Microstructure Devices for Process Intensification: Influence of Manufacturing Tolerances and Measurement Uncertainties

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Abstract Process intensification by miniaturization is a common task for several fields of technology. Starting from manufacturing of electronic devices, miniaturization with the accompanying opportunities and problems gained also interest in chemistry and chemical process engineering. While the integration of enhanced functions, e.g. integrated sensors and actuators, is still under consideration, miniaturization itself has been realized in all material classes, namely metals, ceramics and polymers. First devices have been manufactured by scaling down macro-scale devices. However, manufacturing tolerances, material properties and design show much larger influence to the process than in macro scale. Many of the devices generated alike the macro ones work properly, but possibly could be optimized to a certain extend by adjusting the design and manufacturing tolerances to the special demands of miniaturization. Thus, some considerations on the design and production of devices for micro process engineering should be made to provide devices which show reproducible and controllable process behavior. This following publication gives some examples.

Keywords: Microstructure Design, Tolerances, Surface Characterization, Micro Scale

1. Introduction

In many fields of technology, process intensification is a major task to deal with. Integration of more functionality and greater flexibility as well as higher selectivity and/or higher yield is an objective for developments in communication technology as well as in mechanical, chemical and biological process engineering. The success of miniaturization in intensifying communication technology is easy to see due to the fact that the power and abilities of microelectronic equipment have increased drastically within the last decades – cellular phones and modern computer technologies are examples of this.
In terms of process engineering, the advantages of miniaturization are easy to describe. Heat and mass transfer using fluids can be greatly increased if the characteristic distances are reduced. According to (1), the mixing time t_M based on diffusion with the fluid-specific diffusion coefficient D is drastically reduced if the characteristic length x is minimized. This is shown in Fig. 1 for nitrogen and water as sample fluids. Similar considerations hold for the heat transfer time. Finally, it can be shown that miniaturization of process engineering equipment can increase the performance of certain basic operations like heat transfer or mixing by at least one order of magnitude, sometimes even much more [1].

$$t_M = \frac{x^2}{2 \cdot D} \tag{1}$$

However, miniaturization results also in an increased sensitivity to deviations of the process parameters, including the design and properties of the process technology equipment itself.
While designing micro process engineering equipment, there are several restrictions to consider. The application is the major one, but the aspects of material, producibility and re-producibility are not much less important.
Micro process engineering equipment have to be suitably designed for manufacturing in the designated material. Assembly and sealing has to be considered besides the opportunity to generate more than only a single prototype

device, which needs to take into account manufacturing tolerances to obtain the same process behavior in each device [2].

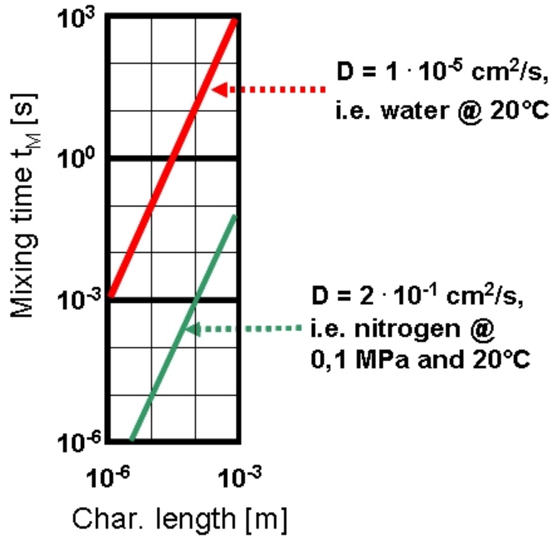

Fig. 1: Diffusion time for N_2 and water as function of the characteristic dimension.

For process engineering equipment of conventional dimensions, surface roughness is not a major task to deal with. In several applications a rough surface may lead to an increased fouling tendency, but in general, the functionality of the devices is not much changed by the surface roughness.

Surface quality and surface roughness in microstructure devices are of major importance due to two reasons: fouling and reduction of hydraulic diameter. Fouling in microstructures will very rapidly lead to malfunction of the complete device. The reduction of the hydraulic diameter due to increased surface roughness will increase the pressure drop as well as a possible mal-distribution of fluids to parallel microstructures.

