Microstructure Devices for efficient Evaporation of Liquids

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Abstract. Different microstructure devices used for evaporation and generation of steam are described in this publication. Starting with simple liquid-heated devices, electrically powered devices containing micro channels as well as non-channel microstructures are shown. An electrically powered device for optical inspection of the microstructures and the processes inside has been designed and manufactured. Exchangeable metallic micro channel array foils as well as an optical inspection of the evaporation process by high-speed videography have been integrated into this test system. Fundamental research onto the influences of the inlet flow distribution system geometry and the geometry and dimensions of the micro channels have been performed. A pre-calculation sheet for micro evaporators with micro channel arrays based on the measurement of inlet parameters for the liquid only was generated. While evaporation of liquids in micro channel devices of more or less conventional design is possible, it is, in many cases, not feasible to generate superheated steam due to certain boundary conditions. Therefore a new design was proposed to obtain complete evaporation and steam superheating, consisting of an arrangement of numerous circular blanks with connecting nozzles. A maximum power density of 1400 kW \cdot m^{-2} has been transferred while water could be completely evaporated and the generated steam superheated.

1. Introduction

Handling of phase transition in microchannels is one of the major tasks in present research activities for heat transfer or for the generation of steam. Since the pioneering work of Tuckerman and Pease [1], single phase operated microstructured devices became important in heat transfer applications due to their high heat transfer capabilities using small device dimensions. High performance state-of-the-art electronic components such as computer chips, laser diodes and voltage transformers require high heat fluxes for cooling. Additional increase of the heat transfer capabilities of single phase operated heat exchangers is enabled by using the latent heat of evaporation.

The research activities of Bowers and Mudawar [2], [3] as well as these of Hetsroni et al. [4] underline the positive characteristics of microstructured evaporators for heat exchange applications using small device dimensions. However, control of evaporation inside microchannels for the generation of a stable phase transition and especially for complete evaporation to generate humid or saturated steam is not trivial and negatively affected by phase transition phenomena such as vapor plugging, vapor slugging or diverting flow direction. These phenomena are caused, among other things...
things, by intensive bubble generation and explosively bubble growing behavior as presented by Maikowske [5]. Additionally, most of these phenomena are related to small channel diameters which lead to confined bubble growing behavior as described by Koşar et al. [6] or Wang et al. [7], to name but a few. Many activities have been done in this field of research for the characterization of these processes to obtain a comprehensive description of phase transition in micro geometries. Brutin et al. [8] studied the unsteady and oscillating behavior of two-phase flow, while Hetsroni et al. [9] and Xu et al. [10] investigated temperature and pressure oscillations during evaporation in parallel microchannels. Additional information about microstructured evaporators, suitable micro-geometries and investigation methods of evaporation are given by Anurjew et al. [11].

2. Microchannel Evaporators and Visualization

First attempts to evaporate water have been done using micro channel heat exchangers in crossflow design. Manufacturing of these devices was described before in details (see, e.g., [12], [13], [14]). Aside of conventional long straight micro channels, different more complex structures have also been tried out. Figure 1 shows different examples for micro structured foils made of stainless steel and integrated into micro heat exchangers.

Several experiments with those devices showed that evaporation of water is possible, using hot thermo oil in the heating passage of the device. However, total evaporation was hard to obtain, wet steam was generated containing very high percentage of droplets, and, in most cases, no superheating could be performed. This was, at least partly, due to short residence time of the fluid and limited temperature of the heating side.

To overcome these restrictions electrically powered micro heat exchangers have been developed, manufactured and tested to provide higher temperatures with good controllability of the power supplied. These devices have been described in details in [15] and [16]. As it was done with the fluidically driven, not only long linear micro channels but complex microstructures have been tested within the electrically powered devices.

Additionally, secondary designs of electrically powered devices providing cylindrical arrangements of one or more micro channels around a centric heater cartridge was manufactured. Figure 2 shows a picture of the simplest design of an electrically powered rod evaporator. This device provides good evaporation performance independently of the direction of the steam outlet.

It could be shown that, depending on the applied mass flow, either a single microstructure device or a two-stage-arrangement, which means two devices in a row, can be used for complete evaporation and superheating of water and other liquids. A superheating was not possible with a single device. Substantial data on the droplet content contained in the vapour flow could be obtained by a simple photometer setup, which gives at least a qualitative result on the steam quality. A photo current was measured, obtained by scattered laser light in full reflection from the vapour outlet of different arrangements of electrically powered devices. The amplitude of photo current could directly be correlated to the droplet content of the vapour as well as to the vapour temperature [12], [17]. Quantification is not possible yet due to the fact that a reference is extremely hard to define.

