Proceedings of the 9th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'22)
Niagara Falls, Canada– June 08-10, 2022
Paper No. 160
DOI: 10.11159/ffhmt22.160

Intensification of Heat Transfer by the Method of Artificial Roughness at a Water Film Flows down on Vertical Pipe

Tengiz Magrakvelidze[1], Giorgi Gigineishvili[2], Avksenti Mikashavidze[1], Tariel Koberidze[1], Khatuna Lomidze[1]
[1]A. Eliashvili Institute of Control Systems of Georgian Technical University
10, Mindeli Street, 0186, Tbilisi, Georgia
qveli17@yahoo.com; g.gigineishvili@gtu.ge
[2]Georgian Technical University
77, Kostava Street, 0160, Tbilisi, Georgia
avksenti.mikashavidze@gtu.ge

Abstract **-** The article presents the results of an experimental study to determine the effect of two-dimensional, pyramidal and combined roughness on heat transfer when a water film flows down the outer surface of a vertical pipe. A two-dimensional roughness was created by winding a wire around a pipe. The pyramidal roughness was created by cutting the left and right screws on the pipe, as a result of which the pipe surface was covered with densely spaced truncated pyramids of height – k. The combined roughness was created by a combination of the above two types with different heights – h and relative step – s/h of two-dimensional roughness. Three regimes of manifestation of the effect of roughness on the intensity of heat transfer were identified: 1. Regime without manifestation of the effect, 2. Regime with partial manifestation of the effect and 3. Regime of full manifestation of the effect of roughness on heat transfer. It was experimentally established that the maximum increase in the heat transfer intensity (more than 3.5-times) is achieved in the case of using a combined roughness with geometric parameters: k=0.25mm, h =0.7mm, s/h =10. It was also found that the effect of the combined roughness (pyramidal + spiral) on heat transfer in the entire range of the Reynolds number investigated by us is higher than the effect of both two-dimensional and pyramidal roughness.

Keywords**:** Heat transfer, laminar motion, roughness, turbulent motion, water film.

1. Introduction

The widespread use of the heat transfer process during film flow in power, chemical, food and other installations makes the task of intensifying heat transfer actual.

The issues of heat transfer during liquid film flow on smooth walls, both under conditions of evaporation or condensation, and without phase transitions, have been studied sufficiently well [1, 2]. Along with this, many issues of heat transfer intensification under conditions of liquid film runoff remain unresolved.

As you know, one of the most effective ways to increase heat transfer is the use of the artificial roughness method. Fundamental studies of hydrodynamics and heat transfer in channels with rough walls were carried out in the middle of the 20th century at the University of Gottingen [3,4].

The effectiveness of the artificial roughness method for the intensification of heat transfer in turbulent flow in the channels of both single-phase and two-phase flows has been thoroughly proven in studies [4–7].

At the same time, the effect of artificial roughness on heat transfer during film flowing over a vertical surface, despite the works [8-10] that have appeared in recent years, cannot be considered sufficiently studied. Many problems in this direction are considered unresolved. In particular, the process of heat transfer from a surface with closely spaced roughness elements in the form of truncated pyramids and combined roughness has not been studied all. The study of the regularities of heat transfer in the transitional regime (laminar-turbulent) film flow is subject of interest.

2. Experimental Setup

To solve the problem of heat transfer from a surface with closely spaced roughness elements in the form of truncated pyramids and combined roughness, the experimental setup was created by us. The experimental setup schematic diagram is shown on the Fig.1.

