International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V68I11P205

Volume 68 Issue 11, 33-48, November 2020

Ways of Intensifying the Heat Exchange Processes in a Single-Well System for Subsoil Deep Thermal Energy Pickup and Transportation

A.V. Ryzhenkov*, A.Y. Likhaeva, S.V. Grigoryev, M.R. Dasaev, I.S. Sokolov

National Research University "Moscow Power Engineering Institute", Moscow, Russia

*artyom.v.ryzhenkov@mail.ru

Abstract: *The main task of a heat supply system is uninterrupted supply of heat energy with the specified parameters to the consumer with minimum losses. The efficiency of heat supply systems largely depends on the heat exchange equipment used. Reducing the weight and dimensions, increasing the amount of heat transferred, and reducing electricity consumption for pumping the heat carrier are the main goals of increasing the efficiency of the heat exchange equipment. This article provides an overview of the traditional and promising methods for intensifying the heat exchange processes in the heat exchange equipment.*

Keywords: *intensification, heat energy, uninterrupted supply.*

I. INTRODUCTION

Today, the problem of energy supply to isolated consumers is solved through the use of power generating plants that consume fossil fuel, which is systematically delivered to the facilities, as well as using nontraditional and renewable energy sources (RES). The main types of RES used for energy supply to autonomous consumers are biomass energy, wind energy, solar energy, energy of small rivers, and steam-hydrothermal energy. The analysis of the listed RES [1], [2] reveals a feature inherent in all their types — the significant unevenness of the gross potential of the energy sources, as well as a significant energy dispersion in the environment of each of the sources. Works [3], [4] on the energy supply from RES to remote and isolated consumers confirm the efficiency of using alternative energy sources, but the restrictions imposed by the features of RES do not allow the widespread use of a separate type of RES.

Petrothermal energy — the deep thermal energy of dry rocks in the Earth's deep interior — is devoid of these disadvantages of RES. This energy source is stable over time, does not depend on the climatic and territorial factors, and is ecologically safe.

The main characteristic that describes the thermal state of the Earth's deep rock is the geothermal temperature gradient, which shows an increase in the rock temperature with the depth increasing. On average, for seismically quiet regions, the values of this indicator vary in the range between 1 and 7 °C per 100 m. In the regions with volcanic activity, higher values may be observed. The analysis of the subsoil thermal state maps on the territory of the Russian Federation down to 3 km shows [5] that the geothermal gradient values in the range from 1.5 to 2.5 °C per 100 m prevail on the territory of Russia; however, according to the data of deeper drilling [6], the geothermal gradient increased to 3 – 3.5 °C per 100 m practically everywhere, and no decrease was observed. Thus, according to the preliminary estimates, the subsoil temperature is expected to reach 150 – 170 °C in various conditions even at the depth of 4 – 5 km, which is very important for the needs of heat supply and, in the case of using power generation cycles with low-boiling working substances, for the needs of power supply.

Petrothermal energy pickup and transportation to the surface consist in creating a soil circulation system (SCS) in the rock mass of the Earth at the depth determined by the heat load of the consumer. Two variants of soil circulation system deployment are mainly used in the world today: the "open" method and the "closed" method. The "open" method consists in drilling at least two wells, one downstream and one production (upstream), and placing a water-permeable area between them at the depth with the required temperature potential. This method is widely used in Europe [7] and the USA. With the "open" method of subsoil heat extraction, an artificial reservoir is created in hard rock by means of hydraulic fracturing that connects two or more wells (downstream and upstream). The pickup system may include only one reservoir, or it may contain several reservoirs located at different depths. The "open" method of pickup has the following disadvantages: pollution and mineralization of the heat carrier due to the large area of contact with the subsoil, heat carrier migration (up to 20% of the total volume of the heat carrier); the technologies used for hydraulic fracturing are not environmentally friendly. The "closed" method is a single-well system: a "pipe-in-pipe" heat exchanger located in a well. This method of pickup is devoid of the disadvantages of the "open" system, while it features sufficiently high hydraulic resistance of the system due to its considerable length. However, due to the need of using only one well for creating a "closed" system, it is possible to use the unused oil and gas, scientific and parametric, exploration, and other wells. In this case, creating a single-well system is actually reduced to lowering the inner pipe column for the transportation of hot heat carrier from the well bottom to the wellhead.

Another problem in creating single-well systems for subsoil heat pickup is the small heat pickup surface, which is actually limited by the casing string. The coefficient of heat transfer from the hot inner surface of the casing may be increased through the use of various methods for intensifying the heat exchange processes.

As mentioned above, a single-well heat pickup system is a long tube-in-tube heat exchanger. Therefore, various methods used in modern heat exchangers of various purpose may be used for intensifying the heat exchange processes. However, it should be noted that special attention should be paid to the methods with the minimum impact on the hydraulic performance of a single-well heat pickup system.

There are several criteria (see Fig. 1) that classify heat exchangers [8]–[13].

