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MICROSTRUCTURE DEVICES FOR WATER EVAPORATION

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ABSTRACT

Evaporation of liquids is of major interest for many topics 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 use of classical pool boiling and evaporation process equipment. Another possibility is creating mixtures of gases and liquids, combined with a heating of this haze. Both methods provide relatively limited performance. Due to the advantages of microstructure devices especially in chemical process engineering [1] the interest in microstructure evaporators and steam generators have been increased through the last decade.

In this publication several microstructure devices used for evaporation and generation of steam as well as superheating will be described. Here, normally electrically powered devices containing micro channels as well as non-channel microstructures are used due to better controllability of the temperature level.

Micro channel heat exchangers have been designed, manufactured and tested at the Institute for Micro Process Engineering of the Karlsruhe Institute of Technology for more than 15 years. Starting with the famous Karlsruhe Cube, a cross-flow micro channel heat exchanger of various dimensions, not only conventional heat transfer between liquids or gases have been theoretically and experimentally examined but also phase transition from liquids to gases (evaporation) and condensation of liquids.

However, the results obtained with sealed microstructure devices have often been unsatisfying. Thus, to learn more onto the evaporation process itself, an electrically powered device for optical inspection of the microstructures and the processes inside has been designed and manufactured [2]. This was further optimized and improved for better controllability and reliable experiments [3]. Exchangeable metallic micro channel array foils as well as an optical inspection of the evaporation process by high-speed videography have been integrated into the experimental setup. Fundamental research onto the influences of the geometry and dimensions of the integrated micro channels, the inlet flow distribution system geometry as well as the surface quality and surface coatings of the micro channels have been performed.

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 [4]. In most cases, the residence time is not sufficiently long, or the evaporation process itself can not be stabilized and controlled precisely enough. Thus, a new design was proposed to obtain complete evaporation and steam superheating. This microstructure evaporator consists of a concentric arrangement of semi-circular walls or semi-elliptic walls providing at least two nozzles to release the generated

steam. The complete arrangement forms a row of circular blanks. An example of such geometry is shown in Figure 8.

A maximum power density of 1400 $kW \cdot m^{-2}$ has been transferred using similar systems, while liquid could be completely evaporated and the generated steam superheated. This is, compared to liquid heat exchanges, a small value, but it has to be taken in account that the specific heat capacity of vapor is considerably smaller than that of liquids. It could also be shown that the arrangement in circular blanks with semi-elliptic side walls acts as a kind of micro mixer for the remaining liquid and generated steam and, therefore, enhances the evaporation.

INTRODUCTION

Microstructured devices have become increasingly important in thermal and chemical process engineering within the last years. Metallic devices are often made out of micro structured foils, which are connected by diffusion bonding, laser welding or soldering (see [5, 6, 7]). The hydraulic diameters of the micro channels, generated by precision machining or wet chemical etching, are in the range of a few ten to some hundred micrometres.

Metallic microstructured devices provide high pressure resistance and small residual volumes. Due to the size of the microstructures they act as flame arresters or explosion barriers; thus they are well suited to handle dangerous or explosive fluids (see e.g. [7, 8, 9]). The small dimensions of micro channels enable very high surface-to-volume ratios up to 30 000 $m^2 \cdot m^{-3}$, which are about one or two orders of magnitude higher than those of conventional process engineering equipment devices. Moreover, the distances for heat and mass transfer are in the range of the diffusion length of the fluids, as explained in [5, 10]. Therefore, microstructured devices are well suited for operations dealing with high heat fluxes and rapid mass transfer like evaporation.

Phase transition phenomena and multiphase flow in macro channels have been intensively investigated and are well known and understood. Even pre-calculation of certain structures is sometimes possible. In micro channels, phase transition, related phenomena and multiphase flow have only been partially investigated (see e.g. [11]). Many results presented so far have been obtained with single micro channels, sometimes multi-micro channel arrays have been investigated for their behavior in evaporation. Most structures have been obtained from silicon or as single capillaries, rarely other microstructures have been used for research.