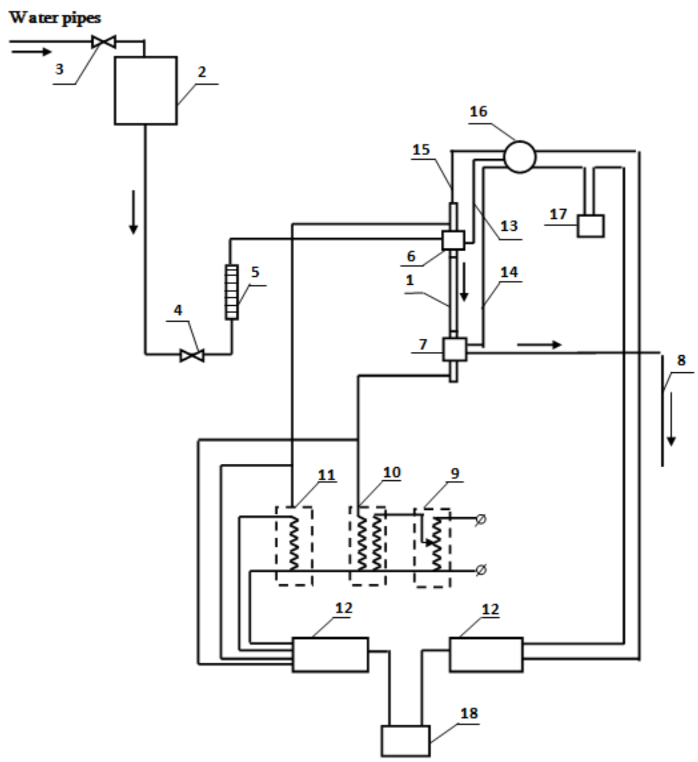

Fig. 1: Experimental setup;
1 –Test pipe, 2 –Tank, 3,4 – Valves, 5 – Flow meter, 6 – Upper chamber, 7 – Bottom Chamber, 8 – Drain, 9 – Regulating transformer, 10 – Voltage transformer, 11 – Current transformer, 12 – Digital multimeters, 13, 14, 15 – Thermocouples, 16 – Switch, 17 – "0" device, 18 – Computer.

The installation was an open circuit, the main element of which was a heat transfer pipe (1). From the tank (2) through the valve (4) and the flow meter (5), water entered the upper chamber (6), from where it flowed along the outer surface of the pipe (1) in the form of a film and through the lower chamber (7) was discharged into the sewer network.

A constant water level in the tank during the experiments was maintained using an automatic device. The water flow was regulated by means of a valve (4). The heat transfer pipe (1) was made of stainless steel. The outer diameter of the pipe – d = 10mm, and the heated length – l = 200mm. A section of hydrodynamic stabilization was also envisaged. The water flow rate was measured with a pre-calibrated flow meter (5) type LZS-15. The heat transfer tube was positioned vertically and was heated by directly passing a low voltage alternating current through it. To lower the voltage, a transformer (10) of the OSU-20 type was used.

The power supplied to the test pipe was regulated by an autotransformer (9) of the RNO-250-10 type. The current strength and voltage drop across the test tube were measured with a UT804 digital multimeter (12). The electromotive force of the thermocouples was also measured with a DM3068 digital multimeter (12). The temperatures at the inlet and outlet of the experimental section were measured by chromel-alumel thermocouples located in chambers (6) and (7). The temperature of the inner surface of the test pipe was measured in five places by a thermocouple sliding inside the pipe, placed in a Teflon chamber.

The measured of the magnitudes was automatically entered into a computer (18) and processed using the program created with us in TurboPascal. The following values were determined: water flow rate, power released in the test pipe, heat flux, heat flux density (was determined by the ratio of the heat flux to the area of the smooth surface of the experimental tube), average temperature of the outer surface of the test pipe, average water temperature, heat transfer coefficient.

3. Results and Discussion

The experimental results were processed in dimensionless quantities:

$$Nu = \frac{\alpha}{\lambda}\left(\frac{\nu^2}{g}\right)^{1/3}, \quad Pr = \frac{\nu}{a}, \quad Re = \frac{4G}{\nu} \tag{1}$$

where, α – heat transfer coefficient, w/(m^2 K); λ – coefficient of thermal conductivity of water, w/(mK); ν – coefficient of kinematic viscosity (m^2/s); g – acceleration of gravity, (m/s^2). a – coefficient of thermal diffusivity, (m^2/s); G – irrigation coefficient (volumetric flow rate of the liquid divided by the perimeter of the pipe), (m^2/s); *Nu* – Nusselt number; *Pr* – Prandtl number; *Re* – Reynolds number.

