Study of convective heat transfer in small-diameter channels

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Abstract. This paper investigates the convective heat transfer in a tube made of stainless steel 12X18H9T with outer diameter of 2 mm and inner diameter of 1.5 mm. For the research an experimental setup has been designed and assembled. The experimental setup consists of a fluid pumping system and flow-measuring device, working area, electrical power system and temperature measuring system. The experiment studies of heat transfer intensity in small diameter channels are performed. The study compares experimental data obtained with the theoretical ones. The paper presents the graphs of the Nusselt criterion dependence on the Reynolds criterion and the dependence of the convective heat transfer coefficient on the Reynolds criterion.

1. Introduction
The study of convective heat transfer in the channels of cooling systems in electronic equipment is an actual problem to solve. Miniaturization of electronic equipment elements and increase of power dissipation leads to a reduction of the size of electronic equipment cooling systems. In modern power modules for industrial applications, the level of power dissipation per square centimeter of a casing area reaches several hundred watts. Liquid cooling systems can become a solution to heat dissipation problems.

The main conditions that determine the use of a cooling system for devices are the maximum allowable operating temperature of a device and the maximum amount of heat generated per unit surface area of a device. For example, laser diodes generate heat fluxes with density which is more than 5 kW / cm² at the temperature difference of 30-40°C [1]. To calculate the parameters of cooling systems, it is necessary to know the intensity of convective heat transfer [2-5]. Therefore, this paper aims to study the convective heat transfer in tubes with an internal diameter of 1.5 mm. Small diameter channels require the use of highly purified liquids.

2. Experimental setup for study of convective heat transfer in tubes
The experimental setup for studying convective heat transfer in small diameter tubes was designed and assembled. The scheme of this experimental setup is shown in Figure 1.
The experimental setup consists of the elements, which are indicated in Figure 1 by numbers: 1 - thermostat; 2 - connecting tube; 3 - pump; 4 - connecting tube; 5 - working area; 6 - measuring cylinder; 7 - power supply; 8 - universal voltmeter for measuring electrical resistance; 9 - thermistor; 10 - voltmeter measures the voltage going to tube heating; 11 - measuring transformer; 12 - ampermeter; 13 - step - down transformer; 14 - laboratory autotransformer.

In this paper, distilled water was used as a highly purified liquid. Distilled water is poured into the thermostat 1. The thermostat has an embedded system for external circulation. Water is pumped through working area 5 by the use of pump 4 and embedded system in thermostat for fluid pumping. The flow control occurs by changing current-voltage characteristics of the pump with the help of power supply 7 (Figure 1). The volume flow liquid is measured by measuring cylinder 6 and a stopwatch. It is determined how long it takes a fixed volume of liquid to fill the measuring cylinder. Then, the volume flow is calculated by the equation:

\[ G_v = \frac{V}{\tau}, \]  

where \( V \) - volume, \( \tau \) - the time of liquid outflow.
The volumetric flow rate and the corresponding voltage at the power source supplied to the pump are calibrated. Figure 2 shows the electrical power system of working area 5. Heating of working area 5 is conducted by electric current. For this purpose electric current is supplied to terminals 15. The terminals are soldered to the tube through which the liquid is pumped. Alternating current 220V goes to transformer 13 from laboratory autotransformer 14. Then, the electric current is measured with measuring transformer 11 and amperemeter 12. The voltage supplied to terminals 15 is measured by a voltmeter.

The temperature is measured indirectly. To do this, the electrical resistance of thermoresistor 9 is calibrated and thermoresistor 9 reeled on the tube. Increasing the temperature of the liquid pumped heats the tube from 30 to 95°C. Simultaneously, the corresponding value of the electrical resistance is read using a universal voltmeter. After graduating the thermoresistor, the working area is heated by electric current. The values of the electrical resistance before and after heating and temperature corresponding to these resistances are taken.

3. Preparation of the working area

The paper has investigated a tube made of stainless steel 12X18H9T with an outer diameter of 2 mm and an inner diameter of 1.5 mm. The terminals for electric current are soldered to the tube tested. Wrapping of the thermoresistor is performed manually. The tube is fixed in a machining station which movable part reels the thermoresistor. Then the area with the thermoresistor is covered with a layer of glue.

The thermoresistor is a thin wire covered with an electrical-insulating varnish. After reeling the thermoresistor on the tube, the ends of the thermoresistor are cleaned. Thermoresistor copper wire is soldered to the wires located on Teflon tubes. The wires, on which the electrical resistance is read by a universal voltmeter, are soldered to a wire fixed to the Teflon tubes. Plastic foam is glued to the thermoresistor and terminals to reduce the temperature fluctuations on the thermoresistor and decrease the loss of thermal energy. The tube is connected to the pump through an adapter and a silicone tube. The outer diameter of the tube is measured by a micrometer. The inner diameter of the tube is measured by a microscope. For this purpose, the number of visible divisions under microscope for the outer and inner diameter of the tube are measured. The proportion and the inner diameter of the tube are calculated by the equation:

\[ d_1 = \frac{d_2 n_1}{n_2}, \]  

(2)

where \( d_1 \) is the inner diameter of the tube; \( d_2 \) is the outer diameter of the tube; \( n_1 \) – the number of visible divisions under a microscope for the inner diameter of the tube; \( n_2 \) - the number of visible divisions under a microscope for the outer diameter of the tube.