However, results about the phenomena occurring in multi micro channel arrays are often not consistent, depending on the experimental setup, the fluid looked at and the measurement methods. Moreover, in most cases researchers do not take care for the volume increase while the fluid is transferred from the liquid to the gas phase in terms of changing the microstructure design to avoid high pressure pulsation, pressure rise and backflow or other phenomena. Thus, microstructure devices taking this effect into account should provide better performance in terms of phase transition than the simple micro channel devices.

METALLIC MULTI-MICRO CHANNEL DEVICES

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., [5, 6, 7]). 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.

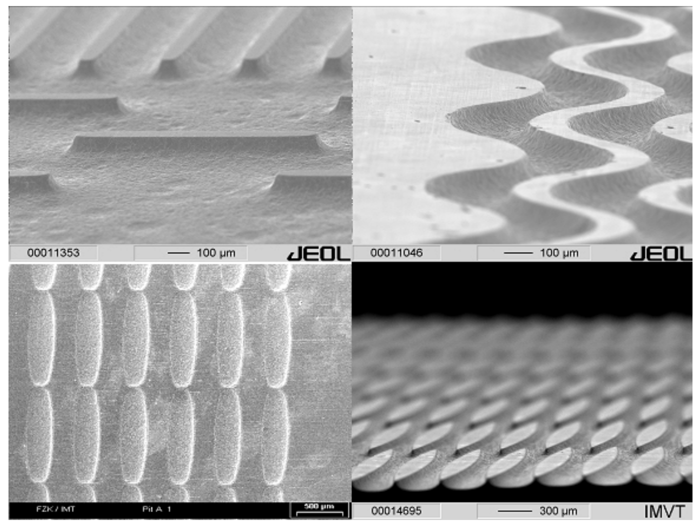

Figure 1: Microstructures manufactured in stainless steel integrated into micro heat exchangers.

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 [12, 13]. 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 single a cylindrical arrangement 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.

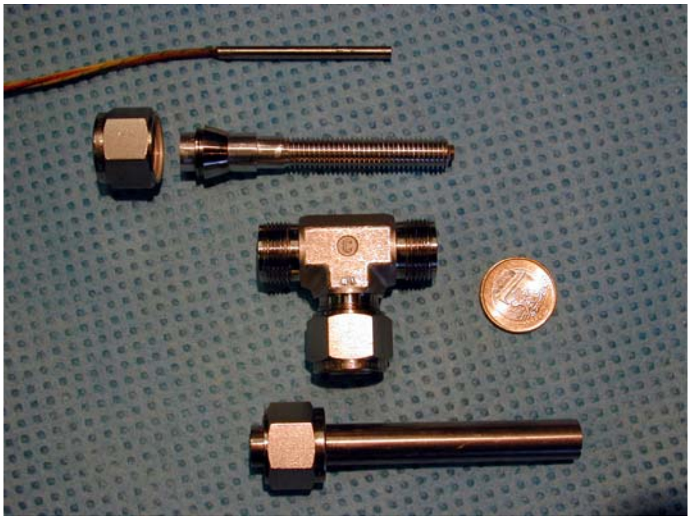

Figure 2: Electrically powered micro channel rod evaporator.

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 [14, 15]. Substantial data on the droplet content contained in the vapor 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 vapor outlet of different arrangements of electrically powered devices. The amplitude of photo current could directly be correlated to the droplet content of the vapor as well as to the vapor temperature [5, 16]. Quantification is not possible yet due to the fact that a reference is extremely hard to define. First experiments have been performed by using a simple boiling pot and a commercially available steam cleaner, but led to preliminary results only (see [16]). Figure 3 shows a schematic of the experimental setup for the steam quality evaluation as well as some pictures of the laser scattering, depending of the droplet content of the steam.

MULTI-MICRO CHANNEL DEVICE FOR VISUALIZATION OF EVAPORATION PROCESSES

Although evaporation of liquids can be performed successfully using devices like those described in the section above, 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 and fluid flow regimes taking place in single micro channels (see e.g. [17, 18, 19, 20, 21]), but not so many research activities have been dedicated to multi-micro channel array evaporators.

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 high speed videography [2, 5]. An improved device providing the same characteristics but better performance is shown in Figure 4 [3, 22, 23]. Here, also the method of high-speed visualization is described in detail.

