Heat transfer crisis investigation in a microchannel with and without nanoparticles coating

Yu A Kuzma-Kichta¹, A V Lavrikov¹, M Shustov², E A Kustova¹, N S Ivanov¹, E A Kuleshov¹ and A S Kiselev¹

¹ National research University "MPEI", Moscow, 111250, Russia
² Technion–Israel Institute of Technology, Haifa, Israel

fortynaalex088@gmail.com

Abstract. Heat transfer crisis was investigated during water boiling in a microchannel without coating and with coating of aluminum oxide nanoparticles. Experiments were performed on an advanced setup with a horizontally located microchannel with dimensions of 12.5x3x0.2 mm. Calculation of the critical heat flux in the microchannel without coating and with a coating from nanoparticles, carried out by formulas for heat transfer crisis in a horizontal pipe with microporous coating and one-sided heating. For the microchannel coated with nanoparticles the critical heat flux was calculated for the conditions of no influence of liquid subcooling and initial section. The satisfactory agreement between the experimental and calculated data was obtained. dependences of the critical heat flux from the coating thickness and characteristic size of particles were also shown. However, the data array is limited and needs to be expanded what will improve the equations for critical heat flux in a microchannel with nanoparticles coating.

Introduction

Microchannel heat exchangers can increase the efficiency of cooling. In [1,2] the heat transfer crisis in microchannel was investigated and it was shown that it is very important to increase the heat transfer. Boiling critical heat flux (CHF) can be increased by application of nanoparticles and increasing the wetting [3]. Nanoparticles coating can improve heat transfer in pool boiling on a polished surface and nanoparticles decrease heat flux if the surface is technically smooth [4]. In [5-7] heat transfer enhancement in microchannel with nanorelief was investigated and it was found that the nanoparticles coating increases the critical heat flux at water boiling to 50 %.

In papers [8-11] the calculation of critical heat flux and characteristics of porous structures are discussed. In [8] the formula was proposed for critical heat flux during boiling. This formula predicts CHF increase with decreasing contact angle. In [9] dependence of critical heat flux from the channel height was obtained. The CHF decreases with decreasing channel height (from 3 down to 0.2 mm). Results were obtained for water at mass velocities is from 5000 to 15000 kg / (m² · s). Formula for critical heat flux in narrow rectangular channels and small diameter pipes was proposed using a dimensionless parameter. However, formulas for coated channel were not proposed. In [10] effect of Al₂O₃ nanoparticles coating of on the critical heat flux during boiling of R-123 in a pipe (diameter - 5.45 mm, length - 280 mm) was studied. The range of mass velocities was from 1600 to 2100 kg / (m² · s). Not all of parameters in the formula for the critical heat flux were defined in its final expression. In [11] authors investigated...
porosity of sintered coatings of various metal fibers. Formulas for the average, maximum, and minimum pore diameters were proposed.

Formulas for calculating the critical heat flux in the microchannel with the porous coating aren’t known to the authors. Existing formulas for the critical heat flux in the microchannel without coating have a lot of assumptions. Therefore, investigation of the heat transfer crisis during the boiling in a microchannel without coating and with nanoparticles coating is relevant task.

**Experimental setup and research methodology**

The experimental setup consists of a circuit where the circulation is created by a DLX VFT / MBB pump. The working area is a microchannel of 13.5x3x0.2 mm, it is assembled of two glass plates and a copper wedge, which serves to supply heat to the microchannel (Figure 1). Unlike the previous one [7], this setup uses hard pipe lines instead of flexible ones. This improvement made it possible to reduce pulsations of parameters in the channel.

![Figure 1. Work area in 3D geometry and fluid flow](image)

Heat transfer in a microchannel was determined by measuring the temperature gradient in the copper block using a thermal imager. Surface of the copper block is covered by a layer of TiN particles. That ensures the stability of the emissivity over time (the surface does not oxidize) and in space. Before the experiments, the imager is calibrated (the emissivity of the surface was determinated) by measuring the temperature of the copper block with a thermocouple. To calculate the heat flux density a linear approximation of the temperature distribution in the working section was done.

Then, in accordance with the law of Fourier:

\[ q = \lambda \cdot K, \]  

where \( \lambda \) is the coefficient of thermal conductivity of the work area (copper), \( K \) is the angular coefficient obtained by the linear approximation of the temperature distribution in the copper block. The temperature of the microchannel is calculated as an extrapolation of the temperature in the copper block.

To form the nanoparticles coating on the surface of the microchannel (Figure 2) the colloidal solution of Al₂O₃ in water was boiled on its surface before the main experiment.