The physical parameters for the average temperatures of the water and the wall of the experimental pipe were taken from the tables [11].

Experiments were carried out for both smooth and rough surfaces. Two-dimensional roughness was created by spirally winding copper wire on a smooth pipe. The experiments were carried out at a value of the height of the elements of two-dimensional roughness (diameter of the wound wire) of 0.5mm. The relative step between the elements of the two-dimensional roughness s/h was equal to 10.

The pyramidal roughness was created on a lathe by cutting both left and right threads. As a result, the pipe surface was covered with densely spaced truncated pyramids. The height of the pyramids – k = 0.25 mm.

The combined roughness was created by spirally winding copper wire onto a pyramidal roughness pipe. In this case, the height of the two-dimensional roughness elements (the diameter of the wound wire) was 0.35mm, 0.5mm, and 0.7mm, and the relative pitch between the two-dimensional roughness elements s/h was 10, 40, and 60.

A series of experiments were also carried out in which a two-dimensional roughness on a tube with pyramids was created by wire rings. The height of the roughness elements in these experiments is – h =0.5mm, and the ratio of the step between the roughness elements to their height is – s/h = 40 and 60.

The experiments were carried out on water. The Prandtl number in the experiments – *Pr* =7, the Reynolds number – *Re* varied in the range 250÷25000.

Fig.2 shows the results of experiments for a smooth surface and surfaces with two-dimensional, pyramidal and combined roughness.

In the graph, the experimental data are averaged by dotted lines. The solid line I corresponds to the well-known formula of Chung and Seban, which is valid for the laminar-wave regime [12]:

$$Nu = 2.03Re^{1/3} \tag{2}$$

Line II corresponds to the Labuntsov formula for the transition regime from wave to turbulent [13]:

$$Nu = \frac{0.17Pr^{0.5}\left(Re/Re_{cr}\right)}{Pr^{0.5}+1.6\left[\left(Re/Re_{cr}\right)^{3/4}-1\right]} \tag{3}$$

were Re_{cr}=1600.