Aside of the considerations for design and manufacturing, measurement and control of the process parameters are essential to run them in a desired way. Therefore, the choice of measurement method and sensors as well as the correct positioning of those within the microstructure process equipment is a relatively complex task to deal with.

2. Influence of Material, Manufacturing and Design

2.1 Material influences

Material properties have to be considered first when thinking of a certain application to be run in microstructure devices. The questions arising here are for mechanical stability, chemical or corrosion resistance, thermal and electrical properties as well as the way of manufacturing. The choice of material also defines the manufacturing method – some materials can not be used for, i.e., precision machining [2, 3].

2.1 Manufacturing influences

Manufacturing influences can be classified as surface quality (or roughness) and manufacturing precision (or tolerances).

High surface roughness may increase the heat transfer, but also make a device more prone to fouling and generation of deposit layers. Figure 2 shows examples of structures manufactured by laser machining (Fig. 2a), wet chemical etching (Fig. 2b) and precision milling (Fig. 2c). It is clear to see that the surface roughness can be influenced by the correct manufacturing method and parameters.

Moreover, the influence of roughness to the flow behavior and to the fluid dynamic properties of microstructure devices is much stronger than that in macro scale. This is due to a different ratio between the structural dimensions and the roughness. A brief example shall show this in an easy way.

Assuming a conventional tube with a hydraulic diameter of 0.1 m. This tube can be purchased off the shelf, the mean roughness in such a tube – i.e. stainless steel – being about 100µm. Thus, the ratio between roughness and hydraulic diameter is only 10^{-3}. The roughness dimensions are only in the range of 0.1% of the structural dimensions.

Taking now a micro capillary tube, which can also be ordered off the shelf. The hydraulic diameter is 100µm, and the mean roughness is 10µm – thus, the ratio is 0.1! The roughness dimensions are now in the range of 10% of the structural dimensions.

If now the pressure drop for a fluid running through these devices is calculated, assuming strictly laminar flow, then it is quite clear that in the conventional case the reduction of the hydraulic diameter by 0.1% does not reveal a major pressure drop increase. In fact, an increase of 0.4% is, in most cases, below the measurement resolution.