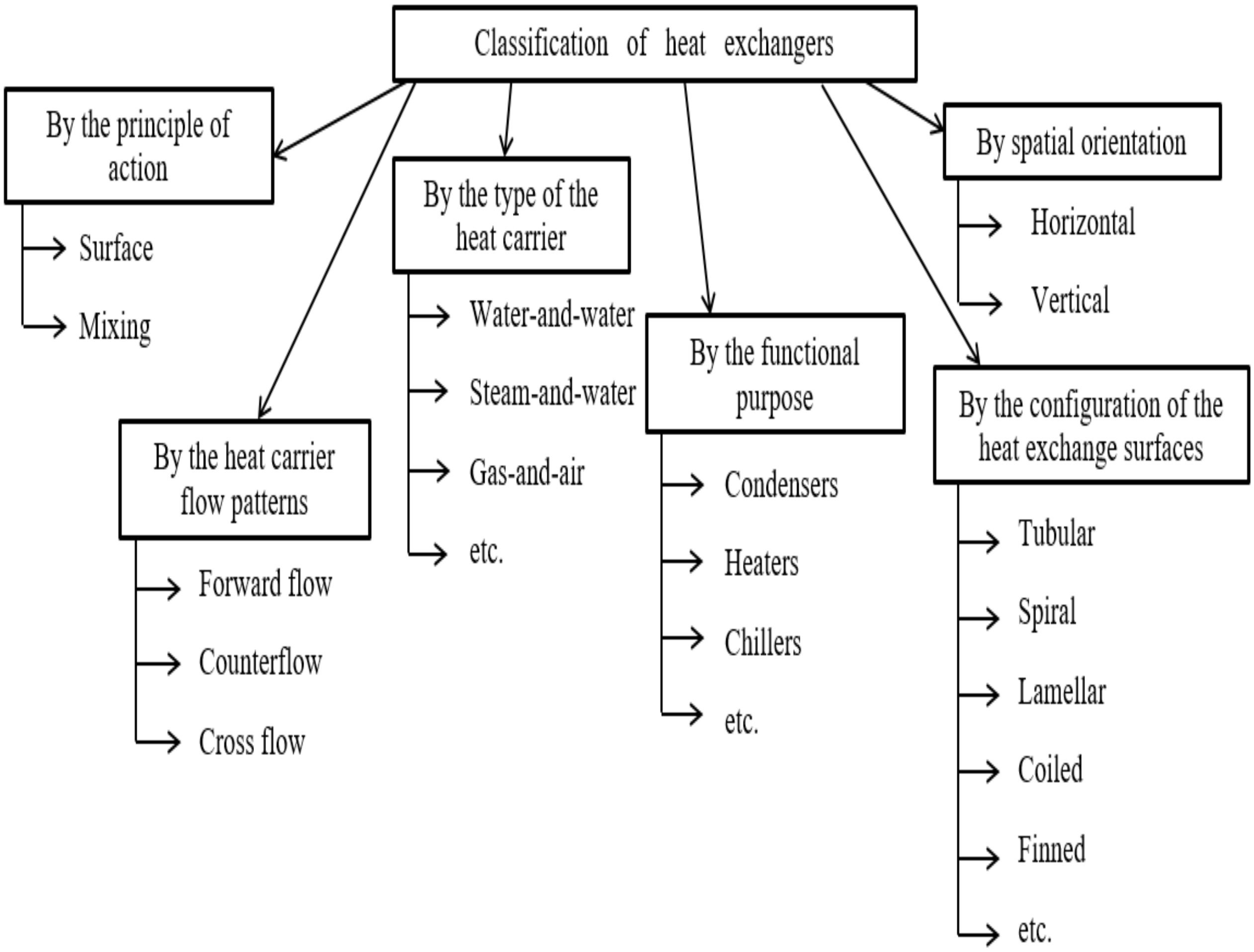


Fig. 1 Classification of heat exchangers

Despite the wide variety of heat exchangers as to the principle of operation, the design, the type of heat carrier and the purpose, the general basic thermal, hydrodynamic, operational, constructive and technological requirements may be formulated, which are to be considered in choosing the type of heat exchanger and in calculating and designing the heat exchange equipment. The main thermodynamic requirement is the achieving of the maximum heat transfer coefficient with the minimum hydrodynamic resistance.

II. METHODS

There are various ways of improving the efficiency of heat transfer equipment (see Fig. 2), which are divided into two main groups.

The first group includes the methods where the heat carrier is acted on by purifying it from dissolved substances and corrosive compounds. The second group includes the methods with the effect on the heat exchange surface. The most common approaches to increasing the efficiency by modifying the heat exchange surfaces of heat exchangers include developing fundamentally new heat exchangers and improving the existing ones. The methods that consist in developing fundamentally new types of heat exchangers are not covered in this article.

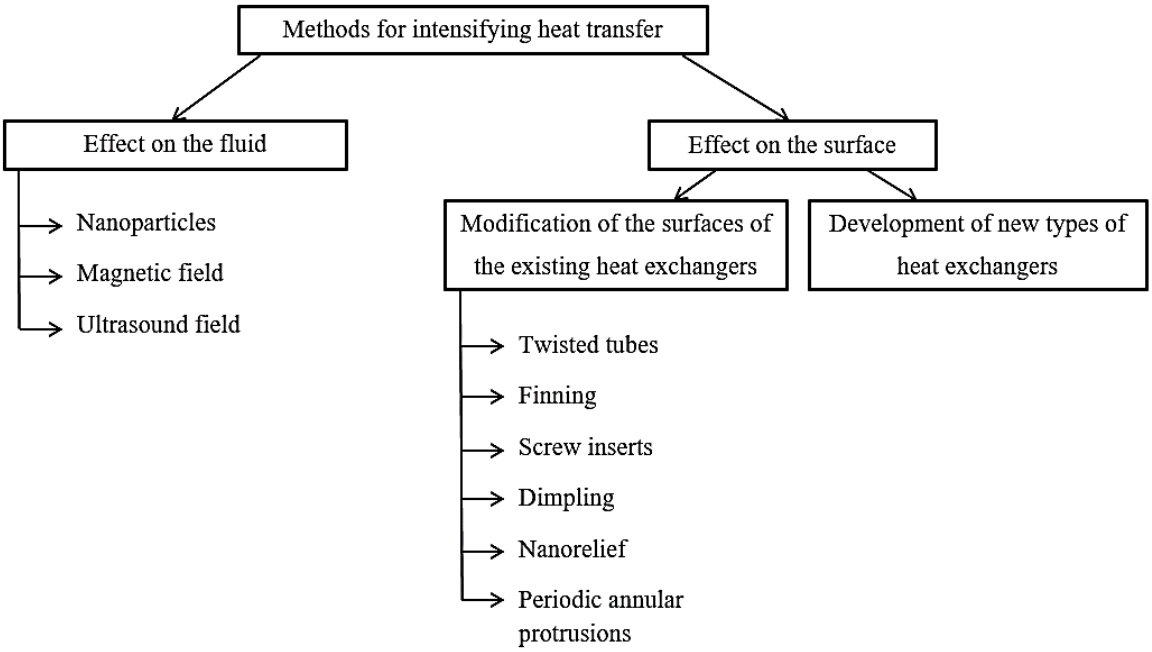


Fig. 2 Methods of intensifying the heat transfer

Currently, various methods of intensifying heat transfer by modifying the heat exchange surfaces have been suggested and studied, such as periodic annular protrusions, screw inserts used for swirling flow in the pipes, and various types of finning. These methods have currently been well studied [14]–[21]. Therefore, this article will cover modern works on the ways of improving the heat transfer surfaces.

The methods of increasing the efficiency of the heat exchange equipment with the effect on the heat exchange surface include twisting the heat exchange tubes [22]–[24]. Changing the shape of the pipe contributes to the flow turbulence, which causes vortexing that destroys the boundary heat layer and has a beneficial effect on the heat transfer. However, in addition to increasing the heat transfer coefficient, such a modification of the heat exchange surface increases the hydraulic resistance. The greatest effect of intensification by twisting the pipes is achieved at low Reynolds numbers [23].

The greatest effect was achieved when two methods of intensifying the heat transfer were used simultaneously [24]: a coiled tube and placing a twisted metal tape in the tube (see Fig. 3).

