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ANTI FOULING INVESTIGATIONS WITH ULTRASOUND IN A MICROSTRUCTURED HEAT EXCHANGER

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ABSTRACT

Microstructured heat exchangers show significant advantages in comparison with conventional heat exchangers. The unique properties of microreaction systems provide for example high overall heat transfer coefficients. Small characteristic dimensions are in the order of a few hundred µm [1-3]. Therefore the attention has been directed to the reduction of possible fouling processes within the channels. One strategy to reduce the fouling is the use of ultrasonic power. For the investigations an electrically heated micro heat exchanger was developed. A solution of calcium nitrate/sodium hydrogen carbonate is pumped through the channels of a microstructured device at a mass flow of 1.5 kg/h. The temperature causes the precipitation of solid calcium carbonate on the surface. This results in a decreasing heat transfer coefficient. An ultrasonic pulse of 1 min duration breaks up the fouling layer and the heat transfer coefficient reaches again its starting value. This is done in several cycles.

But a comparison of each cycle shows, that after each ultrasonic pulse the heat transfer coefficient decreases with a higher rate than the cycle before. Also a decrease of the outlet temperature to lower values is found.

The aim of this study is to show the influence of the ultrasound on the fouling behaviour of a microstructured device. The investigations indicate that the use of ultrasonic power influences the fouling and opens up possibilities to diminish the fouling in microchannels significantly.

INTRODUCTION

Fouling phenomena in conventional systems like plate heat exchangers or tube bundle heat exchangers are well known and well investigated, but not in microreaction systems. The most important disadvantages of the small dimensions of a micro heat exchanger are the problems of fouling and even clogging in the small channels. This is a serious problem in many applications in which micro heat exchangers may be used. As a result the thermohydraulic properties of microstructured devices decline remarkably during the heating of fluids. Our research efforts have been focused on fouling within microchannels caused by the precipitation of calcium carbonate and the use of ultrasound as cleaning technique. It has been shown that surface coatings could be removed by ultrasound at a power level which is insufficient to cause cavitation [4]. This may be attributed to acoustic microstreaming near the liquid/solid boundary. Thus sufficient vibration of the surface by ultrasound should remove the calcium carbonate incrustion on the heat transfer surface, combined with a restoration of the thermohydraulic properties. Ultrasound seems to be a practical technique for the prevention of fouling. Direct sonification of the heat transfer surface area causes vibrations of the surface and thus prevents undesired deposition.

The use of a special layer like an anti-fouling protection of the heat exchanger surface or the combination of both anti-fouling layer and ultrasound are topics of future work.

EXPERIMENTAL

The experimental equipment consists essentially of three parts:

- the sonotrode (20 kHz, 35 W), which is connected to an aluminium block.
- the stereolithographic formed microstructured device (60 mm length x 40 mm width x 5 mm height) with 21 channels (22 mm length x 800 µm width x 100 µm height), which is fixed on the metallic foil (stainless steel). The microstructured device is sealed with a rubber ring to a metallic foil with a thickness of 0.1 mm; both are screwed tightly with a coverplate to the aluminium block.
- the aluminium block (80 mm length x 50 mm width x 30 mm height) with 2 holes at the lower end to insert heater cartridges (P=200W); at the upper end a thermocouple to control the surface temperature is placed centrically under the metallic foil and the microstructured device.

A schematic sketch of the test arrangement is shown in Figure 1, details of the microstructured device are shown in Figure 2. The properties of the microstructured device and the metallic foil can be seen in Table 1.

The test arrangement with the microstructured device at the top is integrated vertically in a test rig. The aqueous solution is fed over the coverplate.

