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Microstructure devices for water evaporation

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ABSTRACT

Evaporation of liquids is of major interest for many fields in process engineering. One of these is chemical process engineering, where evaporation of liquids and generation of superheated steam is mandatory for numerous processes. Generally, this is performed by the use of classical pool boiling and evaporation process equipment, providing relatively limited performance, or by other systems like falling-film or membrane evaporators. Due to the advantages of microstructure devices especially in chemical process engineering the interest in microstructure evaporators and steam generators has increased through the last decade. In this publication different microstructure devices used for evaporation and generation of steam are described. Starting with simple liquid-heated devices, different types of electrically powered devices containing micro channels as well as non-channel microstructures will be shown. While evaporation of liquids in crossflow and counterflow or co-current flow micro-channel devices is possible, it is, in many cases, not possible to obtain superheated steam due to certain boundary conditions. Thus, a new design was proposed to obtain complete evaporation and superheating of the generated steam.

1. Introduction

Microstructured devices have become increasingly important in thermal and chemical process engineering within the last years. These devices are often made out of microstructured metal foils, which are connected by diffusion bonding, as it was described in detail by Brandner [1] and Brandner et al. [2]. The hydraulic diameters of the micro channels, generated by precision machining or wet chemical etching, are in the range of a few hundred micrometres.

Metallic microstructure devices provide high pressure resistance and small residual volumes. Due to the size of the microstructures they act as flame stoppers or explosion barriers; thus they are well suited to handle dangerous or explosive fluids (see e.g. Schubert et al. [3], Goedde et al. [4]). The small dimensions of micro channels enable very high surface-to-volume ratios up to 30 000 $m^2\ m^{-3}$ and more, which are about one or two orders of magnitude higher than those of conventional process engineering devices. As pointed out by Brandner [1] and Brandner et al. [5], this high surface-to-volume ratio leads to increased heat transfer, the micro dimensions of the channels to short diffusion lengths. Therefore, microstructure devices are well suited for operations dealing with high heat fluxes and rapid mass transfer like evaporation.

Phase transition and multiphase flow in macro channels have been intensively investigated and are well known and understood. In micro channels, phase transition related phenomena and multiphase flow have been partially investigated and described, e.g. by Thome [6]. Most results presented so far have been obtained with single micro channels, sometimes micro-channel arrays have been investigated for their behaviour in evaporation. However, results about the phenomena occurring in micro-channel arrays are often not consistent, depending on the experimental setup, the fluid looked at the measurement methods. Hsieh et al. [7] described saturated flow boiling of a refrigerant, taking place in a microstructured annular duct. In principle, the duct was a single micro-channel, arranged in a helical way on the outside of a copper tube. The authors present interesting results of the microstructured duct rather different to that of a smooth one. Wang et al. [8] published results of water flow boiling in a single micro-channel as well as in an array of parallel micro channels. They examined the influences of the inlet void to evaporation and, therefore, showed significant differences between flow boiling in a single micro-channel compared to that in a parallel micro-channel array, caused by the inlet structure and a possible crosstalk between neighbouring micro channels through the inlet void. Zhang et al. [9] gave a correlation for the evaporation heat transfer in miniaturized channel systems, based on the modification of an older correlation presented by Chen [10]. Zhang et al. reviewed numerous correlations obtained theoretically and experimentally with different fluids, and compared those for their applicability to channels providing small dimensions.

More research activities have been focused on micro-pin-fin arrays, mostly made of silicon (see Honda et al. [11], Krishnamurthy

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et al. [12], Koşar et al. [13], Lie et al. [14] and Ma et al. [15]). Some research groups used copper as base material (Qu and Siu-Ho [16], Qu and Siu-Ho [17]). In most of these studies, a refrigerant was used as coolant liquid, rarely water was used. All publications showed flow boiling enhancement by the microstructure arrays. Krishnamurthy and Peles [12] stated that the flow boiling heat transfer coefficient was independent from the heat flux but depending on the mass flux. They tried also to predict the experimental values by a superposition of a Reynolds-type analogy, which showed reasonable deviations attributed to insufficient correlations for the two-phase frictional multiplier in micro scale. Therefore, Qu and Siu-Ho [16] presented an improved model showing good agreement between experimental data and prediction, followed by a comparison of existing correlations to predict the pressure drop in pin-fin heat sinks while evaporation and two-phase flow takes place (see Ref. [17]) In the latter publication, the authors also stated that micro-pin-fin structures provide better evaporation and flow stability than micro-channel arrays due to the interconnections between the single micro structures. Finally, Honda et al. [11] took also the roughness of the structures themselves into account. However, micro-pin-fin arrays in all the named publications were made of numerous micro columns of certain shape, which have been arranged in a more or less staggered way.