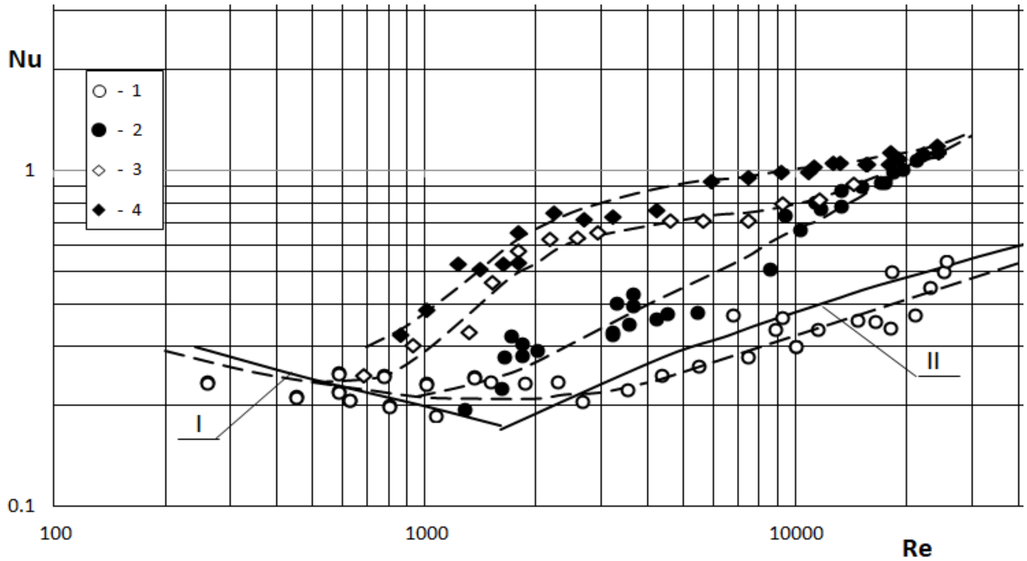

Fig. 2: Dependence of the heat transfer intensity on the Reynolds number;
1 – Smooth surface; Rough surfaces: 2 – Pyramidal roughness, k = 0.25mm; 3 – Two-dimensional roughness, h = 0.5mm, s/h = 10; 4 – Combined roughness, k = 0.25mm; h = 0.5mm; s/h = 10;
I – According to the formula of Chung and Seban [12]; II – According to the Labuntsov formula [13].

Formulas (2) and (3) are valid for a smooth surface.

As can be seen from Fig.2 our experimental data for a smooth surface are in good agreement with the indicated formulas (2) and (3).

It is also seen from this graph that in the case of a surface with pyramidal roughness at relatively low Reynolds values (*Re*<1500), the heat transfer intensity practically coincides with the intensity for a smooth surface.

At higher values of the Re number, the effect of roughness manifests itself, and at Re≥(15000÷20000), the intensity of heat transfer of a pipe with pyramidal roughness is more than 2.5 times higher than the same value for a smooth surface.

The experimental data for the two-dimensional roughness presented in Fig. 2 show that the roughness effect begins to manifest itself already at $Re>10^3$. Our results show that, in the entire investigated range of Reynolds numbers, the surface with the combined roughness has become the most effective.

It is important to note here that in the case of pyramidal roughness, the intensification of heat transfer is largely achieved by increasing the area of the heat transfer surface. Taking this into account, the equality of the heat transfer intensity for a smooth surface and a surface with a pyramidal roughness can be explained as follows: at low values of the Re number, so-called "dead" zones are formed in the depressions between the pyramids, which clearly worsen the heat transfer intensity. But, on the other hand, pyramids, as mentioned above, cause a significant increase in surface area, which, in turn, increases heat removal from the pipe surface. It can be assumed that these two opposing factors balance each other, and as a result, the heat transfer coefficient is the same for smooth and rough surfaces.

With an increase in the Reynolds number, the movement of the liquid in the "dead" zones and accordingly the intensity of heat transfer increases.

Of interest is the influence of the relative pitch (s/h) of the two-dimensional roughness created on the surface of a pipe with a pyramidal roughness. The height of the pyramidal roughness elements in these experiments, as in the previous ones, was 0.25mm.

The results of such experiments are presented in Fig.3. In this, as in the following graphs, the experimental data obtained for a smooth pipe and for a pipe with pyramidal roughness are presented by averaging dashed lines 1 and 2, respectively.

As can be seen from the indicated graph, in the investigated range of both the Reynolds number and the geometric parameter – s/h, the maximum intensification of heat transfer is achieved at – s/h = 10. With an increase in s/h, the degree of intensification decreases. However, in contrast to the case of the effect of s/h of two-dimensional roughness on heat transfer when moving in pipes [5], in this case, the intensity of heat transfer decreases to a lesser extent.