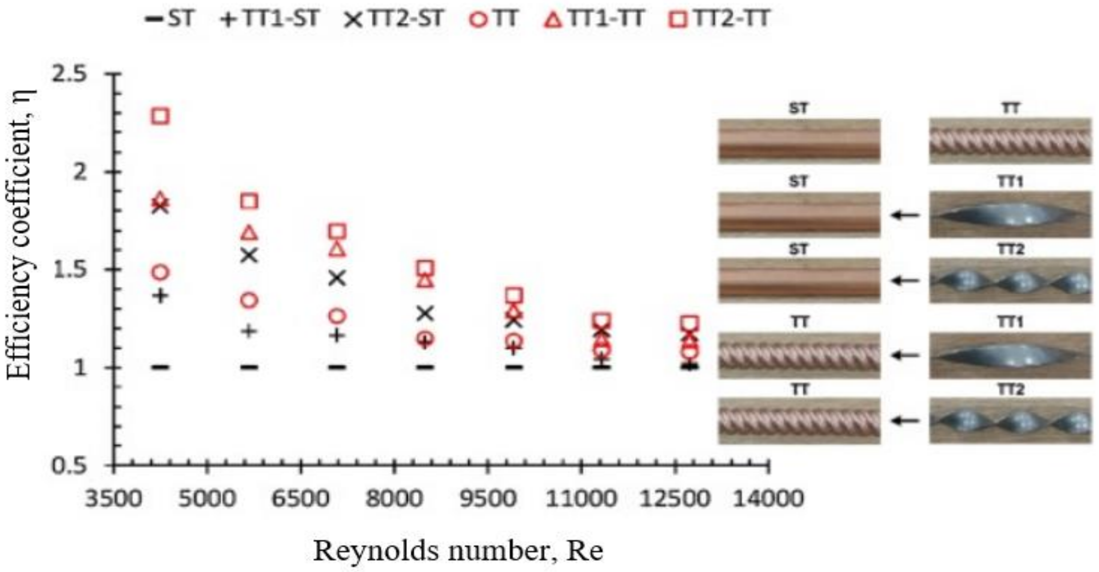


Fig. 3 Dependence of the efficiency coefficient for various combinations of heat transfer intensification methods on the Reynolds number, where ST is the straight tube, TT is the twisted tube, and TT1, TT2 are the twisted tapes

It should be noted that the efficiency of twisted tape with the shorter turn length is higher. This may be explained by the fact that with the long loop length, there is no sufficient flow turbulence and boundary layer destruction.

In addition to the usual flat twisted tapes, tapes with U-shaped and V-shaped notches, as well as perforated tapes (see Fig. 4) are also used. Modifying the twisted tape increases its efficiency, while the greatest effect was obtained when using a tape with V-shaped notches [23].

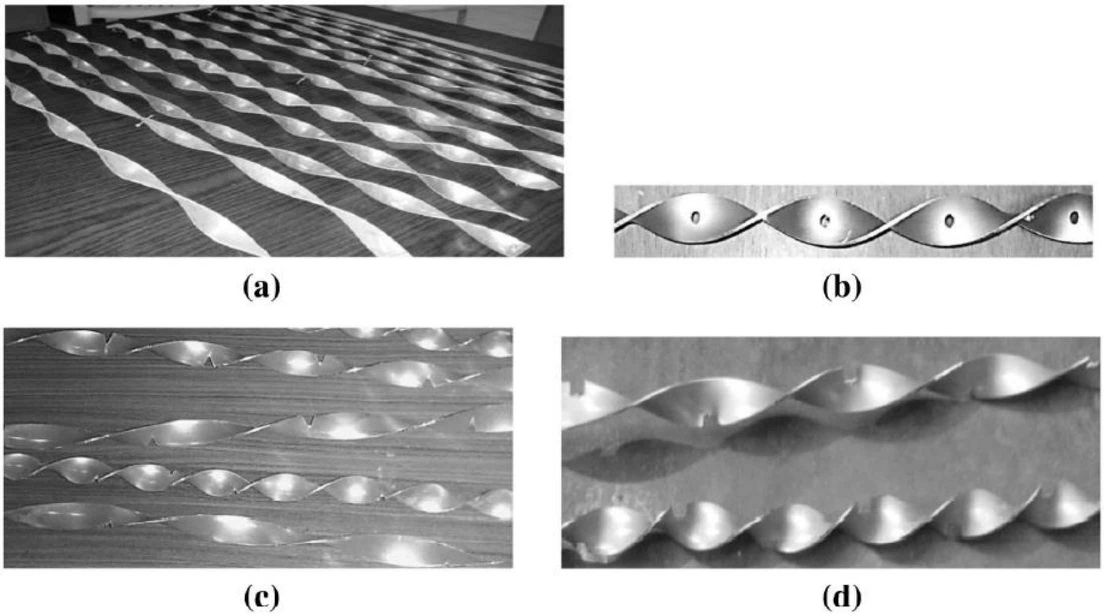
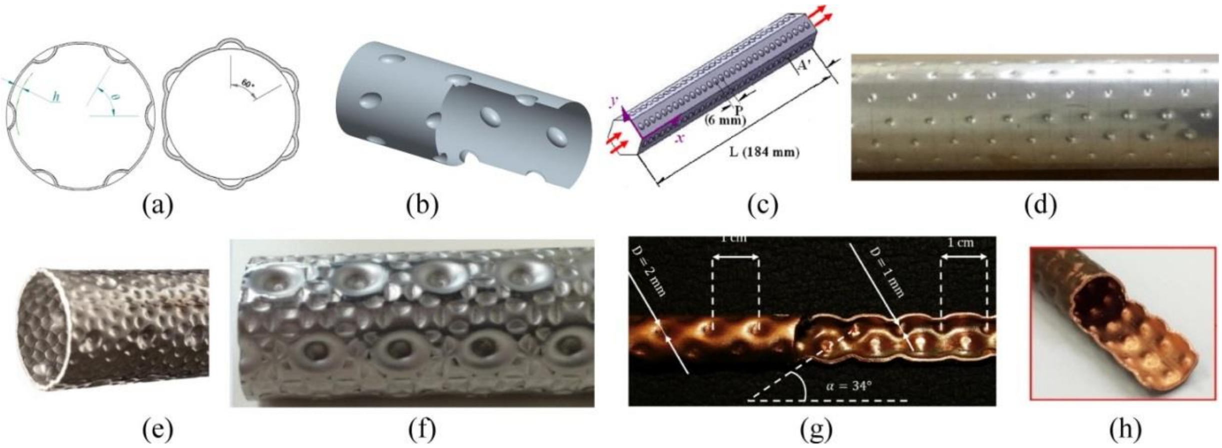

(a) (b) (c) (d)

Fig. 4 Types of twisted tapes for intensifying the heat transfer: a — ordinary tape, b — perforated tape, c — V-notch tape, and d — U-notch tape

Heat exchange is also intensified by "dimpling", which is a special method of tape deformation when the surface of the tube is covered with dimples of various shapes that have an effect on its thermohydraulic parameters. The appearance of the tubes subjected to "dimpling", as well as the geometric parameters of the dimples are shown in Fig. 5 [25].

The dimples and bulges on the surface of the tube intensify fluid flows mixing, which in turn results in the homogenization of the temperature field in the heat carrier flow. Besides, the vortexing that occurs when the flow moves along the dimples and bulges turbulizes the flow and contributes to the destruction of the boundary layer [26], [27], which also results in heat transfer intensification (see Fig. 6 [28]).