The coating thickness varies: in dark areas thickness is about 1 μm, in bright areas - 250 nm (Figure 2) [7].
Method and results of calculation of the critical heat flux in microchannel without coating and with the coating of aluminum oxide nanoparticles

Calculation of the critical heat flux in a microchannel without coating and with the coating of aluminum oxide nanoparticles was carried out using formulas from \[12,13\] which were obtained in a study of the heat transfer crisis in a horizontal pipe with microporous coating with one-sided heating. For microchannel without coating:

\[
q_{\text{crit}} = 9.1 \cdot 10^{-3} q_0 \cdot \left(\frac{D'}{D''}\right)^{0.25} \cdot Re_s^{0.26},
\]

where \(Re_s = \frac{\rho W_0}{\mu s D_{\text{г}}};\) \(W_0 = \frac{\rho w}{\rho'}; q_0 = r \sqrt{\frac{\sigma''}{D_c}}\)

For the microchannel coated with nanoparticles the calculation of the CHF without taking into account the effect of liquid subcooling and initial section is done by formula:

\[
q_{\text{crit}} = q_{\text{crit}}\Psi_c
\]

Effect of the nanoparticles coating on the critical heat flux is described by a modified formula (4):

\[
\Psi_c = 1 + 0.44N^{0.1}(1 - 0.01Re_s^{0.05}),
\]

where \(N = \left(\frac{D_{\text{max}}r\rho/\Delta T_s y}{4\sigma r_E}\right); m\) - selected from \[12\]

\[
m = -16300 \delta_{c\text{eff}} + 4;
\]

\(\delta_c\) – average thickness layers of nanoparticle;

\(D_{\text{max}}\) – nanoparticles size;

\(N\) – characterizes an increase in density of vaporization centers for a coating surface;

\(\lambda_{\text{eff}}\) – calculated by formula (5):

\[
\lambda_{\text{eff}} = \gamma \lambda c + (1 - \gamma)\left(\frac{1-\varepsilon}{\lambda c} + \frac{\varepsilon'}{\lambda'} + \frac{\varepsilon''}{\lambda''}\right)^{-1},
\]

Accept \(\gamma = 0.3;\)

\(\varepsilon'\) and \(\varepsilon''\) equals 0.25;

\(\Delta T_s\) – calculated by Barch and Schroeder-Richter formula \[13\]:

\[
\Delta T_s = T_s \cdot \left[\frac{1}{(1-0.6 \frac{T_s}{T})} - 1\right],
\]

where

\(T_s\) – saturation temperature;

\(r\) – heat of vaporization.

Comparison of the obtained data with known results for the channel without coating

Using equation (2) CHF was calculated for an uncoated microchannel. The results are presented in Figure 2. Data for microchannel without coating is also shown there: \[7\], \[14\].
Obtained results cover a range of mass velocities from 85 kg/(m²·s) to 900 kg/(m²·s). Deviation of calculated data from the experimental results reaches 25%. It is necessary to obtain new data on the critical heat flux and analyze them.

Comparison of the experimental data from [7] for a channel with coating from aluminum oxide nanoparticles with calculation results

Figure 4 shows the results [7] for the microchannel of 0.2 mm high, 3 mm wide, and 13.7 mm long with the coating of aluminum oxide nanoparticles. Two lines represent results of calculation by the formulas (2), (4). Characteristic particle size of 50 nm and a coating thickness of 500 nm adopted from [7]. Coefficient in front of the Re and degree of Re adjusted in equation (4).
That reduce the deviation of the calculated data from the experimental results. The deviations of the calculated data from the results of [7] do not exceed 30%. The critical heat flux for the coated microchannel is 1.5 larger than for the microchannel without nanoparticles coating.

**Effect of thickness and particle size**

The calculation of critical heat flux for coating with different thickness from 50 nm to 1000 nm was performed to understand how the coating thickness affects the critical heat flux (Figure 5a). And calculation of heat flux was performed for coating with different particle size from 50 nm to 1000 nm (agglomerates) [12] to understand how the characteristic size affects the critical heat flux (Figure 5b). Experimental data [7] on the critical heat flux is also shown in Figure 5. The coating thickness of 1000 nm with an average particle size of 50 nm were determined by the images from electronic microscope.

![Figure 5. Dependence of the critical heat flux on (a) the thickness of coating from nanoparticles and (b) particle size
1-calculated; 2- experimental data [7]](image)

The growth of coating thickness reduces the critical heat flux through increasing effect of the coating thermal resistance. Increasing of the coating thickness from 50 nm to 1000 nm decreases the CHF on 50%. But the growth in the characteristic particle size increases the critical heat flux by improving of liquid transport to dry spots on the surface. It is shown from [15] that the liquid lifting high increases with growth in the characteristic size of particles of the coating. Also it was obtained that with an increase in the characteristic size of nanoparticles from 50 nm to 1000 nm, the critical heat load increases by 20%. Formula that takes into account the combination of nanoparticles and their agglomerates should be developed.