2. Metallic multi-micro channel devices

First attempts to evaporate water at KIT have been done using micro-channel heat exchangers in crossflow design. Manufacturing of these devices was described before in detail by Brandner [1], Brandner et al. [2] and Schubert et al. [3]. Fig. 1 shows different examples for microstructure foils integrated into crossflow heat exchangers made of stainless steel, shown in Fig. 2. A stainless steel counterflow heat exchanger is shown in Fig. 3.

Several experiments with crossflow devices showed that evaporation of water is possible, using hot thermo oil in the heating passage of the device. However, wet steam was generated containing very high percentage of droplets, and no superheating could be obtained. This was, at least partly, due to short residence time of the fluid and limited temperature of the heating side. Thus, Henning et al. [18,19], described the development of electrically powered micro heat exchangers which has been manufactured and tested to provide higher temperatures with good controllability of the power supplied. Fig. 4 shows three different sizes of electrically powered micro heat exchangers.

With these devices, not only straight rectangular micro channels but also semi-elliptic micro channels in convoluted or sinusoidal arrangements have been tested for evaporation. It could be shown by Knauss et al. [20] 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.

Substantial data on the droplet content in the vapour flow could be obtained by a simple photometer setup. 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. A more detailed description of this has been given by Brandner [1] and Vittoriosi [21].

3. Multi-micro channel device for visualization of evaporation

Although evaporation of liquids can be performed successfully using devices like those described in Section 2, it was still not quite clear which parameters strongly influence the evaporation process inside a multi-micro-channel system. Numerous research activities have been done to clarify the evaporation processes taking place in single micro channels, e.g. by Bauer [22], Cortina-Diaz [23], Chen et al. [24], Coleman and Garimella [25] and Cubaud and Ho [26], some have been dedicated to multi-micro-channel array evaporators (see e.g. Wang et al. [8], Honda et al. [11], Krishnamurthy and Peles [12]).

An electrically powered stainless steel frame was manufactured to allow the exchange of micro-channel structures as well as the optical inspection of the processes inside the micro channels using

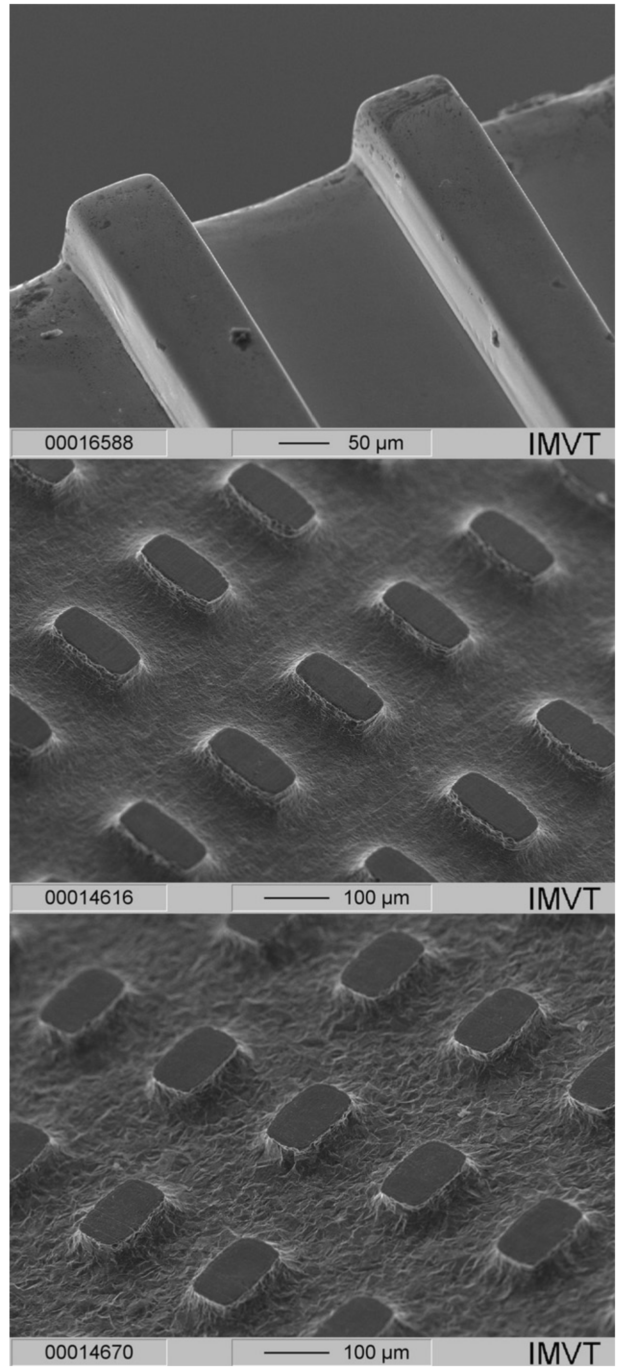

Fig. 1. Stainless steel microstructure foils to be integrated into crossflow heat exchanger devices. Top–down: Micro-channels arrays, linear micro columns, staggered micro columns. All microstructures have been made of stainless steel.