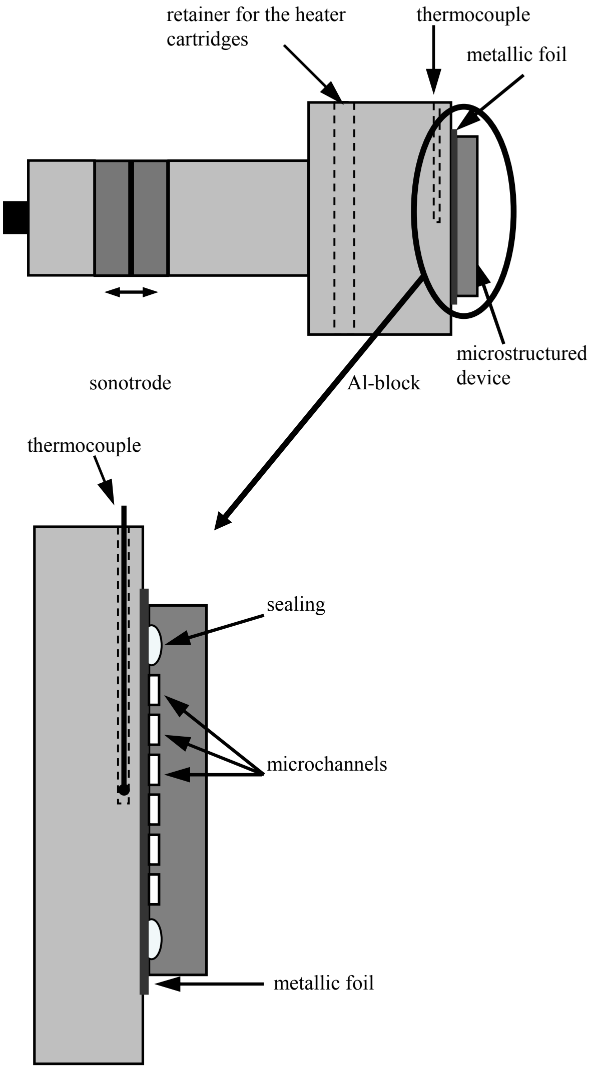

Figure 1: Scheme of the test arrangement; bottom shows the enlarged cross section of the area aluminium block-metallic foil-microstructured device.

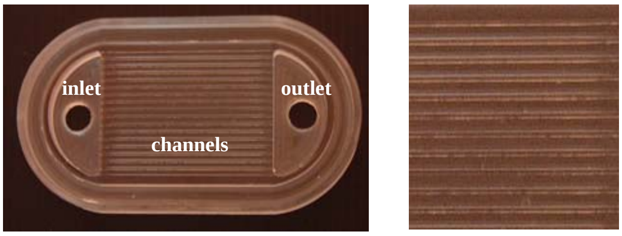

Figure 2: Microstructured device (left), enlargement of the channel area (right).

Table 1: Properties of the microstructured device and the metallic foil.

material	epoxide
number of channels,-	22
length of channels, mm	23
height of channels, µm	100
width of channels, µm	800
width of bars, µm	200
foil material	stainless steel (1.4435)
thickness of the foil, mm	0.1

An aqueous solution of $Ca(NO_3)_2/NaHCO_3$ is pumped through the microchannels of the microstructured device at a mass flow of 1.5 kg/h. The microstructured device is connected to the metallic foil, which itself is placed on the electrically heatable aluminium block. The temperature of the aluminium block (ϑ) is set to 100°C. The surface temperature and the "wall" temperature of the metallic foil, respectively, is kept at a constant level because of the high thermal conductivity of the aluminium (λ= 200 W m^{-1} K^{-1}). Because the microstructured device is made of a polymer it has a low thermal conductivity, which leads to a heat transfer through the metallic foil only. The heat transfer depends on one dimension only (thermal boundary condition of the first kind [5]). The aqueous solution runs over the hot surface with a constant temperature level (ϑ_{wall} = const.).

The aqueous solution is heated up to a temperature level higher than the solubility temperature of $CaCO_3$ ($CaCO_3$ shows an inverse solubility). The heat causes a precipitation of white particles which stick to the wall. The additional layer consequently reduces the heat transfer properties. The temperature of the outgoing aqueous solution continuously decreases. When the temperature reaches a value of 15K below the starting temperature, an ultrasound pulse of 1 minute duration is applied.

The temperature of the solution is measured by thermocouples which are directly placed in the inlet and outlet respectively. The pressure is measured before and after the microstructured device.

The mass flow is determined by a flow meter (coriolis type). All experiments are done under the following conditions (Table 2).

Table 2: Experimental conditions.

inlet temperature T_{in}, °C	25
massflow, kg/h	1.5
temperature of the aluminium block ϑ, °C	100
$Ca(NO_3)_2$, mol/l	0.005
$NaHCO_3$, mol/l	0.01
system pressure p, bar	1

RESULTS

In Figure 3 results for the heating of an aqueous solution of $Ca(NO_3)_2/NaHCO_3$ are shown.