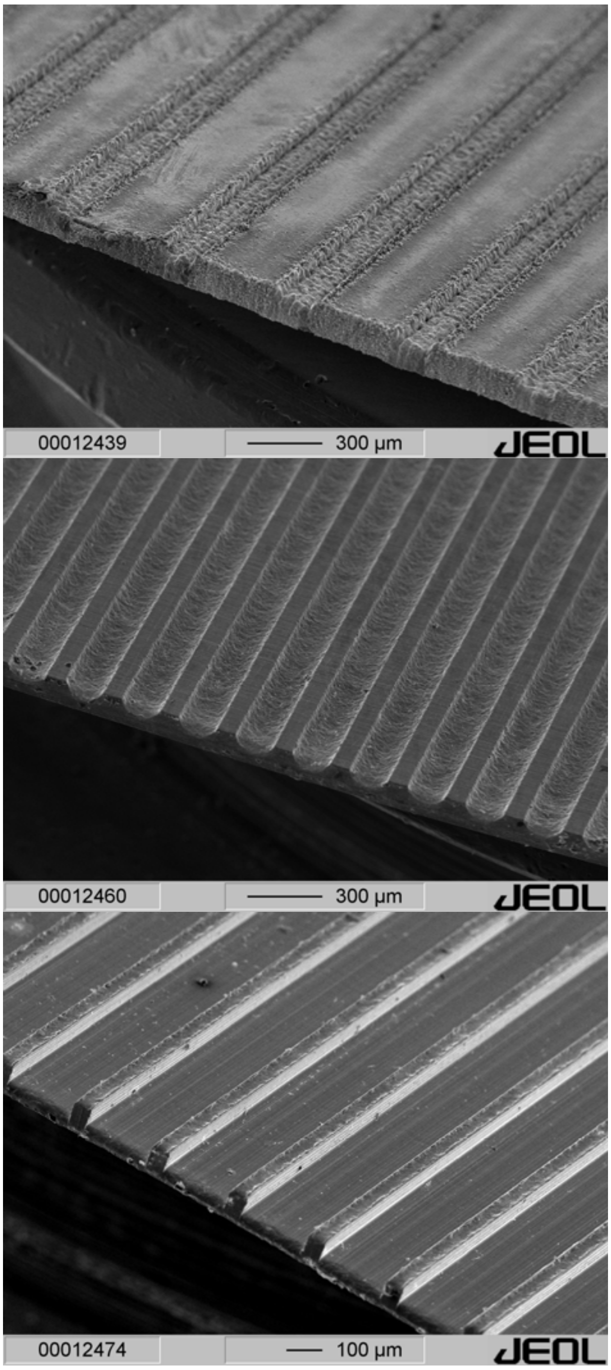

Fig. 2: SEM pictures of micro channels manufactured by laser machining (2a, top), wet chemical etching (2b, middle) and precision milling (2c, bottom). Obviously the parameters for laser machining have not been chosen correctly.

For the micro scale capillary, the hydraulic diameter is reduced by 10% - which results in an increase of the pressure drop by 52.5%.

However, surface roughness is unavoidable, it can be taken into account when designing microstructure devices to use, e.g., structural dimensions slightly larger than those really needed to avoid effects like the one described above.

Of higher importance is the manufacturing precision, i.e. the tolerances that can be obtained by the technique considered. Tolerances in the dimensions of microstructures can have a large influence on the distribution of the fluid in the microstructure system. An example explains this in greater detail:

Assuming two micro channels C_1 and C_2, laying directly beneath each other. For channel C_1, the hydraulic diameter is given by d_h. The hydraulic diameter of the other channel C_2 should be the same, but is, due to manufacturing tolerances, reduced by a fraction of x (taken in %). Assuming laminar flow through both micro channels, the pressure drop Δp_1 or Δp_2, respectively, can be calculated for each of them. Building the ratio between those two pressure drop values leads to a result which is free of fluid parameters but only depending on the ratio of the hydraulic diameters. It is given in eq. (2).

$$\frac{\Delta p_2}{\Delta p_1} = \frac{1}{(1-x)^4} \qquad (2)$$

It is quite obvious from this equation that the pressure drop in the smaller channel C_2 is much higher than that in the larger one – the difference follows a calculation law to the fourth power! This will, of course, lead to deviations in the mass flow per channel as well as in the fluid distribution of the complete micro system [4]. Moreover, variables like reaction rate, heat transfer, temperature distribution and generation of hot spots or cold spots are influenced more or less strongly.

However, the generation of hot spots or uneven temperature or flow distribution can be highly influenced by design of the microstructure devices.

2.3 Design influences

The design of microstructure devices can have large influence on the distribution of temperature as well as that of the fluid. Related to those, mass and energy transfer are influenced to a major extent. This will be shown by two examples.

2.3.1 Micro heat exchanger design

Micro heat exchangers of different design can be obtained for numerous applications. Most common designs are crossflow devices and countercurrent or co-current flow devices. The difference in both designs seems not to be very large, but the difference in the integral outlet temperature is reasonable [5].
Figure 3 shows an example of a crossflow microstructure heat exchanger. Fig. 3a gives an inside view of the micro channel system, while Fig. 3b shows the full device.
Figure 4a shows a single micro channel foil for a countercurrent / co-current flow heat exchanger, while in Figure 4b a complete device is presented. The device can be used for both flow methods, countercurrent and co-current flow. The flow mode simply depends on the application of the fluids to the inlet and outlet fittings.
The devices given in Figure 3 and 4 are manufactured from stainless steel, assembled and bonded by diffusion bonding. A detailed description of the manufacturing processes can be found in [5, 6, 7].
It is well known from conventional devices that the temperature behavior is different for the flow modes obtained in the devices. A similar, but more visible trend can be obtained with microstructure devices. The plots in Figure 5 a- c give an overview of the possibility of controlling the integral outlet temperature behavior by simply changing the configuration of the microstructure device.
All data shown in the plots have been obtained by experiments using water in both liquid passages. Temperatures at the inlet and the outlet have been measured with PT100 temperature sensors, installed in the center of the adapter fitting to the respective inlet or outlet, keeping a distance of about two centimeters to the microstructures. In the figures, the inlet and outlet temperatures for three configurations, crossflow, countercurrent and co-current flow, are plotted against the Reynolds number Re.