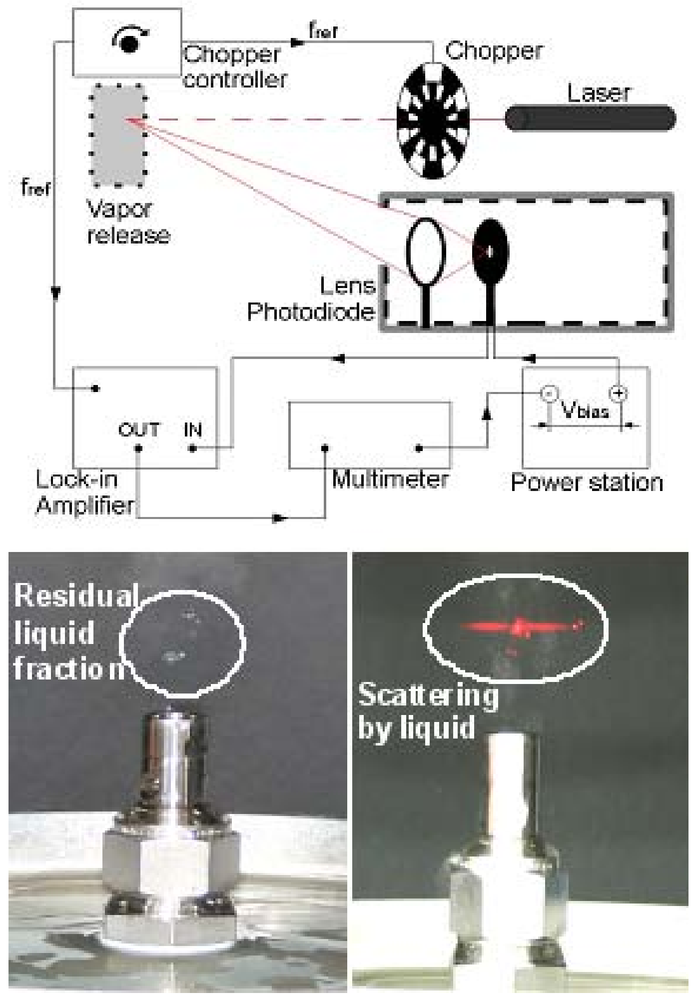

Figure 3: Experimental setup for steam quality determination, laser scattering by drops (left) and foggy vapor (right).

Parameters like 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.

Figure 4: Electrically powered microstructure device, providing exchangeable micro channel foils and a glass lid for high speed videography.

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.

PHASE TRANSITION FRONTLINE

Aside of the well-known phenomena like crosstalk between nearby micro channels, crosstalk via the inlet void, backflow of bubbles, bubble blocking and slugging etc. a special focus was set to obtain a stable and controllable phase transition frontline. All observations of evaporation were performed with liquid water and related steam in micro channels or microstructures with rectangular cross-sections in the range of about 200 µm (width) and 100 µm (depth).

The above mentioned phase transition phenomena lead to non-uniform fluid flow distribution in multi-micro channel arrays and result in non-uniform vapor quality at evaporator outlets. Controlling or reducing these phenomena results in a nearly constant phase transition inside of multi-micro channel arrays and in a related constant vapor quality at the evaporator outlet. Figure 5 shows an example of such a nearly constant phase transition inside of a multi-micro channel array.

The parabolic shape is most likely caused by non-uniform fluid flow distribution at the channel entrances.

By use of a tree-like distribution system at the entrance of the multi-micro channel array to provide equal distribution of flow velocity to all micro channels the parabolic shape might be avoided. This type of distributing system shows an equal distribution of the residence time in the evaporation area. Figure 6 shows a microstructure foil with a tree-like distribution system and detailed SEM pictures of the branches. The dimensions have been pre-calculated according to the bifurcation law (Bejans law) [24].