4. Calculation of convective heat transfer coefficient

Electrical power used to heating the tube:

\[ P = U I \quad [W] \]  

(3)

Convective heat transfer coefficient:

\[ \alpha = \frac{P}{\delta_{\text{at}}} \quad [W / m^2 \cdot K] \]  

(4)

The temperature difference between the mean temperature of the inner surface of wall tube and the mean fluid temperature:

\[ \Delta T = \Delta T_{\text{i}} - \Delta T_{\text{sur}} - \Delta T_{\text{heat}} \quad [K]. \]  

(5)

The temperature difference between the mean temperature of the tube and the mean temperature of the liquid at the inlet of the tube:
\[ \Delta T_t = \frac{\Delta R}{R_{\alpha \alpha}} \text{[K]} \]  

Differential temperature on the wall:

\[ \Delta t_w = \frac{q_v}{4 \lambda_w \left[ 2 \ln \left( \frac{r_2}{r_1} \right) + \left( \frac{r_1}{r_2} \right)^2 - 1 \right]} = \bar{t}_{w2} - \bar{t}_{w1} \text{[K]} \]  

Volumetric power density:

\[ q_v = \frac{P}{V} = \frac{4P}{\pi \left( d_2^4 - d_1^4 \right) L} \text{[W/m}^3] \]  

The temperature on the inner surface of the wall:

\[ \bar{t}_{w1} = \bar{t}_{w2} - \Delta t_w \text{[K]} \]  

The mean liquid temperature:

\[ \bar{t}_f = t_{in} + \frac{F}{2cp \rho_0} \text{[K]} \]  

The convective heat transfer coefficient:

\[ \alpha = \frac{F}{S(\bar{t}_{w2} - \bar{t}_f)} \text{[W/ m}^2 \cdot \text{K]} \]  

Nusselt number:

\[ Nu = \frac{a d}{\lambda} \]  

The calculation of the temperature difference between mean fluid temperature and the mean temperature at the inlet:

\[ \Delta T_{\text{heat}} = \frac{P}{2cp \rho_w} \text{[K]} \]  

The program Scilab was used for data processing of the results and compared them with the theoretical ones. The equations of Mikheev, Hausen, Ramm, Kutateladze, for heat transfer at movement of liquid in pipes, are used for calculation and given below.

The equation for heat transfer in the transient behavior of fluid motion (\(2 \cdot 10^3 \leq Re_f \leq 10^4\)): [7]

\[ \overline{Nu}_f = K \cdot M; M = Pr_f^{0.43} \left( \frac{Pr_f}{Pr_w} \right)^{0.25} \]  

The equation for heat transfer in the transient regime of fluid motion [8]:

\[ \overline{Nu}_f = 0.0225 Re_f^{0.8} Pr_f^{0.4} \cdot f; f = 1 - \left( \frac{6 \cdot 10^5}{Re_f^{1.5}} \right) \]  

The equation for heat transfer (for Re from 2300 and for the entire region of turbulent fluid flow) [9]:

\[ \overline{Nu}_f = 0.12 \left( Re_f^2 - 125 \right) Pr_f^{0.4} \left( \frac{\mu}{\mu_w} \right)^{0.14} \]  

The equation for turbulent behavior:

\[ \overline{Nu}_f = 0.021 Re_{df}^{0.8} Pr_f^{0.43} \left( \frac{Pr_f}{Pr_w} \right)^{0.25} \]  

where \( \varepsilon_l \) is the change of mean heat transfer coefficient along the length of the tube [10].

The equation for the turbulent behavior:

\[ Nu_f = \frac{0.023 \cdot Pr \cdot Re^{0.8}}{1 + 2.14 Re^{-0.1} \left( Pr^{2/3} - 1 \right)} \] [11]
After data processing, the graphs were built which are shown in Figure 3 and Figure 4.

**Figure 3.** Dependency graphs of Nusselt number on Reynolds number Nu (Re) according to experimental and theoretical data.

**Figure 4.** Dependency graphs of the convective heat transfer coefficient on the Reynolds criterion $\alpha$ (Re) according to experimental and theoretical data.
5. Conclusion
The experimental setup has been designed and assembled to investigate heat transfer in small diameter tubes. The working area was fabricated for the study of convective heat transfer in tubes with an internal diameter of 1.5 mm. The intensity of convective heat transfer in the liquid flow inside a smooth tube of circular cross-section is investigated. The dependency graphs of the convective heat transfer coefficient on Reynolds number \( \alpha(Re) \) are compared according to experimental and theoretical data. Moreover, the dependency graphs of Nusselt number on Reynolds number \( Nu(Re) \) are compared according to experimental and theoretical data. The experimental data has revealed no contradictions with the dependencies previously known.

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