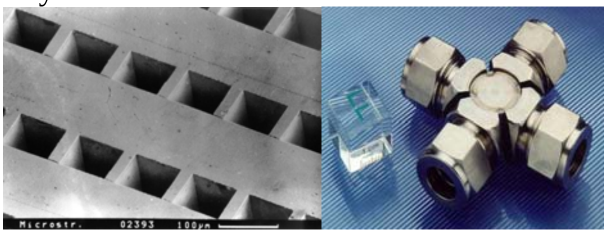

Fig. 3: Crossflow micro channel arrangement (Fig. 3a, left), crossflow micro heat exchanger (Fig. 3b, right).

Figure 4a shows the results of the crossflow heat exchanger. A crossing-over of the temperatures is obvious at a Reynolds number of about 150. The final temperature difference of the streams at outlet reaches a maximum of 20K.
For a countercurrent configuration, the temperature crossing is reached at a much higher Reynolds number of about 300, and the outlet temperature difference is much smaller, reaching only about 10K (see Figure 5b). Finally, in co-current flow configuration, there is no crossing of the outlet temperatures anymore. They will run into saturation and meet somewhere more or less precisely, which could not obtained here due to some pressure drop limitations. Knowing the temperature plots, it is relatively easy to control the temperature behavior of a process by simply choosing the flow configuration best suited for it.

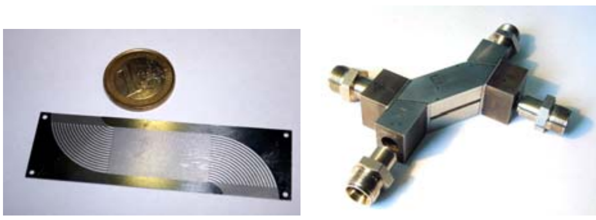

Fig. 4: Countercurrent / co-current flow micro channel arrangement (Fig. 4a, left), countercurrent / co-current micro heat exchanger (Fig. 4b, right).

Even stronger influences can be obtained by changing the integrated microstructure [8]. Examples for the microstructures to be integrated in such devices are given in Figure 6. In crossflow configuration, changing from an array of linear micro channels to a linear arrangement of micro columns or to a staggered arrangement of micro columns (see Figure 6 top left, bottom left, bottom middle) shows a shift of the temperature behavior to high Reynolds numbers, as can be seen in Figure 7 as well as in Figure 8. As it is presented in Figure 8, it may result the temperature behavior of a crossflow device being similar to that of a co-current flow device.

While the temperature behavior is just shifted by changing the integrated microstructure design, the pressure drop behavior is very different, as shown in Figure 9. Here, the pressure drop is plotted against the cold water mass flow for three different microstructure heat exchangers in crossflow mode, namely long linear micro channels, a linear arrangement of micro columns and a staggered arrangement of micro columns.

Figure 10 shows the overall heat transfer coefficient obtained for the same three configurations and as a function of pressure drop.

From this it is obvious that it might be useful to have variations in the microstructure design. At first sight, the increased pressure drop (as shown in Figure 9) may be a major drawback for some devices. However, the increase in the overall heat transfer coefficient as shown in Figure 10 is substantial. Thus, depending on the application, it might be worth looking more closely at such a design and to apply it where it shows advantages. In fact, an attempt should be made to combine together low pressure drop and high overall heat transfer coefficients together. This can be achieved by a very careful change of the integrated microstructure, as shown in [8].

