

# Study of pool boiling heat transfer with FC-72 on open microchannel surfaces

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**Abstract.** The paper presents investigations into pool boiling heat transfer for open microchannel surfaces. The experiments were carried out with saturated FC-72 at atmospheric pressure. Parallel microchannels fabricated by machining were about 0.2 to 0.4 mm wide and 0.2 to 0.5 mm deep. Analyzed surfaces with microchannels allowed to obtain heat transfer coefficients within the range of 6.1 – 9.8 kW/m<sup>2</sup>K, which in relation to the flat surface gives a 3 – 5 - fold increase in HTC. One of the reasons for the increase in the heat transfer coefficient when increasing the heat flux was the growing number of active nucleation sites at the bottom of microchannels and its side surfaces.

## 1 Introduction

The use of a refrigerant phase change on a properly designed enhanced surface gives the possibility of obtaining significant values of heat transfer coefficients. The selection of geometric parameters, i.e. the width, height, distance between microchannels, allows to increase the transferred heat flux while the superheat decreases.

The authors in [1] have determined the boiling curves for n-pentane at atmospheric pressure. Enhanced surfaces were formed from copper particles with a diameter of 200 μm and sintered. Forms took the shape of a monolayer i.e. a layer of sintered powder, columnar posts wicks and mushroom posts wick. It was found that the monolayer wicks without and with the mushroom post structure provide 20% and 87% CHF enhancements, respectively, compared to the plain surface. In the work of Udaya Kumar et al. [2] surfaces were made with an electrodeposition technique. Copper wires with diameters of 35 nm, 70 nm, 130 nm and 200 nm were deposited on copper specimens with a smooth surface. The working fluid was Fluorinert FC-72. The percentage increases observed in CHF for the samples with nanowires were 38.37%, 40.16%, 48.48% and 45.57% whereas the percentage increase in the heat transfer coefficient were 86.36%, 95.45%, 184.1% and 131.82% respectively as compared to the bare copper surface. Whereas in the publication [3] boiling curves for FC-72, depending on pressure (100 - 300 kPa) and subcooling (0 - 72 K) were obtained using a silicon heater coated with microporous layers. Microporous, diamondcoated chips were found to provide an average 1.6 enhancement

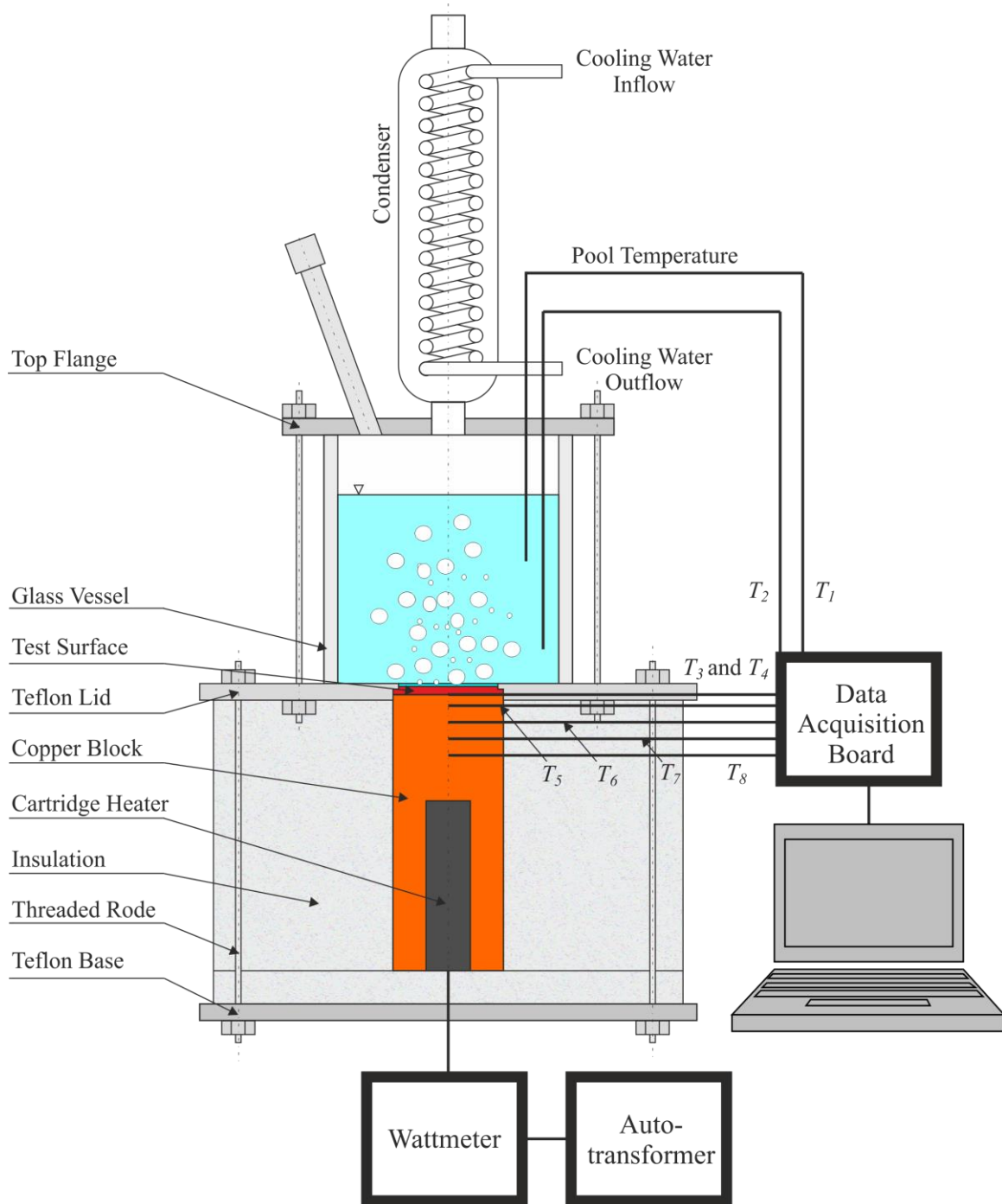
factor on FC-72 CHF, relative to a bare chip, yielding values that ranged from 19.4 W/cm<sup>2</sup> at 1 atm and 1.6 K of subcooling to 47 W/cm<sup>2</sup> for 3 atm in 71 K of subcooling. In the paper [4] experiments were carried out on these surfaces at atmospheric pressure, using FC-72 as the working fluid. The results showed that in comparison to the smooth surface, pool boiling heat transfer was significantly enhanced by the micro-pin-fin surfaces and the maximum superheat was considerably decreased.