(a) (b) (c) (d)
(e) (f) (g) (h)

Fig. 5 a — dimpled and curved tubes; b — a tube with elliptical dimples; c — a hexagonal dimpled tube; d — a tube with alternating dimples and bulges; e — a dimpled tube; f — a dimpled stainless steel tube; g — geometric parameters of the holes; h — a dimpled copper tube

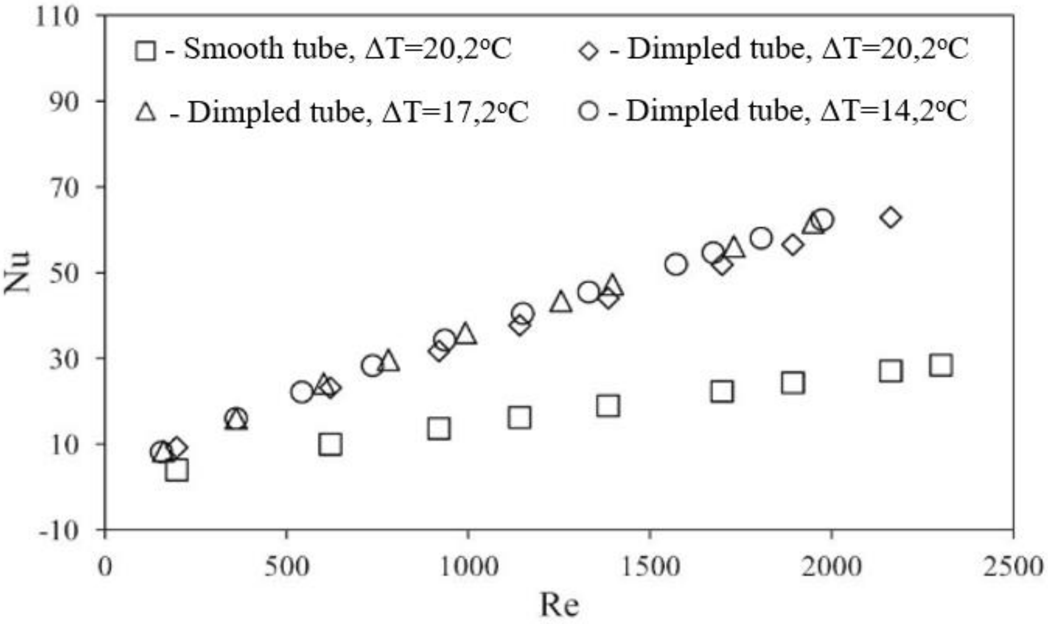


Fig. 6 The Nusselt number dependence on the Reynolds number for dimpled and undimpled tubes at various thermal differentials

The methods of increasing the efficiency of the heat exchange equipment acting on the fluid include the Toms effect [29]–[31]. The essence of the effect is introducing polymers with high molecular weight into the fluid flow to decrease the hydraulic resistance due to decreasing the turbulent vortexing and pulsations in the transition layer, and, accordingly, the laminar sublayer stabilization (see Fig. 7 [31]). However, the Toms effect has not become common in heat transfer intensification.

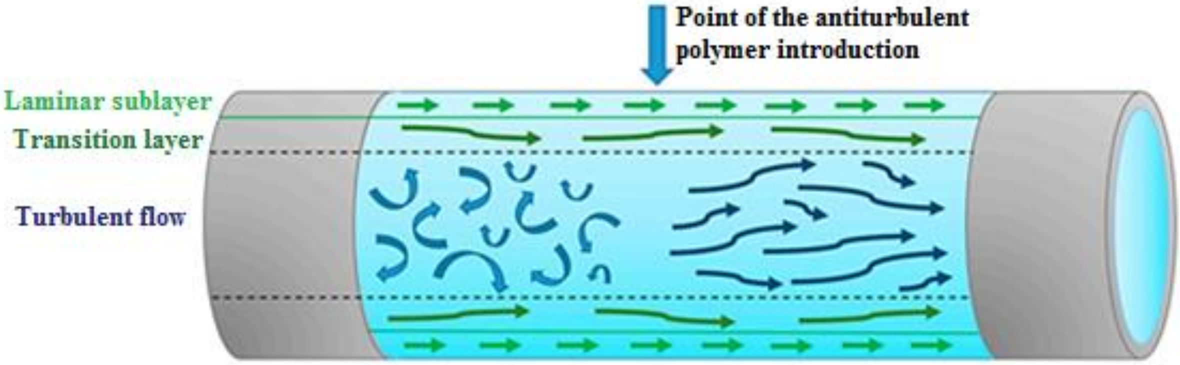


Fig. 7 A schematic representation of the effect of reducing flow turbulence with the introduction of the polymers with high molecular weight

Adding nanoparticles to the heat carrier is one of modern and promising methods of intensifying heat transfer. For example, for the plate heat exchangers, studies related to the use of nanofluids have accounted for 56% of all the studies on heat transfer intensification over the past twenty years [32].

Due to the changes in the thermophysical properties of the modified heat carrier caused by adding nanoparticles of various materials, such as copper oxide CuO [33], aluminum oxide Al2O3 [34], titanium oxide TiO2 [35], zinc oxide ZnO [36] and graphene multilayer nanotubes [37], the heat transfer is intensified.

As a result of studying multilayer graphene nanotubes and aluminum oxide [37], a positive total effect from modifying the heat carrier was obtained, as shown in Figs. 8 and 9 [37]. A 2 – 5% increase in the heat transfer coefficient was achieved, depending on the Reynolds number, compared to the traditional composition of the heat carrier. The reason for such an insignificant increase in the heat transfer coefficient is mainly the factor of decreasing flow turbulence, which is caused by increased viscosity of the heat carrier due to the increased concentration of nanoparticles. In study [37], the negative effect of increasing viscosity was greater than the positive effect of increasing thermal conductivity upon increasing the concentration of nanoparticles in the heat carrier.

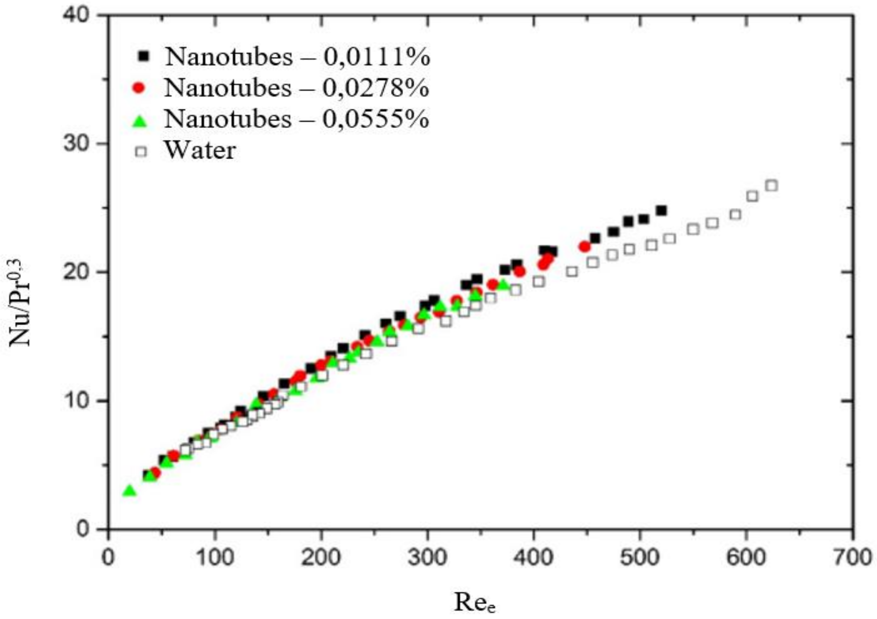


Fig. 8 Comparison of the Nusselt number as a function of the Prandtl number and the Reynolds number ratio for various concentrations of nanotubes and unmodified heat carrier