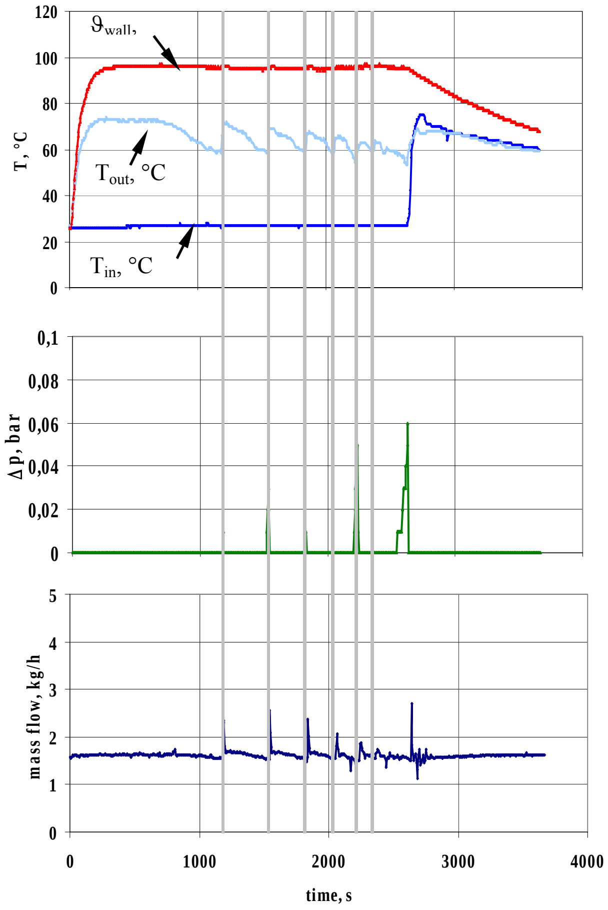

Figure 3: From top to bottom: temperature, pressure drop, mass flow as a function of time for the heating of an aqueous solution of $Ca(NO_3)_2/NaHCO_3$. Grey bars mark the ultrasound pulses.

In the top diagram of Figure 3, the temperature is shown as function of time. The upper line marks the temperature of the metallic foil (ϑ_{wall}), the mid line denotes the temperature of the incoming aqueous solution (T_{in}) and the bottom line shows the temperature of the aqueous solution at the outlet of the microstructured device (T_{out}). At the beginning of the experiments the thermal conditions are at a constant level (steady state conditions). The temperatures have the following starting values (Table 3).

Table 3: Measured values of the temperatures at the beginning of the experiment.

temperature of the metallic foil ϑ_{wall}, °C	96
inlet temperature T_{in}; °C	27
outlet temperature T_{out}; °C	73

After an incubation time of 13 minutes the temperature of the aqueous solution at the outlet of the microstructured device decreases to lower values. (Respectively the transferred heat $\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T$ decreases. The transferred heat $\dot{Q}$ is proportional to the difference of temperature between inlet and outlet ΔT. Mass flow and heat capacity are considered to be constant. Due to the fact that the inlet temperature and the mass flow are constant (Table 2), we refer to the temperature of the aqueous solution at the outlet of the microstructured device as a measure for the decrease of heat transfer.) When the temperature of the aqueous solution at the outlet of the microstructured device reaches a value of 58°C an ultrasound pulse of 1 minute duration is applied (grey bars in Figure 3). The temperature of the aqueous solution at the outlet of the microstructured device jumps up to 72°C again. In the following cycle a faster decrease of the temperature of the aqueous solution at the outlet of the microstructured device can be observed. At a temperature of 58°C (after 26 min) a new ultrasound pulse is applied. Again the temperature of the aqueous solution at the outlet of the microstructured device jumps up but only to 69°C. The periodical run of temperature decrease and rapid increase after the ultrasound pulse can be found six times. Thus a “period” can be characterized by:

- the decrease of the temperature of the aqueous solution at the outlet of the microstructured device corresponding to a rate in K/min.
- the temperature $T_{out,max}$ reached after ultrasound pulse.
- the time range between two ultrasound pulses.

Data for the experiment are given in Table 4.

Table 4: Rate of the temperature decrease of the aqueous solution at the outlet of the microstructured device r_d, temperature $T_{out,max}$ after ultrasound pulse and time range Δt between two ultrasound pulses for the experiment corresponding to Figure 3.

period	rate of temperature decrease r_d, K/min	$T_{out,\ max}$, °C	Δt, min
1	1.8	72	-
2	2.5	69	6
3	2.7	68	5
4	3.6	66	4
5	4.7	63	3
6	4.3	63	2

In the mid diagram of Figure 3 the pressure drop as function of time is shown. At each ultrasound pulse a pressure peak can be seen.

In the bottom diagram of Figure 3 the mass flow as function of time is shown. A constant value of 1.5 kg/h was applied. The mass flow shows a slight decrease correlated to the temperature of the aqueous solution at the outlet of the microstructured device. After the application of the ultrasound pulse, an increase in the mass flow is observed.

The experiment was finished after a duration of 2640 seconds (44 minutes).

DISCUSSION

While heating an aqueous solution of $Ca(NO_3)_2/NaHCO_3$, the following chemical reactions will take place:

$$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+$$

$$HCO_3^- + H_2O \leftrightarrow \text{„}H_2CO_3\text{“} + OH^-$$

$$\underline{Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3}$$

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + \text{„}H_2CO_3\text{“}$$

Calcium carbonate has a decreasing solubility with increasing temperature. At elevated temperature the formation and precipitation of calcium carbonate on the hot metallic foil of the microstructured heater occurs. In order to prove this a special test run (test run no. 1) was done. After the temperature of the aqueous solution at the outlet of the microstructured device has reached a value of 58°C the test run no. 1 was stopped without application of ultrasound. The experimental equipment was disassembled and a photo has been made. The metallic foil is covered by a layer of calcium carbonate (Figure 4).