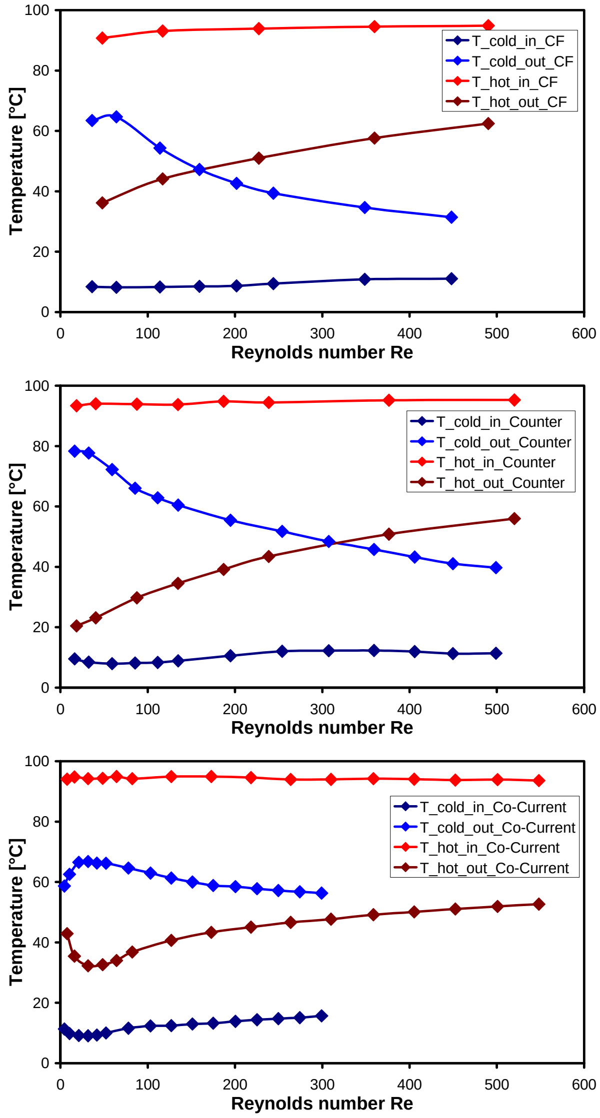

Fig. 5: Integral inlet and outlet temperatures of micro heat exchangers in different flow configurations, plotted against the Reynolds number Re. 5a (top): Crossflow mode; 5b (middle): Countercurrent flow mode; 5c (bottom): Co-current flow mode.

2.3.2 Microstructure evaporators

Phase transition in microstructures is a process very sensitive to many parameters, including applied mass flow, temperature distribution, applied thermal power, surface quality and design of the microstructures and some others more.

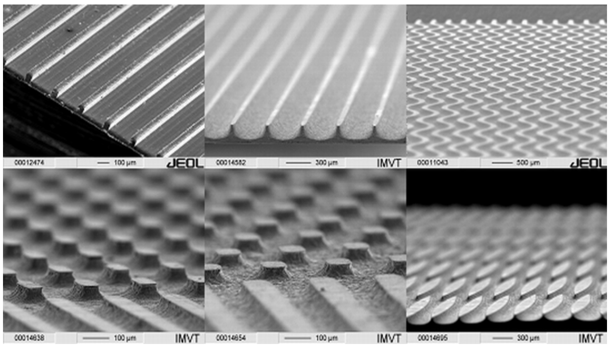

Fig. 6: Different microstructure arrangements manufactured in stainless steel.

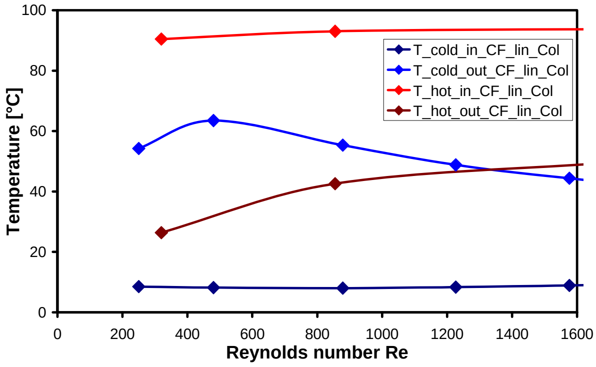

Fig. 7: Temperature plotted vs. Reynolds number for a linear arrangement of micro columns in a crossflow micro heat exchanger. The plot shows a detailed view to the crossing over of the outlet temperature at high Re.

In most cases, microstructure evaporators are designed using parallel arrangements of numerous micro channels providing dimensions large enough to obtain full evaporation [9, 10]. The most critical dimension here is the length of the micro channels, which can not be predicted precisely. Thus, in most cases very long micro channels are used to provide a residence time sufficiently high for full evaporation. This leads to an increased pressure drop and to undesired side effects like superheating of steam.

A parameter often neglected is the flow distribution at entry to the evaporation channels. Some authors considered improving the flow distribution for single phase flows [11, 12, 13]. Moreover, it could be shown that the design of the flow distributor at the inlet of a micro channel array has a major influence on the phase transition [14].