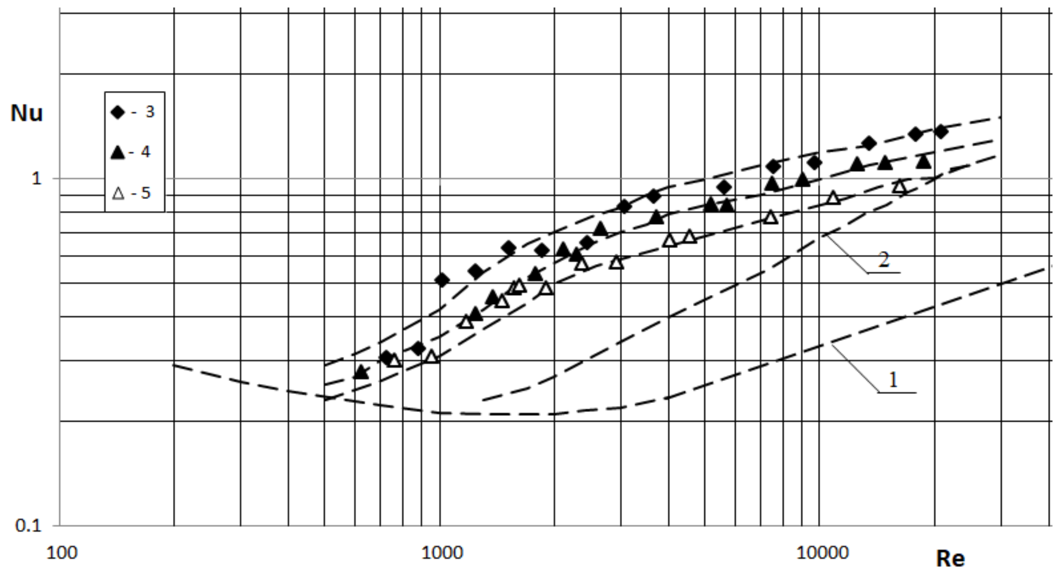

Fig. 3: Dependence of the heat transfer intensity on the Reynolds number;
1 – Smooth surface; Rough surfaces: 2 – Pyramidal roughness, k = 0.25mm; 3 – Combined roughness, k = 0.25mm; h= 0.5mm; s/h =10; 4 – Combined roughness, k = 0.25mm; h = 0.5mm; s/h = 40; 5 – Combined roughness, k = 0.25mm; h = 0.5mm; s/h = 60.

Fig.4 shows the results obtained at various values of the height of the elements of two-dimensional roughness - h (the diameter of a spirally wound wire on a pipe with a pyramidal roughness).

The presented data show that the height of two-dimensional roughness elements created on a pipe with densely spaced truncated pyramids significantly affects the intensity of heat transfer. In particular, an increase in h increases the intensity of heat transfer.

Obviously, with spiral winding, a rotational component of the fluid motion appears, and this component will be the greater, the larger the pitch of the spiral winding. In this regard, the question of what is the role of this component in the intensification of heat transfer during film flow deserves attention.