Studies on pool boiling heat transfer with water, ethanol, FC-72 and Novec-649 from tunnel structures, microfins, microchannels, microcavities [5–8] and boiling heat transfer with FC-72 flowing in narrow channels [9–13] have been conducted at the Kielce University of Technology for more a decade.

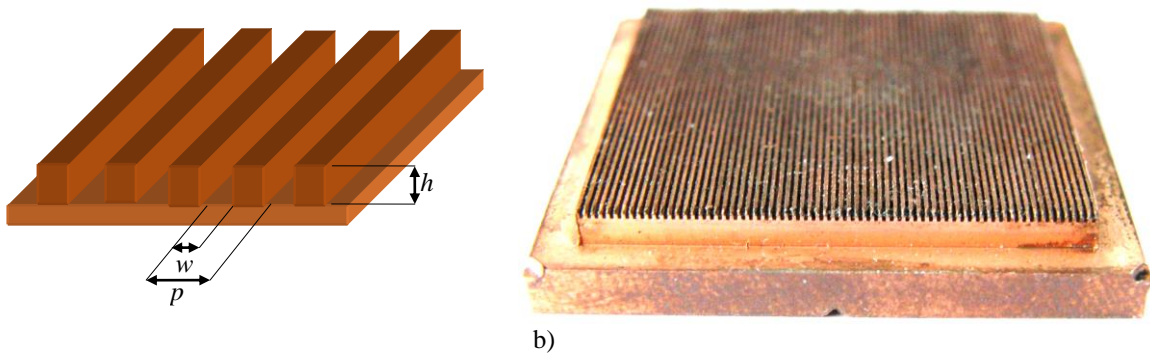
## 2 Experimental setup

Thermal and visualization measurements were made at the measurement stand, Fig. 1 [5-8], which allowed measuring the temperature difference between the working fluid and the heating surface and determining the heat flux. These parameters are necessary to determine the boiling curves. The temperature measurement was carried out using a K-type (NiCr-NiAl) thermocouple with a thickness of 0.5 mm. The measurement data acquisition system was a product of FLUKE Hydra 2635A. Calibration of the thermocouples was carried out using the Altek calibrator.

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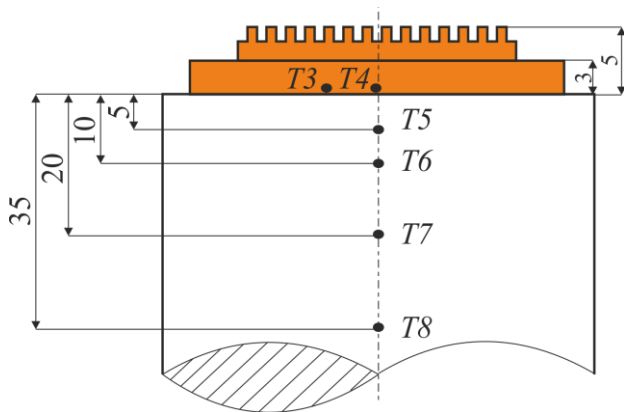
**Fig. 1.** Pool boiling measurement stand.



