. 4 and Fig. 5 present influences of the fluid flow distribution systems on the phase transition behavior. Fluid flow direction is form left to right. The liquid fluid is heated up in the microchannels (left-hand side in Fig. 4, 5) to the evaporation temperature and phase transition (evaporation) occurs (line between red markings). Hereafter the generated vapor is superheated (right-hand side in Fig. 4, 5). Fig. 4 depicts a parabolic phase transition front in a microchannel using the V-shaped fluid flow distribution system shown in Fig. 3-A. The parabolic shape of the phase transition front in Fig. 4-A might be caused by an inhomogeneous fluid flow distribution at the channel inlets. Different flow paths between inlet distribution entrance to channel inlets and resulting pressure drop differences, which are slightly higher at the outer channels, lead to inhomogeneous fluid flow distribution. Fig. 4-B presents a CFD simulation of the fluid flow distribution using the V-shaped distribution system. The Simulation was introduced in [27]. It depicts the fluid flow distribution at an overall volumetric flow rate of $3.3 \cdot 10^{-7}\ m^{-3} \cdot s^{-1}$. The simulation also shows an inhomogeneous fluid flow distribution at the channel inlets. Both shapes of phase transition front and flow distribution simulation present similar aspects.

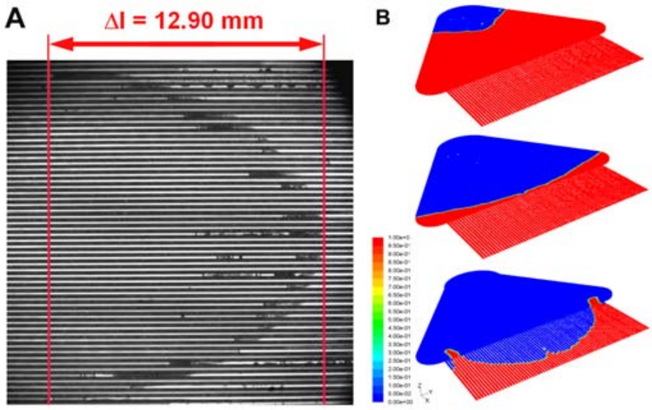

Figure 4: Phase transition using V-shaped fluid flow distribution system; A: parabolic phase transition front ($T \sim 403$ K, $G = 65\ kg \cdot m^{-2} \cdot s^{-1}$), B: simulation of fluid flow distribution (introduced in [27], $\dot{V} = 3.3 \cdot 10^{-7}\ m^3 \cdot s^{-1}$, $t = 0.104$ s, $t = 0.299$ s and $t = 0.334$ s).

Fig. 5 presents the shape of a phase transition front using a treelike inlet fluid flow distribution system shown in Fig. 3-C. This pressure drop optimized system (bifurcation law) should lead to identical pressure drops in every possible flow path of the microstructure in fluid flow direction. The phase transition front in Fig. 5-A is nearly perpendicular to fluid flow direction. This behavior suggests a homogeneous fluid flow distribution which is confirmed by a simulation of the fluid distribution in Fig. 5-B (introduced in [27]).

The length of the phase transition in fluid flow direction could be reduced (nearly halved) from $12.90 \cdot 10^{-3}$ m (V-shaped) to $6.70 \cdot 10^{-3}$ m using the treelike inlet fluid flow distribution system under nearly identical values of temperature, pressure, mass flow and channel cross-sectional area.

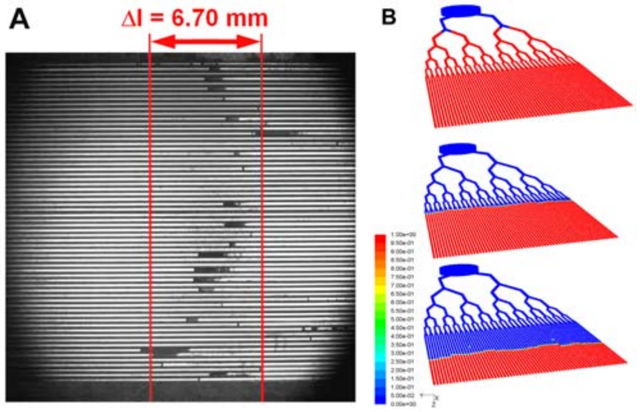

Figure 5: Phase transition using treelike inlet fluid flow distribution system (bifurcation-law); A: phase transition front perpendicular to the fluid flow direction ($T \sim 423$ K, $G = 65\ kg \cdot m^{-2} \cdot s^{-1}$), B: simulation of the fluid flow distribution (introduced in [27], $\dot{V} = 3.3 \cdot 10^{-7}\ m^3 \cdot s^{-1}$, $t = 0.209$ s, $t = 0.258$ s and $t = 0.287$ s).

A complete evaporation in a microchannel array is presented in Fig. 6. In this case, the array consists of 64 parallel microchannels (100 µm × 200 µm) and the used inlet distribution system is shown in Fig. 3-B. By using special defined temperature distributions at the heating blocks which create definite temperature profiles at the microchannels, it is possible to create a stable evaporation front and, additionally, a steam superheating of up to approximately 460 K.

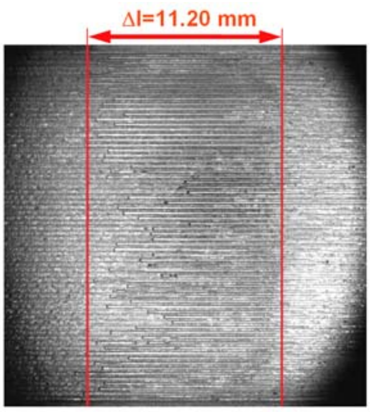

Figure 6: Complete evaporation and steam superheating up to approximately 460 K using water in a microchannel array out of 64 parallel microchannels (unstructured fluid flow distribution system, $T \sim 459$ K, $\Delta p = 1.53 \cdot 10^5$ Pa, $G = 65\ kg \cdot m^{-2} \cdot s^{-1}$).

CONCLUSION

A special test device has been designed for optical investigations of phase transition and accompanying phenomena in microchannels and microchannel arrays. This test device provides several degrees of freedom for variation of different parameters such as microstructure, temperature, pressure drop or mass flow. It enables to set temperature profiles to the microchannel arrays or to evaporate at increased pressure.

Influence of microstructure geometries like fluid flow distribution systems or channel outlets on phase transition and accompanying multiphase flow as well as different phase transition phenomena have been investigated during these research studies.

High-speed videography is a powerful tool for observing transient processes during phase transition in microchannel arrays. Phase transition phenomena like explosively and confined bubble growing behavior, diverting flow direction or fluctuating (oscillating) fluid flow have been observed.

By using special inlet flow distribution systems and defined temperature arrangements at the microchannels array, it is possible to create stable and controllable phase transition fronts in microchannel arrays. Temperature distribution as well as the inlet flow distribution system affects the shape, the length and the position of phase transition lines in the microchannel array.

Finally, stable and complete evaporation in microchannel arrays with different inlet distribution systems, including steam superheating, using various flow distribution systems have been realized and observed.

NOMENCLATURE

G	$kg \cdot m^{-2} \cdot s^{-1}$	cross sectional mass flow
Δl	m	length
Δp	Pa	overall pressure drop
t	s	time
T	K	temperature
$\dot{V}$	$m^3 \cdot s^{-1}$	overall volumetric flow rate

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