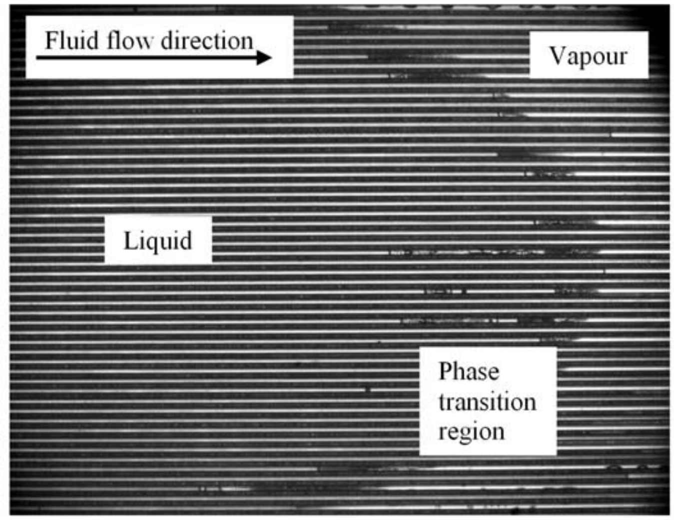

Figure 5: Nearly constant phase transition inside of a multi-micro channel array at a temperature of about 130°C.

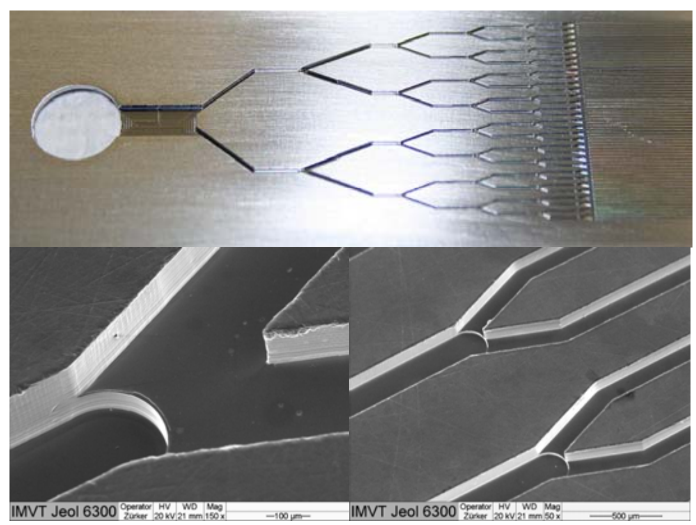

Figure 6: Tree-like distribution system for the fluid inlet to a micro channel evaporator.

The tree-like system was tested, and, as predicted, the parabolic shape of the phase transition front could be drastically changed to a phase transition front more or less perpendicular to the streamline and the micro channel direction.

It could be shown by CFD simulations that the open, triangular void results in a parabolic phase transition line, while the tree-like branching system will lead to an almost rectangular phase transition line inside the multi-micro channel array [25, 26]. Figure 7 shows CFD simulation pictures as well as experimental results for both cases, the triangular and the tree-like inlet structure.

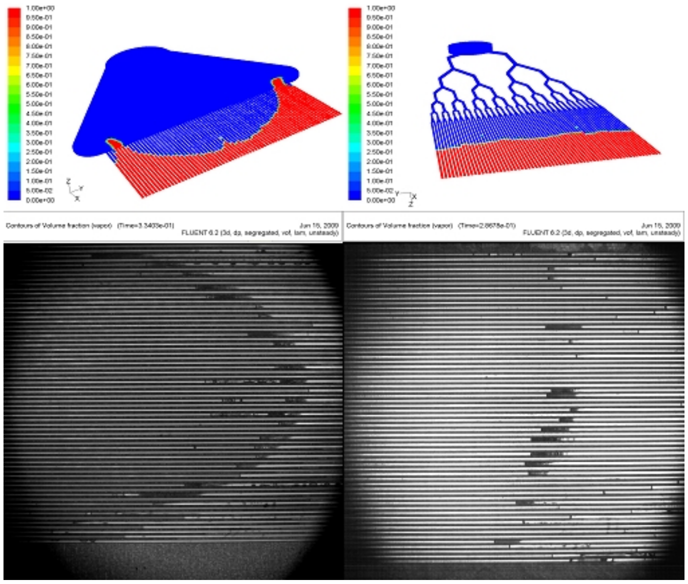

Figure 7: CFD-simulation and experimental results for a triangular inlet and a tree-like inlet for the multi-micro channel evaporator. Left column: Triangular inlet void, right column: tree-like shaped inlet structure.