**Fig. 2.** Specimen with microchannels: a) dimension, b) view.

**Table 1.** MC surface codes and specifications.; constant  $C$  and exponent  $n$  in dependence approximating experimental data

Sample code	$w$ mm	$h$ mm	$p$ mm	$C$	$n$
Smooth surface	-	-	-	0.001	3.57
MC-0.2-0.4-0.4	0.2	0.4	0.4	0.051	3.38
MC-0.2-0.3-0.4	0.2	0.3	0.4	0.125	2.78
MC-0.2-0.2-0.4	0.2	0.2	0.4	0.160	2.55
MC-0.3-0.5-0.6	0.3	0.5	0.6	0.302	2.08
MC-0.3-0.4-0.6	0.3	0.4	0.6	0.574	2.20
MC-0.3-0.3-0.6	0.3	0.3	0.6	0.078	2.81
MC-0.3-0.2-0.6	0.3	0.2	0.6	0.305	2.61
MC-0.4-0.5-0.8	0.4	0.5	0.8	0.661	2.03
MC-0.4-0.4-0.8	0.4	0.4	0.8	0.168	2.44
MC-0.4-0.3-0.8	0.4	0.3	0.8	0.156	2.59
MC-0.4-0.2-0.8	0.4	0.2	0.8	0.330	2.23



**Fig. 3.** Arrangement of thermocouples.

The specimens with test surfaces were made of copper and had parallel grooves with a constant pitch, made with an end mill of 0.2 – 0.4 mm in diameter (CNC machining process) and 0.2 to 0.5 mm deep. The test section consisted of a 32 x 32 mm<sup>2</sup> square copper specimen with a 27 x 27 mm<sup>2</sup> boiling region. Table 1 compiles the surface codes, specifications according to Fig. 3a and summarizes calculation results of constant  $C$  and exponent  $n$  in dependence  $q = C\Delta T^n$  for FC-72 boiling on eleven MC surfaces and smooth surface.

By Newton's law of cooling, HTC is equal:

$$\alpha = \frac{q}{\Delta T}, \quad (1)$$

According to Fourier's law:

$$q = \lambda_{Cu} \frac{dT}{dX}, \quad (2)$$

The temperature gradient was calculated using three point's backward finite difference method as given below, Fig. 3.

$$\frac{dT}{dX} = \frac{3T_{T3} + T_{T4} - 4T_{T6} + T_{T7}}{2l_{T7-T3}}, \quad (3)$$

$T_w$  was extrapolated by following equation as:

$$T_w = \frac{T_{T3} + T_{T4}}{2} - q \left( \frac{\delta_s}{\lambda_{Cu}} + \frac{\delta_{Sn}}{\lambda_{Sn}} \right), \quad (4)$$

where  $\delta_s$  is distance between microchannel bottom (base) and thermocouples  $T3$  and  $T4$ .

The difference between temperatures of the heated surface and liquid  $\Delta T$  (superheat) is shown by the following equation:

$$\Delta T = T_w - \frac{T_{T1} + T_{T2}}{2}, \quad (5)$$

Based on the analysis of errors, estimates for the uncertainty limit on the calculated values were as follows:

- at low heat flux (2 kW/m<sup>2</sup>) relative error of heat flux  $\pm 35\%$ , relative error of heat transfer coefficient  $\pm 40\%$ ,
- at high heat flux (130 kW/m<sup>2</sup>): relative error of heat flux  $\pm 27\%$ , relative error of heat transfer coefficient  $\pm 31\%$ .