**Conclusion**

In this paper the experimental data of the critical heat flux during water boiling in a microchannel (12.5x3x0.2 mm) without coating and with the coating of aluminum oxide nanoparticles were presented. Results for microchannel with coating from of aluminum oxide nanoparticles were obtained for water at mass velocities is from 50 to 350 kg / (m$^2$ · s) at atmospheric pressure. And results for microchannel without coating were obtained for water at mass velocities is from 50 to 950 kg / (m$^2$ · s) at atmospheric pressure. Calculation of the critical heat flux in the microchannel without coating and with the coating of aluminum oxide nanoparticles was carried out using formulas obtained in the investigation of the heat transfer crisis in a horizontal pipe with microporous coating with one-sided heating but effects of
subcooling of the fluid and initial section were not taken into account. Assessment of the influence of the thickness of coating from Al₂O₃ and nanoparticles size on the critical heat flux was provided.

Paper supported by grant RFFR 18-08-00183

References

[1] Nomura T, Shustov M, Suzuki K, Hong C and Kuzma-Kichta Yu. Subcooled Flow Boiling In Mini And Micro Channel; Contribution Toward High Heat Flux Cooling Technology For Electronics.// Proceedings of IPACK2009 InterPACK’09 July 19-23, 2009, San Francisco, California, USA.

[2] Suzuki K, Kuzma-Kichta Yu and Shustov M. Experimental investigation of boiling in micro-channels. Fifth International Topical Team Workshop on TWO-PHASE SYSTEMS FOR GROUND AND SPACE APPLICATIONS, Kyoto, Japan, September 26-29, 2010.

[3] Kim H and Kim M. Experimental Study of the Characteristics and Mechanism of Pool Boiling CHF Enhancement Using Nanofluids, J. Heat Mass Transfer, Special Issuer. 45, pp. 991-998, 2009.

[4] Kuzma-Kichta Yu, Lavrikov A, Shustov M, Chursin P, Chistyakova A, Zvonarev Yu, Zhukov V and Vasilyeva L. Research of heat transfer during boiling water on surface with micro- and nanorelief Thermal Engineering. 2014. №3. C35.

[5] Kuzma-Kichta Yu, Suzuki K, Lavrikov A, Shustov M, and Scholl S. Heat transfer investigation in the microchannel with nanorelief ISTP-24 The 24th International Symposium on Transport Phenomena Tokyo University of Science, Yamaguchi JAPAN, 1-5 NOVEMBER 2013, C. 29-31.

[6] Kuzma-Kichta Yu, Leontyev A, Lavrikov A, Shustov M, and Suzuki K. Boiling investigation in the microchannel with nanoparticles coating // Proc.15.IHTC Kyoto, 2014.

[7] Shustov M, Kuzma-Kichta Yu, and Lavrikov A. Microchannel with coating from nanoparticles is an effective method of increasing the critical heat flux Thermal Engineering, 64(4):301-306 • April 2017.

[8] Kandlikar S. A Theoretical Model to Predict Pool Boiling CHF Incorporating Effects of Contact Angle and Orientation, J. Heat Transfer, 123(6) • December 2001.

[9] Kureta M and Akimoto H. Critical heat flux correlation for subcooled boiling flow in narrow channels. Int.J. of Heat and Mass Transfer 45 (2002) 4107-4115c.

[10] Seo S B and Bang I C. Effects of Al₂O₃ nanoparticles deposition on critical heat flux of R=123 in flow boiling heat transfer Nucl Eng Technol 47,2015.

[11] Khairnasov S, Charles E, Baturkin V, Zaripov V and Nishchyk O. Development of advanced high porosity wicks for the high temperature heat pipes of concentrating solar power Joint 18th IHPC and 12th IHPS, Jeju, Korea, June 12-16, 2016 SAND2016-2627C.

[12] Dzybenko B, Kuzma-Kichta Yu, Leontiev A, Fedik I, and Kholpanov L Heat and mass transfer enhancement on macro-, micro-, and nanoscales TSNIATOMINFORM. 2008. C. 530.

[13] Dzybenko B, Kuzma-Kichta Yu, Leontiev A, Fedik I, Kholpanov L. Intensification of Heat and Mass Transfer on Macro-, Micro-, and Nanoscales Begell House, 2016 ISBN: 978-1-56700-284-3

[14] Kuznetsov V and Shamirzaev A The Influence of the Mass Flow Rate on the Critical Heat Flux during Subcooled Deionized Water Boiling in a Microchannel Cooling System, ISSN 1063-7850, Technical Physics Letters, 2018, Vol. 44, No. 10, pp. 938–941.

[15] Kiselev A and Kuzma-Kichta Yu Wetting research of micro- and nano-scale coating. Journal of Physics: Conference Series, 1370:012027, November 2019.