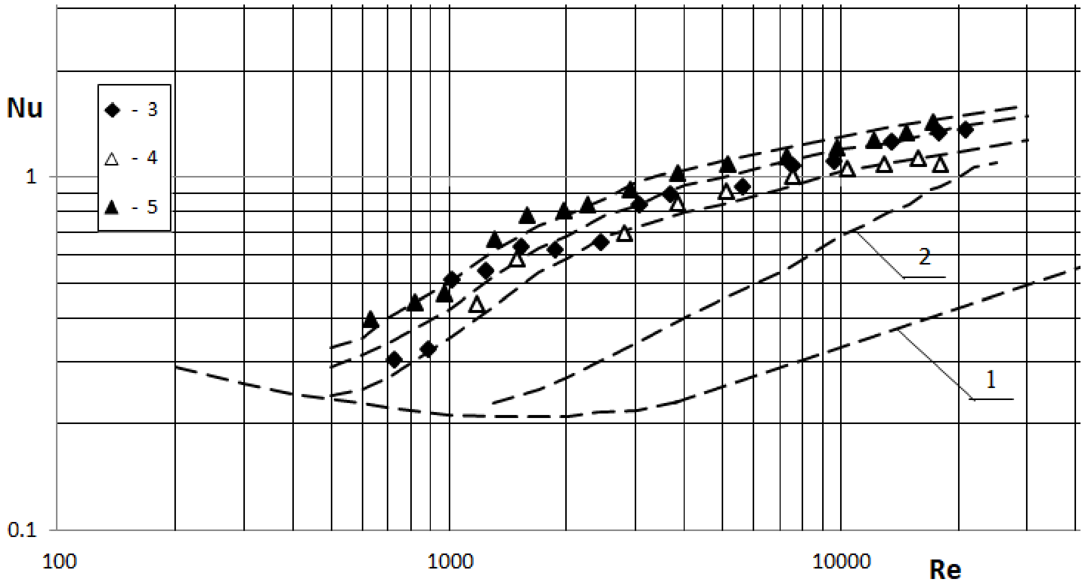

Fig. 4: Dependence of the heat transfer intensity on the Reynolds number;
1 – Smooth surface; Rough surfaces: 2 – Pyramidal roughness, k = 0.25mm; 3 – Combined roughness k = 0.25mm; h= 0.5mm; s/h = 10; 4 – Combined roughness, k = 0.25mm; h = 0.35mm; s/h = 10; 5 – Combined roughness, k = 0.25mm; h = 0.7mm; s/h = 10.

To clarify this issue, we carried out additional experiments in which a two-dimensional roughness on a pipe with a pyramidal roughness was created by wire rings. This meant that in this case, the rotational motion of the liquid is practically completely excluded. The results of such experiments, together with the data obtained for a spiral wound pipe, are presented in Fig.5.

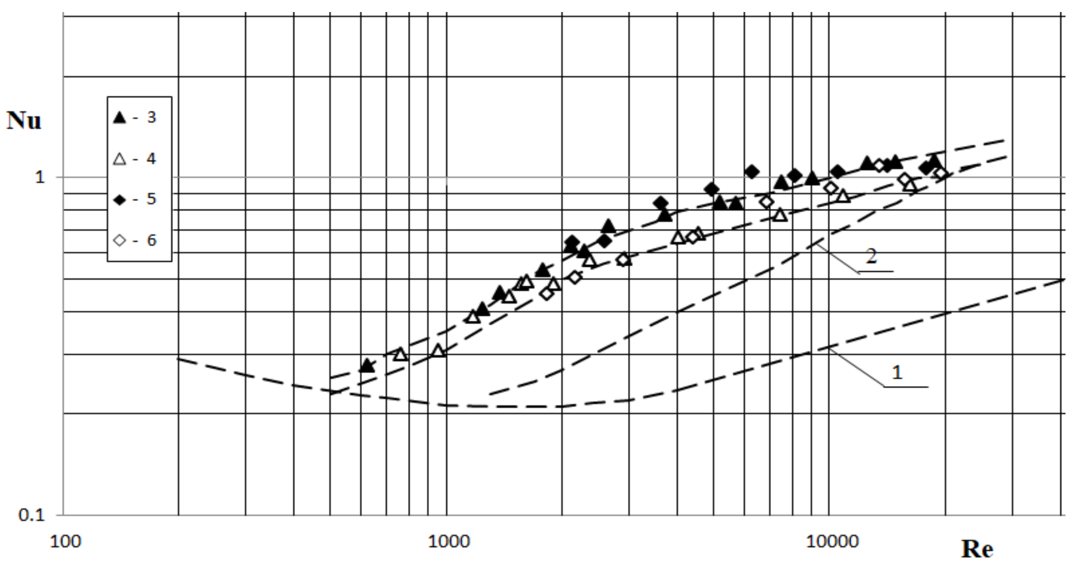

Fig. 5: Dependence of the heat transfer intensity on the Reynolds number;
1 – Smooth surface; Rough surfaces: 2 – pyramidal roughness, k = 0.25mm;
Combined roughness with spiral winding:3 – k = 0.25mm; h = 0.5mm; s/h = 40; 4 – k=0.25mm; h=0.5mm; s/h=60;
Combined roughness with wire rings: 5 – k = 0.25mm; h = 0.5mm; s/h = 40; 6 – k = 0.25mm; h = 0.5mm; s/h = 60.

As can be seen from fig.5, at equal values of h and s/h, the heat transfer rates in both cases are practically equal to each other. These results indicate that the rotational component of the flow velocity does not affect the rate of heat transfer.

4. Conclusion

The experimental results presented in Figures 3-5 give grounds to conclude that the creation of roughness on the heat transfer surface causes, in general, a significant increase in the intensity of heat transfer with the free flow of the liquid film along the vertical pipe.