To obtain more and detailed information about the evaporation process itself, a device with exchangeable microstructure foils was generated, allowing optical access through a glass lid on top of the microstructures. The device, depicted in Figure 3, is heated electrically in three independent sections, providing the possibility to generate three independent temperature zones inside the microstructure. Parameters, such as temperature, applied electrical power, volume flow rate or pressure drop, can be varied easily. Additionally, microstructured metal foils – including multi-micro channel arrays – are exchangeable. Thus, phase transition and multiphase flow in several kinds of different micro channel geometries and arrangements could be investigated.

The experimental setup used contains a microscope in combination with a digital high-speed camera. The microscope is arranged above the horizontal multi-micro channel layer. The digital high-speed camera records pictures at frequencies of up to 200,000 frames per second with very low motion
blur. Special computational algorithms can be used to analyse these recorded high-speed picture sequences to extract information about different phases. With this optical instrumentation, numerous experiments have been performed to clarify bubble generation processes in single microchannels as well as influences of the inlet void and cross talking between parallel microchannels in arrays. However, the evaporation process is somehow limited due to the fact that the glass lid is not heated — thus, re-condensation can take place at this part of the microchannels. Sometimes the analysis of the high-speed visualization shows single droplets re-generated by condensation on the glass lid. However, the influence is estimated to be marginal. Use of electrically heated glasses might be possible, but the authors could not find an electrically heated glass suitable for the device and the process conditions.

Three different types of inlet void geometries have been examined for their influence to the phase transition frontline, namely a triangular distributor, an open rectangular void and a tree-like distributor following the 3rd power law [18]. Numerous microstructure foils providing these different types of voids have been tested. The three different distribution systems are schematically shown in Figure 4. The evaporation frontline obtained with the rectangular open void showed a shape similar to an arrow tip, while that one of the triangular distribution system resulted in a parabolic phase transition frontline, while the phase transition frontline obtained with the tree-like flow distribution systems is more or less linear and perpendicular to the flow direction [18]. The different shapes of the phase transition frontlines are shown in Figure 5 (a)-(c). Results are more or less the same for all tested microstructure foils. In this figure, flow direction is always from left to right.

The different shapes of phase transition frontlines are most likely caused by a residence time distribution of the fluid in the channels. This enables a total evaporation at the outermost channels of the array earlier than in the center channels, due to the higher residence time in the outermost channels. This effect is minimized by using a tree-like distribution system for the flow [19].
3. Precalculation of evaporation

Precalculation or simulation of evaporation processes is amongst the most complex topics in CFD. Currently a full simulation of such processes within microchannel arrays was not described in literature, due to the complexity of the accompanying phenomena as well as the still not precisely enough known specific processes ongoing while the evaporation takes place.

Therefore, it was tried to establish a very simple precalculation algorithm to decide whether a fluid can be fully evaporated (and maybe superheated) or not, linked directly to the design of the microchannel arrays used in devices similar to the one shown in Figure 3.

The calculation method is based on measured flow parameters at the inlet of the microchannel array only, combined with the p,v-diagram of the used fluid. Fundamental considerations of this has been done by Bošnjaković [20]. It was shown in [21] that this prediction model can be used quite well for different fluids when an empirical correction factor (taking tolerances, uncertainties and non-ideal behaviour of the fluid into account) is implemented. However, the method is by far not generally valid but strictly linked to the micro evaporators described here, where it serves well for pre-designing new devices, optimizing the microchannel geometry and finding possible weak points of the evaporator types. It is planned to extend the model also to other device types.
4. New Evaporator design

Using a simple array of parallel microchannels does not take into account the volume increase of the phase transition. For water, the volume is increased by at least a factor of 1000, which somehow limits the evaporation in microchannels. For this reason, new types of microstructure evaporators are considered.

One possibility is the use of concentric circular or elliptic blanks, providing circular or elliptically shaped ring walls which are arranged concentrically around a feed hole [11]. Each of the ring walls show two or more overflow openings, which act as expansion nozzles. Figure 6 shows a schematic example of such a microstructure including the flow path through the device. The evaporator is generated on a round plate with 17 mm diameter. Devices like this have been manufactured from polymer and copper so far, providing either semicircular or semi-elliptic sidewalls in a concentric arrangement. Possible applications may be flash evaporation of liquids (e.g. for chemical processes), surface cooling by evaporation or controlled generation of superheated steam for processes in pharmacy and fine chemical industry. Figure 7 shows an SEM of the overflow structure of an elliptically shaped arrangement.