Besides, comparative studies of the effect of various materials on nanoparticles heat transfer were performed: CeO2, Al2O3, TiO2, SiO2, Cu+Al2O3, ZnO, and multilayer nanotubes [36]. It was found that, in view of the best thermal conductivity of nanotubes, the greatest increase in the heat transfer coefficient, which was 53.05% compared to the conventional heat carrier, had been achieved when using the nanofluid with multilayer nanotubes in a concentration of 0.75%.

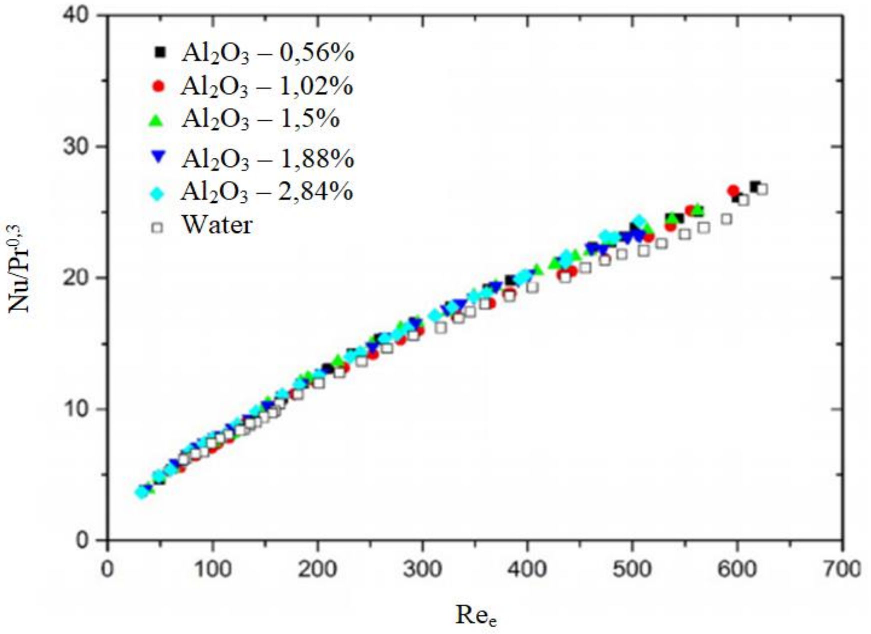


Fig. 9 Comparison of the Nusselt number as a function of the Prandtl number and the Reynolds number ratio for varuous concentrations of aluminum oxide and unmodified heat carrier

When copper oxide nanoparticles had been added to the heat carrier [33], the following results were obtained: for the nanoparticle concentrations of 0.5%, 1%, and 1.5%, an increase in the heat transfer coefficient of about 17.7%, 21.8%, and 24.7% was achieved, respectively, compared to ordinary water (see Fig. 10 [33]). Moreover, adding nanoparticles increased the exergy efficiency of the heat exchanger by 12%, 22%, and 34% for the CuO concentrations of 0.5%, 1%, and 1.5%, respectively.

The nanoparticles effect on the heat transfer process is largely due to increasing the thermal conductivity of the heat carrier, which has a positive effect on the heat transfer coefficient. However, adding foreign particles to the heat carrier also has a negative effect due the increased heat carrier viscosity, since the thickness of the boundary layer increases, which affects the heat transfer efficiency.

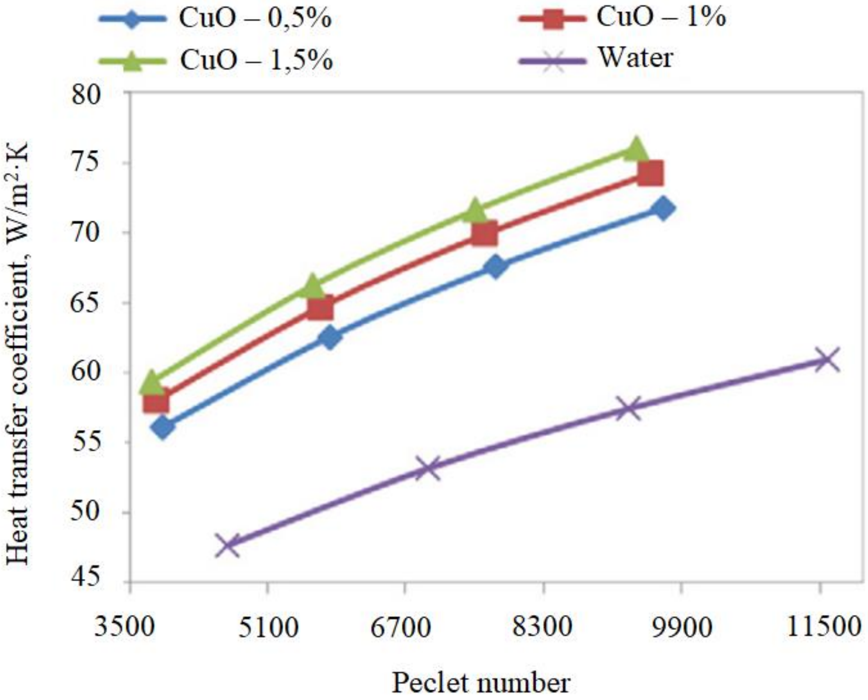


Fig. 10 Change of the heat transfer coefficient as a function of the Peclet number for heat carriers with various concentrations of CuO nanoparticles and for unmodified heat carrier

The method based on a vortex flow induced by a magnetic field also belongs to the methods of heat transfer intensification with the action on the fluid [38]–[40]. To study the effectiveness of the method at various concentrations and velocities of the magnetic flux of the fluid and varying magnetic field intensity, experiments were performed in a two-tube heat exchanger. These experiments showed that when exposed to a magnetic field, a vortex flow arose in the magnetic working fluid, which destroyed the thermal boundary layer and intensified flow mixing, which improved the heat transfer.

The average and total heat transfer coefficients are directly dependent on the Reynolds number and the volume share of nanoparticles (ferrofluid) in the fluid. The average heat transfer coefficient for both hot and cold flows is directly dependent on the magnetic field intensity; it increases in the presence of a magnetic field. The use of a magnetic field from the side of the hot heat carrier allows achieving the most significant increase in efficiency. A significant increase in the total heat transfer coefficient was achieved though the effect of the magnetic field on the heat carrier with ferrofluids, especially at low Reynolds numbers (see Fig. 11).

