Experimental Investigation of Microstructured Evaporators

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Abstract. Microfluidic devices have become more and more popular over the last decades [1]. Cooling is a topic where microstructures offer significant advantages compared to conventional techniques due the much higher possible surface to volume ratios and short heat transfer lengths. By evaporating of a fluid in microchannels, compact, fast and powerful cooling devices become possible [2]. Experimental results for different designs of microstructured evaporators are presented here. They have been obtained either using water as evaporating coolant or the refrigerant R134a (Tetrafluoroethane). A new microstructured evaporator design consisting of bended microchannels instead of straight channels for a better performance is shown and compared to previous results [2] for the evaporation of R134a in straight microchannels.

Nomenclature

- \( c \) (J/kg/K) specific heat capacity
- \( F_c \) (kg/m/s\(^2\)) centrifugal forces
- \( \Delta h \) (J/kg) evaporation enthalpy
- \( m \) (kg) mass
- \( \dot{m} \) (kg/h) mass flow rate of coolant
- \( m_{\text{water}} \) (kg/h) mass flow rate of water
- \( p_{\text{in}} \) (Pa) pressure at evaporator inlet
- \( p_{\text{out}} \) (Pa) pressure at evaporator outlet
- \( T_{\text{in}} \) (°C) temperature at evaporator inlet
- \( T_{\text{out}} \) (°C) temperature at evaporator outlet
- \( T_{\text{waterin}} \) (°C) temperature at water passage inlet
- \( T_{\text{waterout}} \) (°C) temperature at water passage outlet
- \( P_e \) (W) electrical power supplied to heating cartridge
- \( \dot{Q}_{\text{en}} \) (W) cooling power by heat of evaporation due to change in enthalpy
- \( \dot{Q}_{\text{ex}} \) (W) thermal power
1. Introduction

Micro heat exchangers [1,2,3] are often used for a precise process control when large quantities of heat have to be transferred. Micro heat exchangers consist of at least two passages where one passage carries the warm fluid and the other passage the cold one. Each passage itself consists of a certain number of metallic foils containing microstructured channels (typical width and depth <1 mm).

Instant cooling of fluids or the effective removal of heat from integrated circuits of more and more powerful semiconductor chips are applications for microfluidic cooling devices. High rates of cooling power can be achieved when a coolant is evaporated inside a microstructure. Boiling in microchannels is therefore intensively studied and referenced in literature [4,5,6,7].

This work targets on experiments of the evaporation of water in different kind of electrically heated micro evaporators, all of them manufactured at the Institute for Micro Process Engineering (IMVT) at the Karlsruhe Institute of Technology (KIT). Evaporation of the commercial coolant R134a (commonly used in automotive air condition systems) is moreover studied in a newly developed advanced micro evaporator design consisting of bended channels and compared to previous results [2] in straight channels.

2. Experimental Setup

A setup (schematic shown in Figure 1, left side) with a conventional coolant cycle and a water cycle including a preheater was used for tests using the refrigerant R134a.

During the experiments with evaporation of water no cycles were used as the thermal power required for the evaporation was provided by electrical heating cartridges and the water flow (driven by an HLPC pump) was released as steam to the environment.

![Experimental Setup Diagram](image)

**Figure 1.** Left: Sketch of the experimental setup for the evaporation of R134a in microstructured evaporators, right: stainless steel foil, 120 mm × 120 mm, microstructured area (dashed frame): 60 mm × 60 mm (40 etched microchannels).
Cooling Cycle

The R134a cooling cycle consists of a commercial condensing unit (model CAE4440YHR by L’Unite Hermetique), containing a compressor, convection cooled condenser, and coolant liquid receiver (not included in Figure 1) for the cooling/evaporation passage of the micro heat exchanger. Included in this cooling cycle were

1. a Coriolis mass flow meter from Endress and Hauser, which was installed in the liquid high pressure passage of the coolant behind the condenser and before the evaporator to determine the mass flow rate $m\dot{\nu}$ of the coolant,
2. a needle valve to manually regulate the flow rate (this valve was used as an expansion valve for the coolant),
3. a pressure transmitter and a K-Type thermocouple to determine the absolute pressure $p_{in}$ and the temperature $T_{in}$ of the coolant after the needle valve and before it entered the evaporation passage of the micro heat exchanger
4. the microstructured evaporation passage,
5. a pressure transmitter and a K-Type thermocouple to determine the absolute pressure $p_{out}$ and the temperature $T_{out}$ of the coolant when exiting the evaporation passage,
6. a solenoid valve to rapidly shut-off the coolant flow,
7. a R134a compressor.