The semi-elliptic sidewalls provide a better performance in terms of evaporation, since the two-phase flow is constricted before each overflow nozzle (red circle in Figure 7), mixed through and expanded into the next stage of the evaporator. This is schematically shown in Figure 7 with the coloured arrows.

With circular blank designs several tests have been performed using a metallic adapter system to house the microstructures. Water inlet and steam outlet as well as electric heaters and sensors have been integrated into the adapter system, which is shown in Figure 8.

Water mass flow was varied between 0.3 kg · h⁻¹ and 1.0 kg · h⁻¹, and evaporation was performed against ambient outlet pressure. Depending on the design and the number of sidewalls inside the arrangement, entrance pressure was established. The electrical heating power applied was varied according to this mass flow range to obtain full evaporation and superheating. A heating surface temperature limit of about 170 °C was randomly set, resulting in an applied electrical power of about 820 W and an evaporation power of 600 W for the maximum mass flow.
The relatively large difference between applied electrical power and evaporation power is heat losses as well as the power consumed for superheating. In future experiments this will be measured directly to obtain more precise data on the efficiency of the device with regard to evaporation and superheating. The power applied for superheating can be neglected in comparison to what is needed for evaporation. For this reason it can be assumed that most of the power difference is heat losses to the environment. However, newer measurements show a non-negligible influence of the temperature sensor position as well as the thermal insulation of the temperature sensors in relation to the outlet tube systems. More experiments have to be performed to define a system suitable for real heat transfer efficiency measurements.

Several designs have been tested experimentally. The main focus was set to three points: how many semi-circular walls (semi-elliptic walls) are really necessary for evaporation and superheating, what is the influence of the position of these walls, and is there a connection between the steam temperature and the number and arrangements of walls? Therefore, the temperature of the outlet steam was measured at different positions away from the outlet of the evaporator. In any case of the experiments, the outlet pressure was ambient.

It could be shown experimentally that it is possible to fully evaporate a liquid flow with a single sidewall arrangement (which means two nozzles between two parts of walls) of elliptical or circular shape, no matter which position this sidewall is located on the blank. The outlet temperature of the generated steam at ambient pressure was always in the range of 105°C. Such an arrangement is only suitable for superheating, if it is arranged at the outermost circumference of the microstructure inlay.
In this case, the outlet temperature of the steam, measured at ambient pressure, can be raised to several hundred degrees centigrade. A single circular blank with sidewalls arranged directly around the water inlet will lead to complete evaporation, but almost no superheating is possible with this arrangement – a temperature of about 105°C is reached at ambient pressure. Mid positions increase the possibility of superheating slightly. However, a maximum power density of 1400 kW · m⁻² has been transferred using semi-elliptic sidewall systems, while water was completely evaporated and the generated steam superheated.

**Figure 8.** Adapter system for circular blank evaporators. The evaporator structure is exchangeable, while the housing is kept. Electrical heating is obtained from below by commercially available heater cartridges. In the lid of the housing (not shown on this picture), sensors for temperature and pressure have been integrated.

### 5. Conclusion

Metallic microstructure devices with multi-micro channel array arrangements for evaporation of liquids, especially water, have been designed, manufactured and tested. Fluid driven devices in crossflow and counter-current or co-current design are quite limited in evaporation efficiency, while electrically powered devices are much more flexible to use. A special device was generated to allow optical inspection of the evaporation process through a glass lid by high speed videography. Moreover, a very simple pre-calculation model was designed to allow to decide whether a liquid flow can be fully evaporated and superheated within the microstructure. This model is based on measured values of the inlet only and strictly linked to the microstructure design by an empirical correction factor.

Several evaporation effects like micro channel plugging have been visualized, and different designs of the inlet for flow distribution into the micro channel array have been tested. It was found that long straight micro channels are not optimal for evaporation. Moreover, it was found that the inlet distribution system strongly influences the shape of the phase transition front line. Therefore, a tree-like distribution system according to the 3rd power law was designed and tested, which showed very good results.

A new design based on circular blanks including numerous circular or elliptic sidewalls at different positions have been tested. It was shown that full evaporation and superheating could be obtained with a single side wall at the outer limit of the circular arrangement, while a single side wall at the inner perimeter results in full evaporation but no superheating. This arrangement is only suitable for a certain mass flow range, as it was shown. Further investigations will be done to optimize the performance and to allow a pre-calculation of the design to the desired mass flow as well as to the superheating temperature.
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