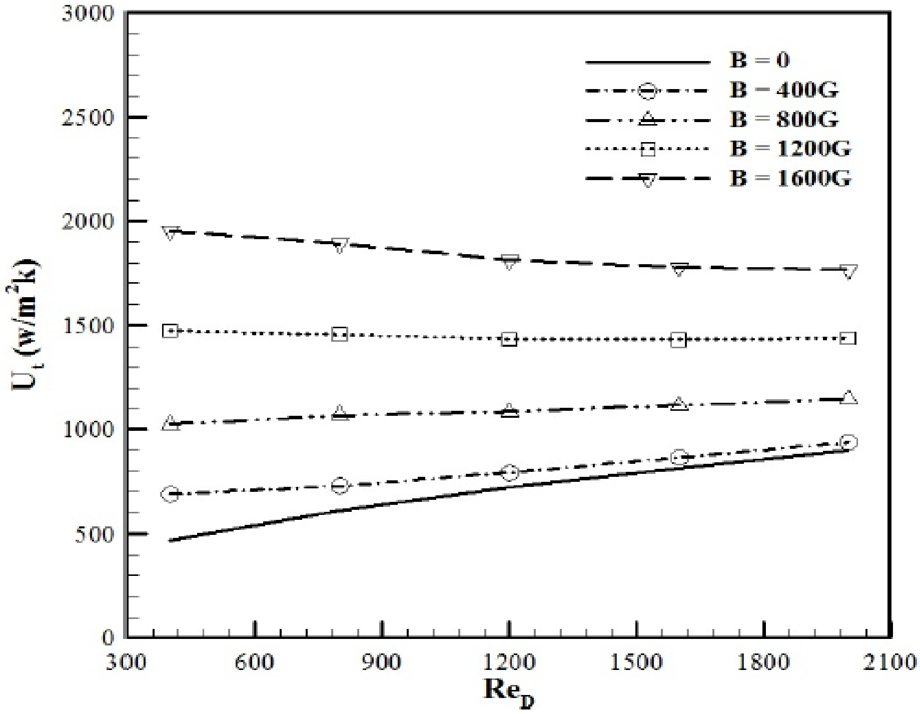


Fig. 11 The total heat transfer coefficient to the Reynolds number ratio with ferrofluid concentration φ = 3% and various magnetic induction values

Increasing the nanoparticles concentration in the heat carrier from 0 to 3% increases the heat flux from 55.3 W to 65.1 W with Reynolds number Re = 400, which may be increased to 230 W due to the effect of a magnetic field with magnetic induction B = 1,600 G [38]. Therefore, the use of an external magnetic field on the ferrofluid may be much more significant than the improvement of the thermophysical properties. It is worth noting that the vortex flow is created without additional obstacles in the flow passage, which, compared to the other methods, for example, inserting twisted tapes, results in a lower flow hydraulic resistance, and hence, in a pressure drop. Thus, this method is effective at low Reynolds numbers, high magnetic field intensity, and high ferrofluid concentration.

The heat transfer is also improved through the action of ultrasonic vibrations on the heat transfer surface. Using the OpenFOAM software, mathematical studies were performed in the study [41] in order to identify the reasons for the heat transfer increase in the presence of ultrasonic waves. Ultrasonic vibrations acted on the outer wall of the heat exchanger (see Fig. 12) [41].

III.RESULTS

In paper [42], a test bench was created that consisted of two concentric tubes and an ultrasonic Langevin transducer attached to the inner tube for creating 26.7 kHz ultrasonic vibrations.

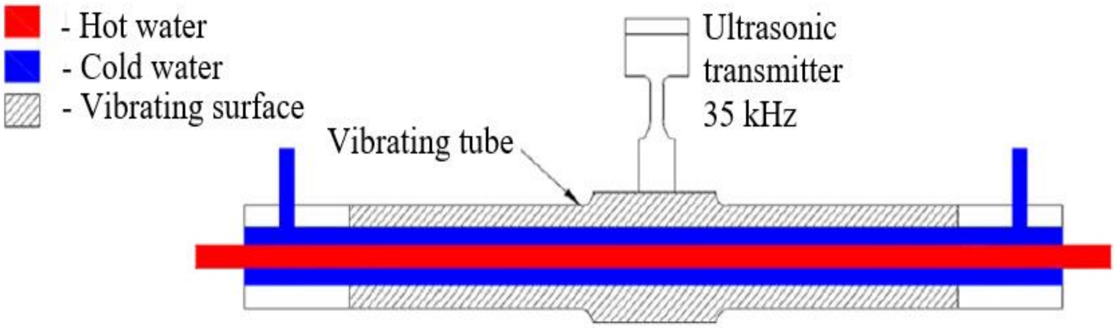


Fig. 12 The layout of a heat exchanger with an ultrasonic transmitter

The results of the experiment showed that the heat transfer coefficient increased with increasing the acoustic power with constant volumetric flow rates of cold and hot fluids due to the fact that the temperature of the cold fluid at the outlet increased, while the temperature of the hot fluid at the outlet decreased. In this case, the main reason for heat transfer intensification is the destruction of the hydrodynamic and thermal boundary layer of the fluid due to the action of acoustic waves and, consequently, the temperature profile alignment and more intensive mixing of the heat carrier layers [43]. For instance, with constant volumetric flow rates of cold and hot fluid equal to 0.5 l/min and the acoustic power P_t = 120 W, the heat transfer coefficient increased by 60%, which is shown in Fig. 13 [42].