Liquid Cycle

The liquid cycle was designed to circulate a water flow which was first heated up to the desired temperature and then cooled again by the micro heat exchanger. This cycle consisted of:

1. an HPLC pump to circulate water at a given mass flow rate $m_{water}\dot{\nu}$,
2. an in-house temperature-controlled, continuous flow micro heater with a maximum electrical heating power of 2000 W to heat the water feed,
3. a K-type thermocouple at the inlet to the water cooling passage of the micro heat exchanger to determine the temperature of the water feed $T_{waterin}$,
4. the water passage through the micro heat exchanger,
5. a K-type thermocouple at the outlet of the cooling passage of the micro heat exchanger to determine the exit fluid temperature of the cooled water $T_{waterout}$.

The accuracy of the K-Type thermocouples used was ±1.5 °C in the range of measurements, for the HPLC pump an accuracy of ±1% was experimentally determined. For the Coriolis mass flow meter the accuracy is < ±0.5 %.

Electrically Powered Heating Cartridges

For the experiments with water as evaporating coolant micro evaporating devices with integrated heating cartridges (electrical power ~1.5-3.5 kW, manufacturer: Watlow) were utilised. Corresponding to the experiments with R134a, a similar measuring technique was used:

1. an HPLC pump to circulate water at a specific mass flow rate $m\dot{\nu}$,
2. a power meter by HAMEG to determine the electrical power consumed by the heating cartridges,
3. Evaluation of the Measurements

For the experiments using R134a as coolant the experimentally transferred cooling power was calculated from the measured temperatures of the water cycle at the inlet and outlet of the water passage for a given water flow rate. For the specific heat of water \[ c = 4.1826 \text{ J/g K} \] the transferred cooling power at given water mass flow rate \( \dot{m}_{\text{water}} \) was determined as

\[
\dot{Q}_{\text{ex}} = \dot{m}_{\text{water}} c (T_{\text{waterin}} - T_{\text{waterout}})
\]

For the experiments using water as evaporating coolant the electrical power \( P \) supplied to the heating cartridges was used as reference value. Therefore, for the experiments using heating cartridges, the transferred power was set equal to the consumed electrical power as

\[
\dot{Q}_{\text{ex}} = P_{el}
\]

The value \( \dot{Q}_{\text{ex}} \) can be compared to the enthalpy of evaporation of the coolant \( \Delta h \) and the measured mass flow rate \( \dot{m} \) of the coolant as

\[
\dot{Q}_{\text{en}} = \dot{m} \Delta h
\]

\( \Delta h \) depends on the actual evaporation temperature (which depends on the evaporation pressure) and also varies along the evaporation microstructure. \( \dot{Q}_{\text{en}} \) does not include superheating. Values for \( \Delta h \) were derived from the measured values of pressure and temperature \( T_{\text{in}}, T_{\text{out}}, P_{\text{in}}, P_{\text{out}} \) at the in- and outlet of the microstructured evaporator according to [8].

The ratio of the actual transferred cooling power \( \dot{Q}_{\text{ex}} \) resp. electrical power \( P_{el} \) and the theoretical cooling power \( \dot{Q}_{\text{en}} \) based on the enthalpy of evaporation is given by

\[
r = \frac{\dot{Q}_{\text{ex}}}{\dot{Q}_{\text{en}}}
\]

For values of \( r < 100\% \) an incomplete evaporation of the coolant has to be assumed. \( r > 100\% \) indicates a possible complete evaporation and an additional heat transfer to the coolant vapor (superheated vapor).