CIRCULAR BLANK EVAPORATOR DESIGN

Due to the strong increase in volume while the phase transition takes place evaporation in long straight micro channels is limited. This is based on thermodynamic considerations. It is, in many cases, possible to evaporate a liquid volume flow completely, but superheating is difficult. A flow velocity limit, depending on the temperature and the pressure inside the evaporation system, can be obtained [4]. This flow velocity limit provides information on the maximum volume flow which can be evaporated and superheated using straight micro channels. A simple pre-calculation sheet was generated to find out whether certain micro channel designs are suitable for evaporation and superheating or not.

However, it is more than useful to think about micro evaporator designs which are not limited by flow velocity. 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. Each of the ring walls show two or more overflow openings, which act as expansion nozzles. Figure 8 shows two principle examples of such microstructures, each generated on a round plate with 17 mm diameter. Devices like this have been manufactured from polymer and copper so far. Figure 9 shows an SEM of the overflow structure of an elliptically shaped arrangement.

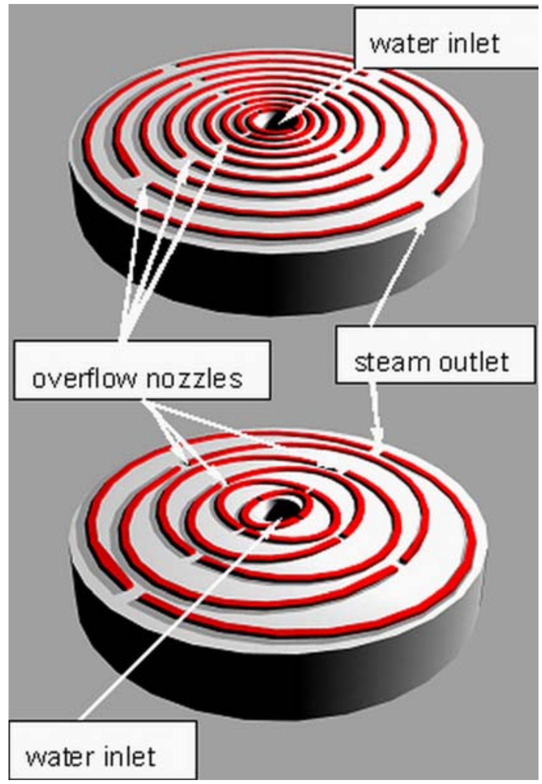

Figure 8: Examples for circular blank arrangements used for water evaporation.

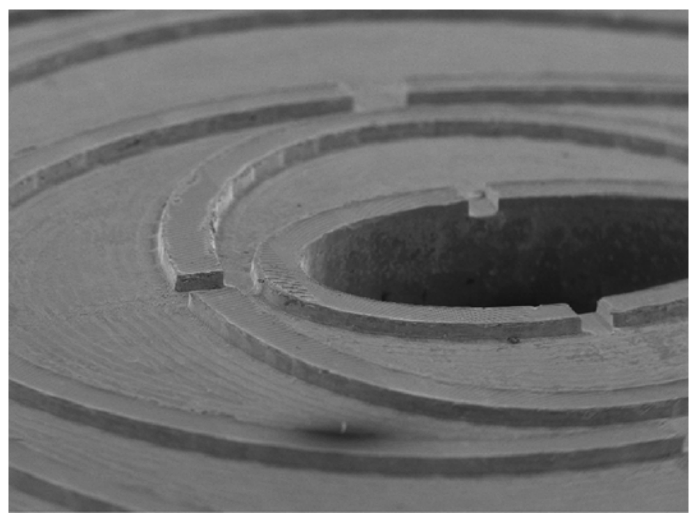

Figure 9: SEM of an elliptically shaped blank arrangement.

The experiments have been performed using a metallic adapter system to house the circular blank arrangements. Water inlet and steam outlet as well as electric heaters and sensors have been integrated into the adapter system, which is shown in Figure 10.

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 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.