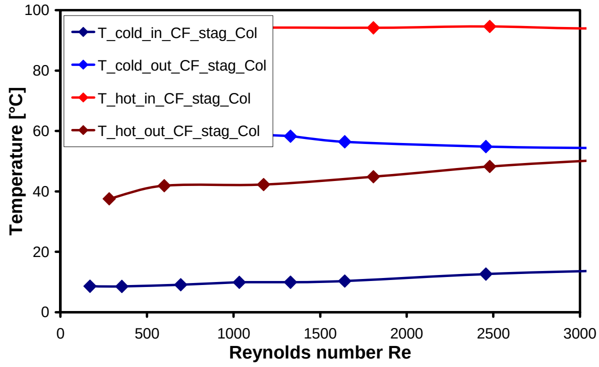

Fig. 8: Temperature plotted vs. Reynolds number for a staggered arrangement of micro columns in a crossflow micro heat exchanger. There might be a crossing over of the outlet temperatures at high Re, but this could not be achieved.

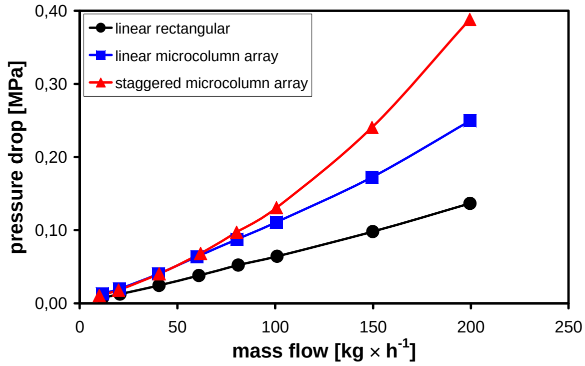

Fig. 9: Pressure drop plotted vs. cold water massflow for three different crossflow micro heat exchangers [8].

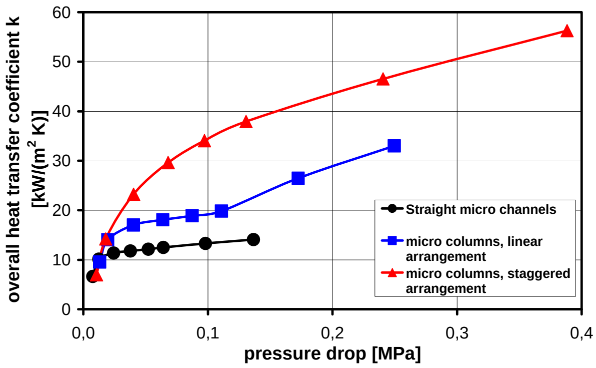

Fig. 10: Overall heat transfer coefficient plotted vs. pressure drop for three different crossflow micro heat exchangers [8].

Figure 11 shows three possible flow distribution systems for a micro channel array: a plain slit (top left), a triangular void (top right) and a tree-like branched system

(middle). The SEM picture at the bottom shows a detail of the branch system.
The hydraulic diameter of the single branches of the latter system have been calculated according to the principle of minimum work (Murray's law, [15]). Hence, the ratio between the hydraulic diameter of an inlet branch d_{h1} and the following up split branch d_{h2} is given by

$$\frac{d_{h1}}{d_{h2}} = 2^{1/3} \tag{3}$$

Easy pre-calculations under the assumption of ideal flow paths for the three different systems shown in Fig. 11 give an idea on the shape of the phase transition frontline generated inside the micro channel array. Figure 12 shows the channel number plotted vs. inverse residence time of the fluid for the slit, compared to a photo of the phase transition. It is clear that the two pictures correspond very well.
Using a triangular flow distribution system, the residence time across the micro channels will form a parabolic shape. This can be seen also in the shape of the phase transition line while evaporation takes place, as given in Figure 13.
Finally, if the tree-like branch flow distributor system is applied, the residence time should be the same in all micro channels of the array, resulting in a phase transition line perpendicular to the flow direction. However, due to manufacturing tolerances and three-dimensional steps in the real microstructure branching system (see Fig. 11), a phase transition area is reached, with a frontline more or less perpendicular to the flow direction. The respective result is shown in Figure 14.

3. Summary

Microscale devices can provide intensification options for processes by using the increased specific surface area, improved heat and mass transfer and other options.
However, such devices have to be designed and manufactured with much more care than at the macro scale. Effects like roughness or manufacturing tolerances have a large influence on the flow behavior as well as on the process. Some examples have been used to show this in overview style.