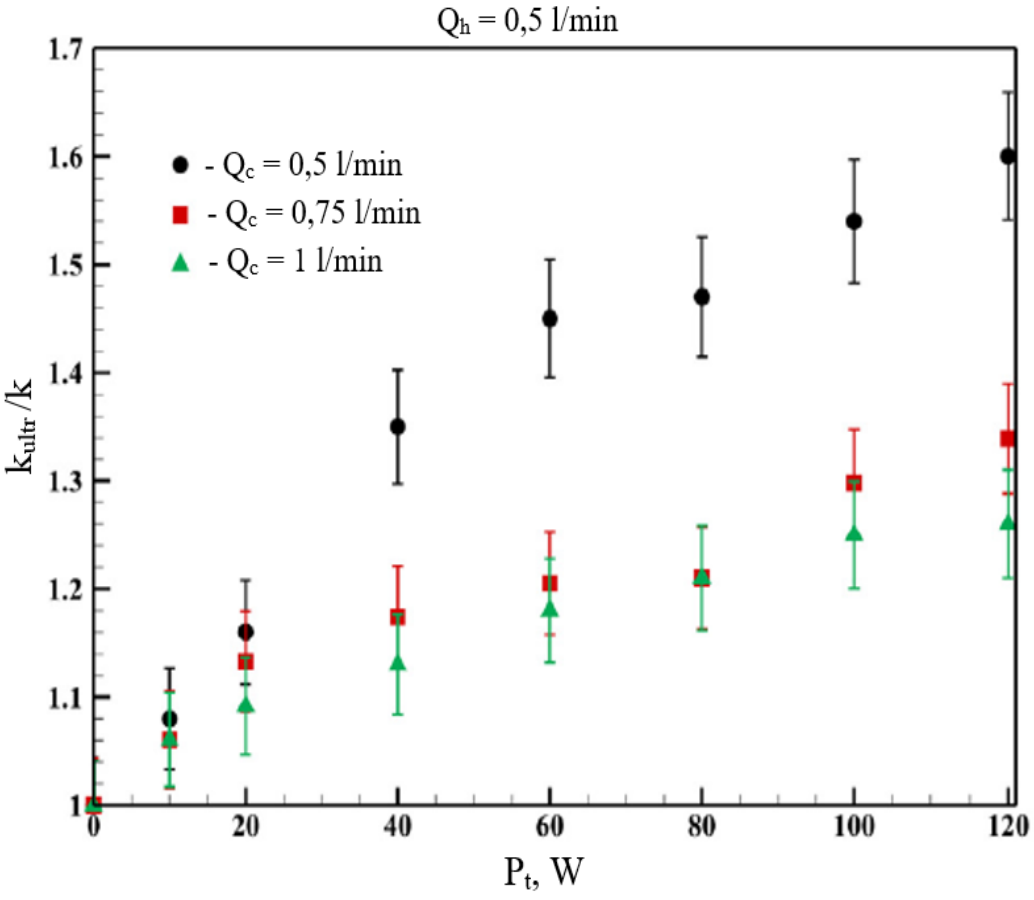


Fig. 13 The ratios of heat transfer coefficients under the influence of ultrasound and without ultrasound, with various cold heat carrier flow rates and various ultrasound intensities

Besides, it was found that the heat transfer coefficient increased with decreasing the fluid flow at a constant acoustic power level, since the ultrasonic waves propagated better in fluid at low flow rates. Therefore, the use of ultrasonic vibrations for intensifying the heat transfer is more effective at low volumetric flow rates of cold and hot fluid.

It is known that a metal surface is a complex structure of interaction between various layers (see Fig. 14) [44]. During operation, layers are formed on the metal surface, which, together with the type of metal the heat exchange surface is made of, influence the properties of the heat exchange surface.

Directly on the metal surface, there is a layer of metal oxides. This layer is firmly bonded to the metal layer and covers all the outer faces of the crystals. The oxide layer has the thickness from single molecules to several tens of angstroms. On the oxide films, adsorption layers of gases are located. On the surface of the gas layers, there are water adsorption layers, which are formed as a result of the absorption from the atmosphere of water vapors with layers of polar and nonpolar molecules of organic substances on the surface [45].

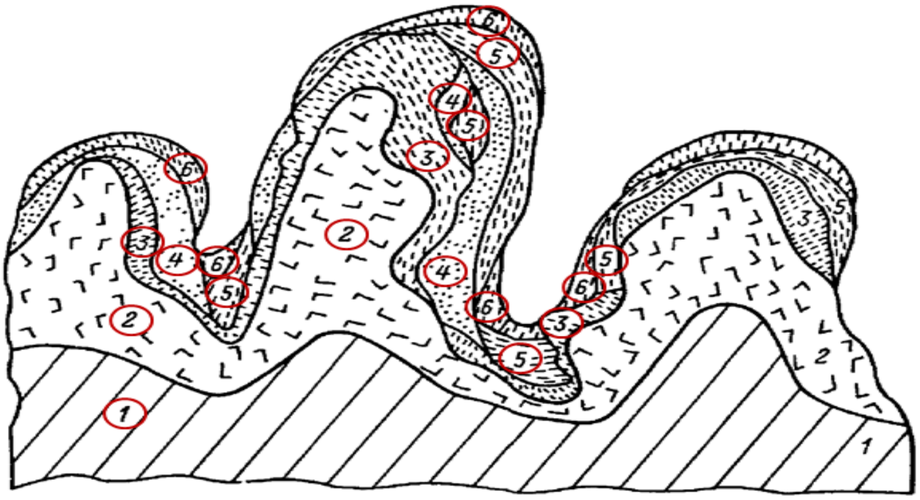


Fig. 14 The scheme of a real metal surface structure (1 — volumetric (correct) crystalline structure; 2 — metal surface structure; 3 — metal oxides; 4 — adsorbed gases; 5 — adsorbed water; 6 — polar molecules of organic substances)

However, in real conditions, the scheme of the layers adsorbed by the metal surface is much more complicated, as shown in Fig. 14. The metal surface has a complex structure consisting of bulges and depressions [46], on the surface of which adsorbed layers are located. Thus, the process of heat exchange is impeded by both gases that accumulate in the depressions on the metal surface and layers of substances adsorbed by the metal surface [45].

In paper [44], experimental studies were performed for determining the effect of functional surface hydrophilization on the thermal and hydraulic characteristics of the heat exchanger, depending on the flow rate and the heat carrier temperature. The pipe surfaces of the heat exchange equipment were treated by introducing melted surfactants into the heat carrier with an ejector. The results of experimental studies showed that hydrophilization of the functional surfaces of a shell-and-tube heat exchanger made of carbon steel increased the heat flux from the hot heat carrier to the cold one, compared to an identical heat exchanger with untreated functional surfaces. Fig. 15 shows the dependence of the heat flow through the wall of a heat exchanger on the reduced flow rate of the hot heat carrier.

Any change in the design of the heat exchange surface, as a rule, increases the heat exchanger hydraulic resistance, which is an important parameter in the operation of such devices. Therefore, a comparison was made between the increase in heat transfer and the increase in the thermal-hydraulic resistance for assessing the effectiveness of this method of heat transfer intensification (see Fig. 16). The analysis of the dependence shown in Fig. 16 revealed that, despite the experimental data scatter, the heat transfer increased faster than hydraulic resistance (region A in Fig. 16), therefore, hydrophilization of the functional surfaces of the heat exchanger was an effective way to intensify heat transfer.