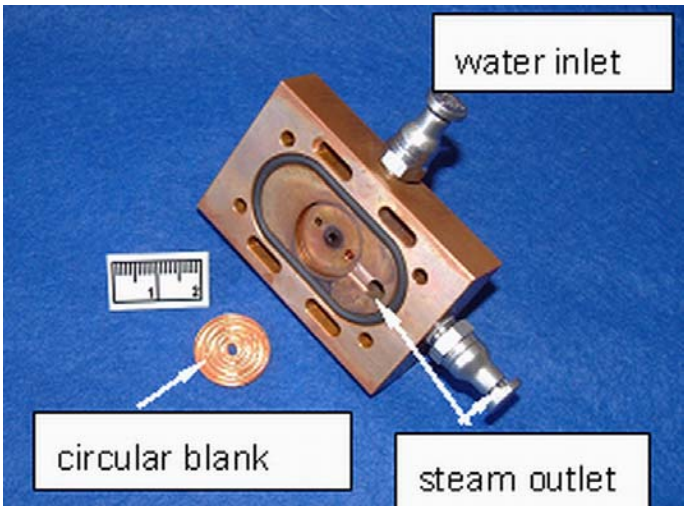

Figure 10: Test adapter system to house copper circular blanks.

Experimental parameters are summarized briefly in Table 1. The differences between applied electrical power and evaporation power are 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 here 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?

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. Such an arrangement is only suitable for superheating, if it is arranged at the outermost circumference of the microstructure inlay. 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. Mid positions increase the possibility of superheating slightly.

Table 1: Evaporation and superheating parameters for experiments with different geometries.

Water mass flow [kg · h^{-1}]	0.3	0.5	0.7	1.0
Heating surface temperature [°C]	130	140	155	170
Applied electrical power [W]	254	407	560	820
Evaporation power [W]	190	306	430	600

Results of such experiments are given in Figure 11 and Figure 12. The outlet steam temperature is plotted against time for complete evaporation. This plot style was chosen to show the transient behaviour of superheating. In all experiments the flow velocity of the steam was increased drastically due to an increase in volume by the evaporation inside the circular blanks. Maximum flow velocity and maximum superheating temperature are coincident, which is shown in both figures Figure 11 and Figure 12 by reaching the saturation.

Figure 11 shows the outlet steam temperature obtained with the same water mass flow of 0.7 kg · h^{-1} and the same electrical power, but different circular blank arrangements. It is clear shown that evaporation and superheating can be obtained with the sidewalls arranged at the outer limit of the circular blank, but not with those arranged at the inner limit. Here, only evaporation is possible.

More experiments showed that the number of sidewalls or structures inside the outer limits of the circular blanks influences the exit temperature of the steam as well as the rise time to the maximum temperature. At the same water mass flow of 1.0 kg · h^{-1} and the same electrical power applied three different arrangements have been tested for their capability to generate superheated steam. It was shown that a slight superheating was possible with a single sidewall arrangement at the outer limits. Higher temperatures have been obtained when several inner sidewalls or structures have been used. The same results have been obtained with circular sidewalls and similar with elliptical ones, as it is shown in Figure 12.

The plots in Figure 12 show that the steam temperature is decreasing with decreasing number of sidewalls, and that steam superheating is slightly possible with a single sidewall arrangement at the outer blank limit. No higher temperature is possible, no matter what electrical power is applied.

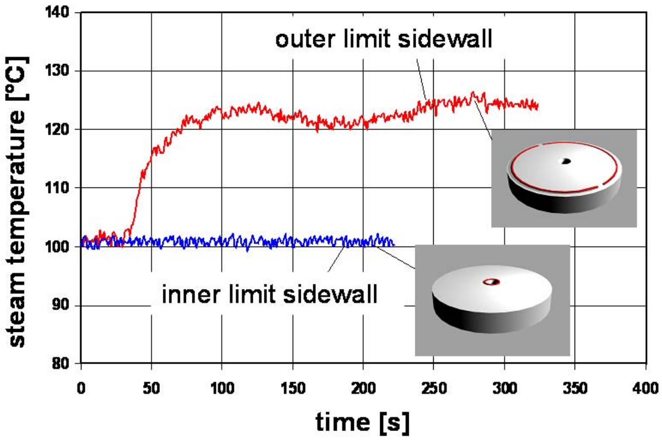

Figure 11: Results obtained with two different sidewall arrangements, applying the same electrical power and water mass flow. It is clearly to see that only the arrangement of sidewalls at the outer limits of the circular blank leads to steam superheating.