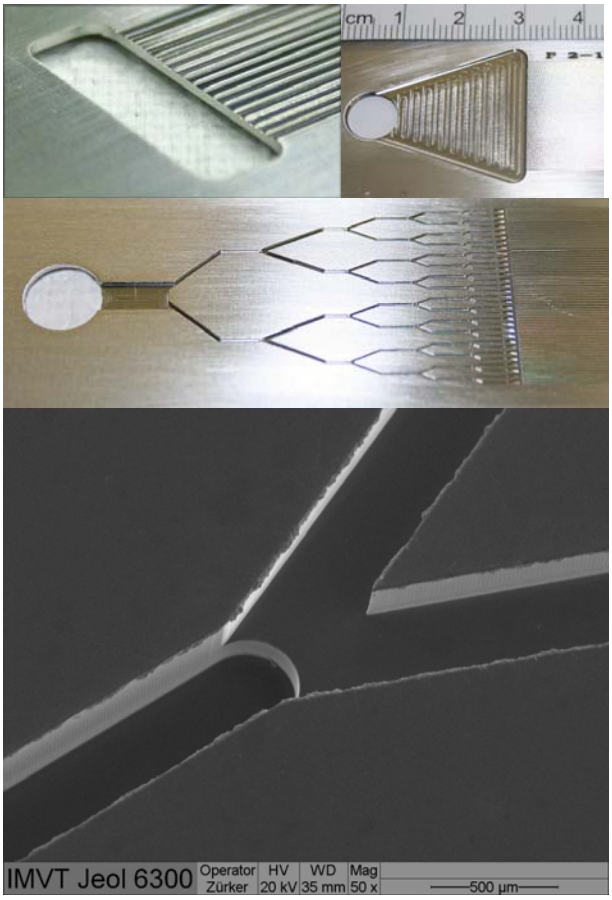

Fig. 11: Different flow distributors for micro channel array evaporators [14, 16].

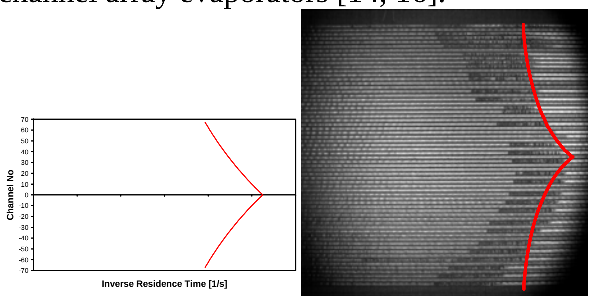

Fig. 12: Inverse residence time plot (left), phase transition line shape (right) for a slit flow distributor.

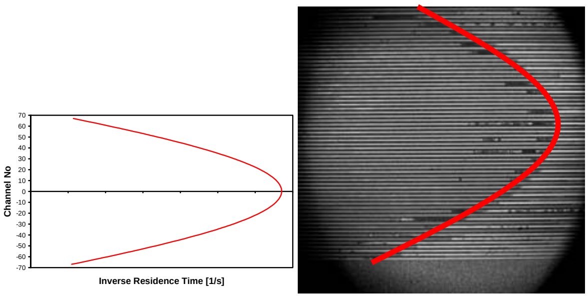

Fig. 13: Inverse residence time plot (left), phase transition line shape (right) for a triangular flow distributor.

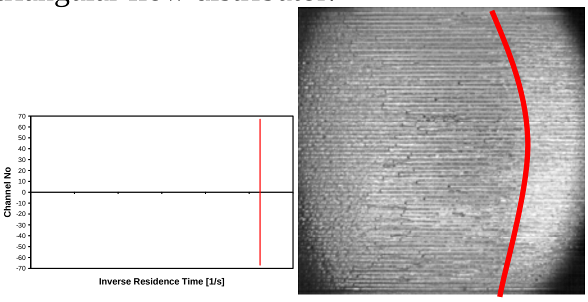

Fig. 14: Inverse residence time plot (left), phase transition line shape (right) for a tree-like flow distributor according to [15].

Nomenclature

D	diffusion coefficient	[m^2/s]
d_h	hydraulic diameter	[m]
p	pressure	[MPa]
t_M	mixing time	[s]
x	length, position	[m]
Δ	difference	[-]

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