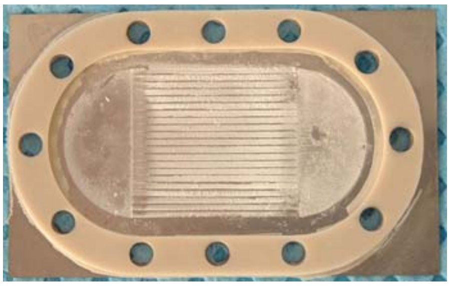

Figure 4: Test run no. 1 without application of ultrasound: photo of the metallic foil covered with a layer of calcium carbonate. The white oval form is the sealing between metallic foil and microstructured device.

This layer having a poor thermal conductivity causes a degradation of the thermal properties. The effect is a significant drop of the temperature of the aqueous solution at the outlet of the microstructured device.

It was shown previously that certain coatings could be removed by the use of ultrasound [4]. The surface is directly sonificated at a power level insufficient to cause cavitation. The cleaning effect is related to acoustic microstreaming close to the solid/liquid boundary. These are small eddies close to the moving solid surface. Direct sonification of the heat transfer surface causes vibrations. The vibrations have a dramatic effect to the surface. When the surface moves up and down with amplitudes of around 0.01 mm at a frequency of 20 kHz, high accelerations will be achieved. The acceleration forces induce the microstreaming effect. This disrupts the deposition on the surface of the metallic foil. Small particles will be transported away by the mass flow running through the channels. Now the thermohydraulic properties of the micro heater are on the base level again. The original temperature of the aqueous solution at the outlet of the microstructured device is achieved again. This could be repeated several times in the experiment (top diagram in Figure 3). But after each ultrasound pulse, a small degradation of the thermal properties could be observed. Like shown in Table 4 a continuous decrease of the temperature of the aqueous solution at the outlet of the microstructured device could be observed after each ultrasound pulse. The rate of temperature decrease (K/min) increases as well as the time range Δt between two ultrasound pulses. An explanation may be that we do not get a complete cleaning of the metallic foil of the micro heater. The power of the ultrasound seems not to be high enough to break off the complete calcium carbonate layer on the surface. To confirm this assumption a special test run (test run no. 2) was done. After the first period the test run no. 2 was stopped directly after the ultrasound pulse. The experimental equipment was disassembled and a photo has been made. It can be seen in Figure 5 that parts of the layer are still remaining after the ultrasound pulse. Not all particles are transported away by the fluid.

Figure 5: Test run no. 2 with application of ultrasound: photo of the sonificated metallic foil. Residues of calcium carbonate can be seen on the surface. The white oval form is the sealing between metallic foil and microstructured device.

On this insufficient cleaned surface, an accelerated process of fouling starts.

The sudden increase of mass flow after the application of ultrasound (lower diagram in Figure 3) could also be related to the breaking of the fouling layer. Because of the reduction of the diameter of the channels due to the up growing fouling layer the mass flow was restricted. The ultrasound pulse releases the mass flow by breaking off the fouling layer.

CONCLUSIONS

Micro heat exchangers are prone to fouling. In this study we could exemplify that the use of ultrasound is a useful supplement of micro heat exchangers. Thus the application potential of the "method" micro heat exchanger is significantly increased. Micro heat exchangers could be used for the heating of substances which show a higher tendency of fouling. The combination micro heat exchanger and ultrasound presents a development, which should improve the performance characteristic.

Further investigations will proceed and the influence of increasing power and different frequencies of ultrasound will mainly be examined. The combination of ultrasound and anti-fouling layers seems to be an interesting research topic. Further results can lead to significant improvements in the prevention of fouling in microchannels.

NOMENCLATURE

$\dot{m}$	massflow, kg/h
$\dot{Q}$	transferred heat, W
r_d	decrease of the temperature of the aqueous solution at the outlet, K/min
T_{in}	temperature of the incoming aqueous solution, °C
T_{out}	temperature of the aqueous solution at the outlet, °C
$T_{out, max}$	temperature after ultrasound pulse, °C
Δt	time range between two ultrasound pulses, min
ΔT	difference of temperature between inlet and outlet, K
λ	thermal conductivity of aluminium, W m^{-1} K^{-1}
ϑ	temperature of the aluminium block, °C
ϑ_{wall}	temperature of the metallic foil, °C

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