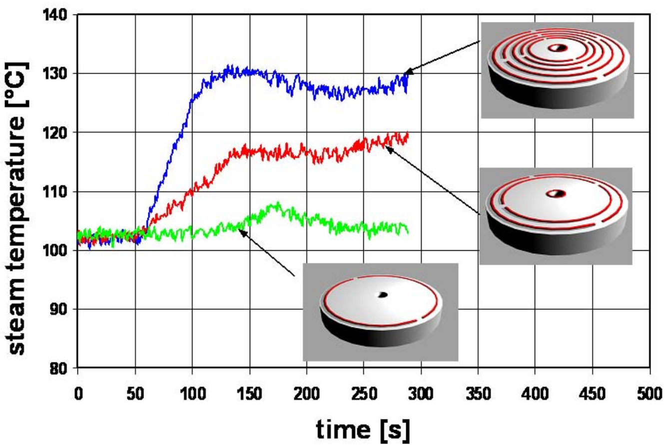

Figure 12: Steam outlet temperature obtained with different numbers of sidewalls.

This can partly be explained by an increase of evaporation pressure due to the larger numbers of circular blanks, but the pressure difference between the two structures used for the middle and the upper plot are within measurement uncertainty. Thus, more experiments have to be performed to clarify the influence of pressure inside the circular blanks. However, the steam temperature shown in Figure 12 was measured at ambient pressure at the outlet of the vapor.

The plots shown in Figure 11 have been obtained with a lower water mass flow of 0.7 kg $\cdot$ h^{-1}. Thus, a mass flow limit for the use of a single sidewall arrangement for superheating seems to be somewhere in between 0.7 kg $\cdot$ h^{-1} and 1.0 kg $\cdot$ h^{-1}. According to this finding, an optimum design in terms of evaporation, superheating temperature and pressure drop can probably be defined for every mass flow range. However, more work has to be done in future to find this optimum. A first, easy-to-use, theoretical model description which allows a pre-calculation of the design is currently under evaluation and shows quite promising results.

SUMMARY

Several 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. 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. 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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REFERENCES

[1] Brandner, J.J., Bohn, L, Henning, T., Schygulla, U., Schubert, K., Microstructure Heat Exchanger Applications in Laboratory and Industry. Heat Transfer Engineering, 28, 8, 761-771 (2007)

[2] Henning, T., Brandner, J.J., Schubert, K. High-speed imaging of flow in microchannel array water evaporators. Microfluidics and Nanofluidics, 1, 128-136 (2005)

[3] S. Maikowske, S., Brandner, J.J., Lange, R., Optical investigation in microchannel water evaporators by high-speed videography. Proc. 3rd Topical Team Workshop on two-phase systems for ground and space applications, Sep 10-12, 2008, Brussels, Belgium, 67 (2008)

[4] Bosnjakovic, F., Technische Thermodynamik Teil 1, 8. corrected Ed., Steinkopf, Darmstadt, Germany (1998)

[5] Brandner, J.J., Micro Process Engineering: Aspects of Miniaturization for a New Technology, Habilitation Thesis, Technical University of Dresden (2008)

[6] Brandner, J.J., T. Gietzelt, T. Henning, M. Kraut, H. Moritz and W. Pfleging, Micro Process Engineering Sec. 10: Microfabrication in Metals and Polymers. Advanced Micro & Nanosystems (O. Brand, G.K. Fedder, C. Hierold, J.G. Korvink, O. Tabata, (Eds.) and N. Kockmann (Volume Ed.)), Wiley-VCH, Weinheim, Germany, 267-319 (2006)

[7] Schubert, K., J.J. Brandner, M. Fichtner, G. Lindner, Schygulla, U. and A. Wenka, Microstructure Devices for Applications in Thermal and Chemical Process Engineering. Microscale Thermophysical Engineering, Vol. 5, No. 1, 17-39 (2001)

[8] Goedde, M., Liebner, C., Hieronymus, H., Sicherheit in der Mikroreaktionstechnik, Chemie Ingenieur Technik, 1-2, 73-78 (2009)