4. Evaporation of water in different kind of electrically heated microstructured evaporators

Two micro devices made by IMVT with integrated heating cartridges were tested using water as evaporating fluid.
4.1 Electrically Heated Microchannel Array
This device consists of an array of 618 parallel microchannels with a channel cross section of 200 µm × 200 µm. A total of 15 heating cartridges allows for a maximum electrical heating power of \( P_{el} = 3.3 \, kW \). Experimental results for this device, however, show, that a high rate of \( r \approx 101 \% \) (slightly superheated) could only be achieved up to a maximum supplied electrical power of \( P_{el} \approx 400 \, W \) and a corresponding coolant flow rate of \( m = 0.3 \, kg/h \). For higher flow rates and corresponding higher supplied \( P_{el} \), however, \( r \) dropped as the coolant could now not be sufficiently evaporated in the microchannel array anymore. This is most likely related to vapor blocking of single channels, a phenomenon often observed for microchannel arrays [4].

4.2 Rod Evaporator
The microstructured rod evaporator consists of a single 157 mm long and 400 µm deep microchannel in a spiral arrangement around a heating cartridge (maximum heating power \( P_{el} = 1.5 \, kW \)). Vapor blocking is impossible for a single channel, evaporation was possible up to the maximum heating power of the heating cartridge at a coolant mass flow rate of \( m = 0.9 \, kg/h \) \( (r \approx 102\%) \).

5. Evaporation of R134a in straight microchannels
For the experiments using R134a as evaporating coolant, square stainless steel foils \((120 \, mm \times 120 \, mm \times 1 \, mm)\) were used for the evaporation passage. The first set of foils consisted of 40 straight, chemically etched microchannels. The channels had a width of 1 mm and a length of 60 mm, foils with varying channel depths (100 µm...400 µm) were manufactured. The microstructured area of the foils was 60 mm × 60 mm.

The boundary conditions for these tests were a constant feed temperature of \( T_{waterin} = 55 \, ^\circ C \) of the water to be cooled and a targeted water outlet temperature of \( T_{waterout} = 7 - 8 \, ^\circ C \) (which was still warm enough to avoid freezing of the water passage). The mass flow rate of the water \( \dot{m}_{water} \) and the coolant \( \dot{m} \) were varied in such a way that maximum values for \( \dot{m}_{water} \) and the ratio \( r \) at the evaporation passage outlet could be achieved for a water outlet temperature of \( T_{waterout} = 7 - 8 \, ^\circ C \) .

The mass flow rate of the water was kept constant at \( \dot{m}_{water} = 3 \, kg/h \); the mass flow rate of the coolant was manually regulated by the needle valve to achieve a water outlet temperature of \( T_{waterout} = 7.8 \, ^\circ C \) (required mass flow rate of coolant \( \dot{m} \approx 3 \, kg/h \)).

Before the measurements were recorded, coolant and water were set to a constant flow rate for one hour. This was done to prevent influences due to the thermal capacity of the stainless steel mounting. The cooling device was thermally isolated to avoid heat transfer of the device to the environment. Each series of measurements consisted of 10 points at one minute intervals, where the data of the measuring sensors were recorded.

This setup showed good results for the evaporation for a counter current configuration [2]. For foils with channels of cross-sectional areas of \( 1 \, mm \times 0.2 \, mm \), a ratio of \( r = 94\% \) was achieved, indicating a nearly complete evaporating of the coolant.

The straight channel concept comprises two main disadvantages:
- There is an increase of volume due to the evaporation in the orders of three magnitudes. This reduces the residence time of the coolant inside the microstructured evaporator tremendously.
- The poor heat conductivity of the vapor reduces the heat transfer to regions of liquid coolant.

From reconsidering these effects an idea for a new concept for a microstructured evaporator evolved. This concept is introduced in the next section.
6. Evaporation of R134a in new developed bended channel microstructure

To enable an efficient evaporation of the coolant at higher mass flow rates a concept for a more efficient microstructure was developed. By this, a smaller size and therefore lower cost for a microstructured evaporating device are intended.

6.1 Concept of “High Efficient Evaporating Device (HEED)”

The idea of this microstructured evaporator is to take advantage of the centrifugal forces $F_c$ acting on a fluid in bended channels. $F_c$ depends on the flow velocity $v$, the radius $r_c$ and the mass $m$ of the fluid.

\[ F_c = m \frac{v^2}{r_c} \quad (5) \]

$F_c$ is strong for microstructured evaporators consisting of bended microchannels as $v$ is high due to the small channel cross sections and the increase of volume due to evaporation. Additionally, $r_c$ is small for microstructures with channel dimension in the range of 10...1000 µm.