Identified three regimes of manifestation of the effect of roughness on the intensity of heat transfer:

1. Regime without manifestation of the effect.

The regime takes place with laminar flow of the film. In this regime, the heat transfer rates of smooth and rough pipes are equal to each other.

2. Regime with partial manifestation of the effect.

This regime starts at a certain value of the Re number depending on the height of the two-dimensional roughness elements. With an increase in the height of the roughness elements, the value of the Re number decreases at which the roughness effect begins to manifest itself.

In this regime, with an increase in the Re number, the heat transfer intensity sharply increases.

3. Regime of full manifestation of the effect of roughness on heat transfer.

At the beginning of the manifestation of this regime, according to the data presented in Fig.4, the maximum intensification of heat transfer is observed (more than 3.5 times). This regime is characterized by a more moderate increase in the heat transfer intensity with an increase of Re number. Accordingly, the degree of intensification is reduced to 2.5 times.

The results presented in Fig. 5 indicate that the rotational motion of the liquid film does not contribute to an additional increase in the intensity of heat transfer.

The results obtained show that the use of the artificial roughness method in heat transfer installations will significantly increase their efficiency.

Acknowledgment

Work is funded by the grant of Shota Rustaveli National Science Foundation of Georgia (Grant Project FR-19-3034).

References

[1] W. Nusselt. Surface condensation of the water vapor. “Zeitschrift“ VDI 1916, Vol. 60, pp. 541-546, 568-575. (In German)

[2] C. Kutateladze, V. Nakariakov. Heat and mass transfer and waves in gas-liquid systems. "Science", 1984. 301 p. (In Russian)

[3] J. Nikuradze. Flow laws in rough pipes, VDI Forschgscheft, N361, 1933, p.16-53. (In German)

[4] W. Nunner. Heat passage and pressure drop in rouhen pipes, VDI research office, 1956, 455s. (In German)

[5] V. Gomelauri. Influence of two – dimensional artificial roughness on convective heat transfer. Int. Journal of Heat and Mass Transfer, v.7, N6, 1964, pp.653-663.

[6] V.Gomelauri, T.Magrakvelodze. Experimental Investigation of Influence of two-dimensional Roughness on critical Heat Fluxes and Heat Transfer in Subcooled water Flow. Thermal Engineering, 1976, No. 6, p.4-8.

[7] E. Kalinin, G. Dreitser, S. Yarkho. Intensification of heat transfer in the channels. M .: Mechanical engineering. 1972, 219s. (In Russian)

[8] T.Magrakvelidze, A.Mikashavidze, N.Bantsadze, Kh.Lomidze, N.Lekveishvili. Influence of artificial roughness on heat transfer of the film flowing down on vertical surface. Archil Eliashvili Institute of Control Systems of the Georgian Technical University. Tbilisi, 2016. N21, pp.39-44. (In Georgian)

[9] T.Magrakvelidze, A.Mikashavidze, Kh.Lomidze, N.Bantsadze. Intensification of heat transfer at the film flow of water on a vertical surface. Archil Eliashvili Institute of Control Systems of the Georgian Technical University. Tbilisi. 2017. N22, pp. 47-51. (In Georgian)

[10] Anders Akesjo. Thesis for the degree of doctor of philosophy. Hydrodynamics and Heat Transfer in Vertical Falling Films with Smooth and Modified Heat-Transfer Surfaces – An Experimental and Numerical Investigation. Gothenburg, Sweden, 2018.

[11] V. Chirkin. Thermophysical properties of materials for nuclear technology. Atomizdat. M., 1968. 483s. (In Russian)

[12] K.Chun, R.Seban. Heat transfer to evaporating liquid films. Heat Transfer Ser. S. - 1971. - T. 93, No. 4. - S. 71-77.

[13] D.Labuntsov. Heat transfer at film condensation of pure vapors on vertical surfaces and horizontal pipes, Teploenergetika. 1957. No. 2, p. 49-51. (In Russian).