### 3 Results

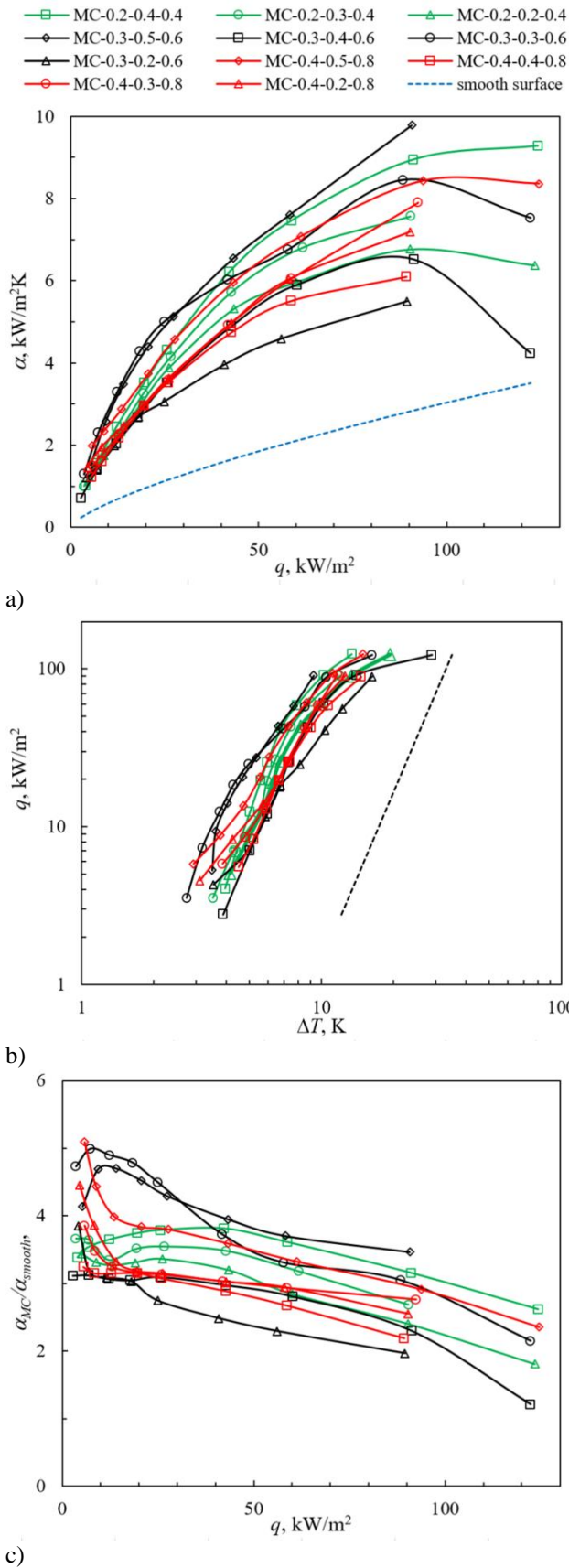
The investigated surfaces with open microchannels provided higher heat transfer coefficients compared to smooth surfaces. For the tested samples with microchannels, Table 1, a significant intensification of heat flux was observed, with the heat transfer coefficient depending on the depth and width of the microchannels. The best results were obtained for sample MC-0.3-0.5-0.6, where the heat transfer coefficient was  $\alpha = 9.8 \text{ W/m}^2\text{K}$  at superheat  $\Delta T \sim 9.3 \text{ K}$  and heat flux about 90 kW/m<sup>2</sup>, Fig. 4a, b.

Analyzed surfaces with microchannels allow to obtain heat transfer coefficients within the range of 6.1 – 9.8 kW/m<sup>2</sup>, which in relation to the flat surface gives a 3 – 5 - fold increase in HTC. The largest maximum heat flux yielded surfaces with microchannels with depths of 0.3 and 0.4 mm. The intensification of heat transfer for samples with microchannels is demonstrated by the ratio of the heat transfer coefficient for the extended surface to the coefficient for the smooth surface, Fig. 4c. For samples MC-0.4-0.5-0.8 and MC-0.3-0.3-0.6 it reached the value  $\alpha_{MC}/\alpha_{smooth} \approx 5$ .

### Conclusion

The analysis of the graphs shows the following conclusions:

- Based on the experimental research carried out, it is not possible to clearly determine the most advantageous parameters of microchannels, enabling the greatest increase of HTC. It can only be said that in the case of boiling FC-72, a significant increase of HTC is possible when combining a smaller width of microchannels (0.2 - 0.3 mm) with their greater depth (0.4 - 0.5 mm).



**Fig. 4.** Boiling curves for FC-72, a) heat transfer coefficient vs. heat flux, b) heat flux vs. temperature difference, c) data in the non-dimensional form for MC surfaces.

- The main reason for the increase in the heat transfer coefficient when increasing the heat flux was the growing number of active nucleation sites at the bottom of microchannels and its side surfaces.

## Nomenclature

CHF – critical heat flux,  
 $h$  – depth, m,  
 HTC – heat transfer coefficient,  
 $l$  – distance between thermocouples, m,  
 MC – microchannel,  
 $p$  – pitch, m,  
 $q$  – heat flux, kW/m<sup>2</sup>,  
 $T$  – temperature, K,  
 $w$  – width, m,

## Greek symbols

$\alpha$  – heat transfer coefficient, W/(m<sup>2</sup>K),  
 $\delta$  – thickness, mm,  
 $\lambda$  – thermal conductivity, W/(mK),  
 $\Delta T$  – difference of temperature, K,

## Subscripts

$Cu$  – copper,  
 $s$  – sample,  
 $Sn$  – tin,  
 $w$  – wall.

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