As there is a large difference in density of the liquid and vapor phase, a phase separation is assumed to take place in bended microchannels. This idea is illustrated in Figure 2 and is basically inspired by the principle of a centrifuge. The heavier liquid fraction of the evaporating coolant is expected to move towards the outside of the curve. By adding a special orifice to the inner side of the curve, a removal of the vapor phase is intended.

Figure 2. Concept of new microstructured evaporator.

By this, the disadvantages of the straight microchannel design can possibly be avoided

- as removing of vapor increases the residence time of the liquid phase inside the evaporator
- as the liquid fraction at the (outer) channel walls is higher, which increases the heat transfer to the liquid fraction.

A first approach to realize this concept is given in Figure 3, showing a stainless steel foil of the same size of the microstructured area as used for the test for evaporating R134a in straight microchannels.
6.2 Experimental Results

The foil shown in Figure 3 was used for the same boundary conditions as the straight channels foils, namely for cooling a liquid water flow from $T_{\text{water in}} = 55 ^\circ C$ to a water outlet temperature of $T_{\text{water out}} = 7...8 ^\circ C$ by evaporating R134a. For this first approach for a new evaporator layout, the mass flow rate of the coolant and water passage could be doubled and enables now cooling of a maximum water flow rate of $m_{\text{water}} = 6 \text{ kg/h}$ at the same size of the microstructure (Table 1). With a channel etching depth of $300 \mu m$ and a channel width of $1 \text{ mm}$ and the density of the liquid and evaporated R134a, the velocity $v$ in the bended channels can be estimated as $v \approx 0.7 \text{ m/s}$ for the liquid coolant at the entrance of the structure up to $v \approx 200 \text{ m/s}$ for the fully evaporated coolant at the outlet of the structure. Considering the velocity dependency of eq. 5 it is obvious that a minimum fluid velocity $v$ is required to achieve the intended phase separation induced by the centrifugal forces $F_c$ to reach an optimum performance of the device.

Figure 3. Left: Stainless steel foil with bended microchannels, 120 mm x 120 mm, microstructured area (dashed frame): 60 mm x 60 mm middle: bended microchannel structure, right: high-speed videography of vapour bubbles inside bended microchannel (fluid: R134a).

| microchannels | $m$   | $m_{\text{water}}$ | $\dot{Q}_{\text{ex}}$ | $\dot{Q}_{\text{in}}$ | $r = \dot{Q}_{\text{ex}} / \dot{Q}_{\text{in}}$ |
|---------------|-------|--------------------|------------------------|------------------------|----------------------------------|
| straight (old)| 3 kg/h| 3 kg/h             | 162 W                  | 172 W                  | 94 %                             |
| bended (new)  | 6 kg/h| 6 kg/h             | 317 W                  | 337 W                  | 94 %                             |

6.3 High-Speed Videography Observations

Optical investigations of this new micro evaporator design were performed for detailed understanding of the new structure. Results for the first design approach (figure 3, right) show the separation of the vapor bubbles from the liquid fractions but also indicate need for an improvement of the design for the orifices to remove the vapor. Whereas a moving of the (lighter) vapor bubbles to the inner side of the
bended channels could be clearly observed, a removal of the vapor phase by the provided orifices could not be detected yet. The high-speed videography observations are, however, limited due to the covering glass plate to lower pressures and velocities as crosstalk between the channels occurs.

7. Conclusions

Beyond the experiments where the evaporation of water in an electrically heated array of microchannels and a microstructured rod evaporator are compared, a new approach for a microstructure evaporator was given. By using bended microchannels and hereby applying centrifugal forces on the evaporating two-phase flow a doubled coolant mass flow could be evaporated in this first approach of a new design, giving a doubled cooling power for the same structure size. With this new design approach, competitive micro evaporators might find their way to the price sensitive mass-market. As for mass production etching of the microstructures is the way to go, these rather complex bended microchannels structures can be easily manufactured at moderate costs. Before this, further investigation for an optimisation of the design with a special focus in the vapour separation orifices has to be done admittedly.

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