[9] Klemm, E., Schirrmeister, S., Microstructured reactors for the production of commodities by heterogeneously catalysed gas phase reactions: Potentials and limits, Proc. South African Chemical Engineering Congress 2009, Sep 20-23, 2009, Somerset West, South Africa (2009)

[10] Brandner, J.J., E. Anurjew, L. Bohn, E. Hansjosten, T. Henning, U. Schygulla, A. Wenka and K. Schubert, Concepts and Realization of Microstructure Heat Exchangers for Enhanced Heat Transfer. Experimental Thermal and Fluid Science, Vol. 30, 801-809 (2006)

[11] Thome, J.R., State-of-the-Art of Boiling and Two-Phase Flows in Microchannels, Heat Transfer Engineering, 27, 9, 4-19 (2006)

[12] Henning, T., Brandner, J.J., Schubert, K., Characterisation of electrically powered micro heat exchangers, Chemical Engineering Journal 101, 1-3, 339-345 (2004)

[13] Henning, T., Brandner, J.J., Schubert, K., Lorenzini, M. and Morini, G.L., Low-Frequency Instabilities in the Operation of Metallic Multi-Microchannel Evaporators. Heat Transfer Engineering, Vol. 28, No. 10, 834-841 (2007)

[14] Vittoriosi, A., Characterization of Microstructure Evaporators using Optical Measurements, Diploma Thesis, Forschungszentrum Karlsruhe, IMVT, Universita di Bologna (2009)

[15] Knauss, R., Marr, R., Brandstätter, R., Dynamic Optimization of an Evaporator by a Nonlinear Model Predictive Controller for Operation at modular Micro Rectification, Proc. Int. Symposium on Micro Chemical Process and Synthesis MIPS2009, Sep 11-13, 2009, Kyoto, Japan, 108-111 (2009)

[16] Vittoriosi, A., Morini, G.L., Brandner, J.J., Characterization of Microstructure Evaporators with Optical Measurements, Proc. IMRET11, Kyoto, Japan, March 8-10, 2010, 246-247 (2010)

[17] Bauer, T., Experimental and theoretical investigations of monolithic reactors for three-phase catalytic reactions, PhD thesis. Faculty of Mechanical Engineering, Dresden University of Technology (2007)

[18] Cortina Diaz, M., Flow boiling heat transfer in narrow channels, PhD thesis, University of Magdeburg, Faculty of Process and System Technology (2008)

[19] Chen, W.L., Twu M.C., Pan, C., Gas-liquid two-phase flow in micro-channels. International Journal of Multiphase Flow, Vol. 28, 1235-1247 (2002)

[20] Coleman, J.W., Garimella, S., Characterization of two-phase flow patterns in small diameter round and rectangular tubes. International Journal of Heat and Mass Transfer, Vol. 42, 2869-2881 (1999)

[21] Cubaud, T., Ho, C.-M., Transport of bubbles in square microchannels. Physics of Fluids, Vol. 16, 4575-4585 (2004)

[22] Maikowske, S., Brandner, J.J., Lange, R., A novel device for the optical investigation of phase transition in micro channel array evaporators. Applied Thermal Engineering (Article in Press), (2010)

[23] Maikowske, S., Brandner, J.J., Lange, R., Optical Investigation of Phase Transition and Accompanying Phenomena in Micro Channel Array Evaporators, Proc. IMRET11, Kyoto, Japan, March 8-10, 2010, 58-59 (2010)

[24] Bejan, A., Rocha, L.A.O., Lorente, S., Thermodynamic optimization of geometry: T- and Y-shaped constructs of fluid streams. International Journal of Thermal Sciences, 39, 9-11, 949-960 (2000)

[25] Wiesegger, L.E., Entwicklung und Untersuchung eines neuartigen Mikrostrukturapparates zur Durchführung einer Absorption und Destillation, Dissertation Thesis, Graz Technical University (2009)

[26] Wiesegger, L.E., Knauss, R., Brandner, J.J., Marr, R., Modelling of Gas-/Vapor-Liquid Distribution, Separation and Continuous Contacting in Novel Microstructures, Proc. 1. GASMEMS Workshop. Eindhoven, 6.&7.09.2009, published as CD-ROM (2009)