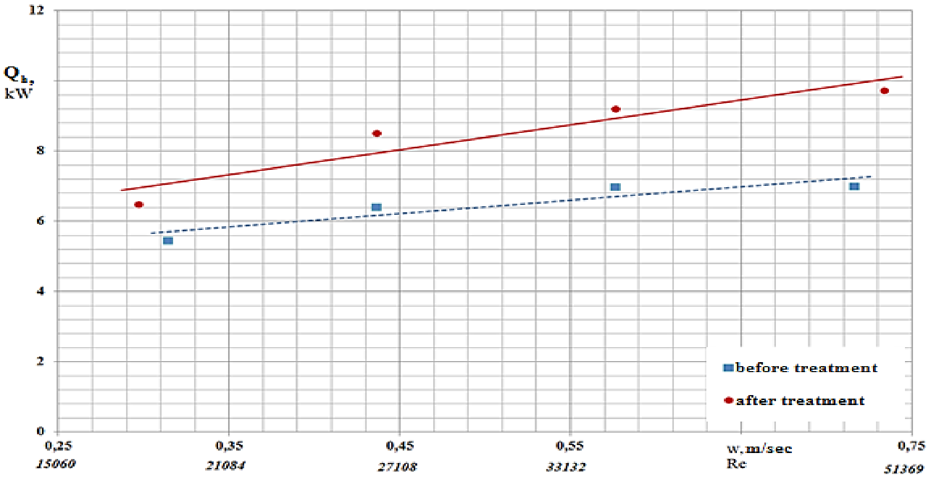


Fig. 15 The dependence of the heat flow through the wall of a heat exchanger on the reduced flow rate of the hot heat carrier. The hot heat carrier temperature at the heat exchanger inlet is 70 °C

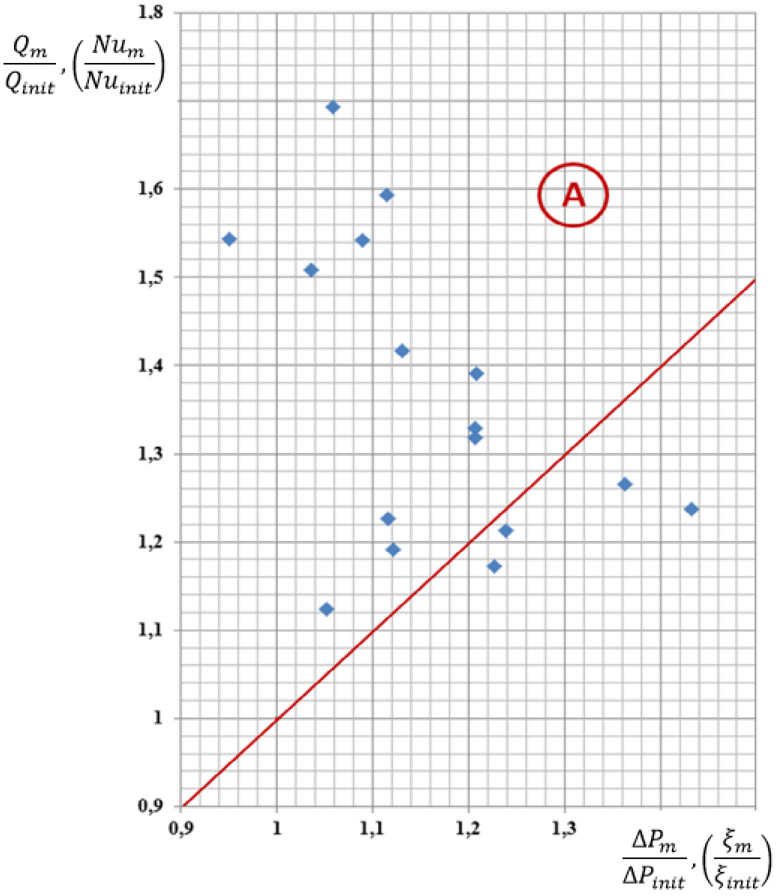


Fig. 16 The dependence of the heat flux increase on the hydraulic resistance increase after heat exchanger modification

In paper [47], the potential of laser textured surfaces for intensifying heat transfer during boiling was studied. The surfaces of the samples, which were thin substrates of stainless steel, were modified using various models of laser texturing and pulse intensities. Depending on the processing parameters, the samples were hydrophilic, superhydrophilic, or had uneven wettability. The comparison of the textured surfaces with boiling surfaces proved the stability of laser-textured surfaces. The heat transfer during vaporization on textured surfaces was assessed through the use of high-speed IR thermography. The results obtained allow making the following important conclusions: a laser-textured surface intensifies the vaporization process at a lower overheat value and makes it possible to increase the heat transfer coefficient by 10%, compared to the initial surface; with certain texturing parameters, as a result of material melting and solidification, an inhomogeneous surface structure with multidimensional microcracks is formed, due to which 20 – 40 times higher density of vaporization areas is achieved, compared to the untreated surface. Fig. 17 shows the dependence of the heat transfer coefficient on the specific heat flux for the untreated surface [47] and the modified surface [48].

By monitoring the texturing parameters, the location of microcracks and, therefore, the areas in which most bubbles form and grow, may be controlled. This suggests that laser texturing allows some control over the complex boiling process. The suggested surface modification technology does not require additional coatings and/or postprocessing. The results showed that treatment with nanosecond laser allowed surface modification for improving the boiling heat transfer efficiency.

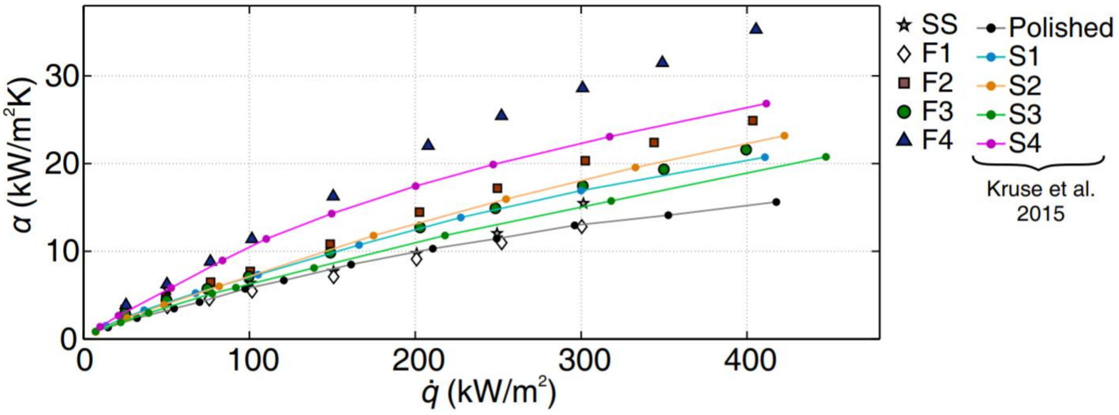


Fig. 17 The heat transfer coefficient to the heat flux ratio.
The results are shown for textured surfaces F1 – F4, untreated surfaces are designated as SS. The points connected by lines (S1 – S4 and Polished) represent the results reported by Kruse et al. [48] and are shown for comparison

A combination of hydrophilic and hydrophobic heat transfer surfaces was considered in [49]. A feature of this study was the use of polydimethylsiloxane silicate as the coating on which superhydrophilic and hydrophobic coatings were formed. After pulsed laser treatment, the critical heat flux through the superhydrophilic coating increased 3.5 times. Such coatings are most effective if the heat carrier boils during the heat exchange process. The increased wettability of the superhydrophilic surface decreases the bubble contact area with the heat-exchange surface, increasing the number of vaporization centers. At the same time, a hydrophobic surface decreased the bubbles diameter, increasing the frequency of their occurrence. The highest value of the heat transfer coefficient, 51.2 kW/m2, was achieved with the area of hydrophobic areas of 250x250 μm2.

In turn, in study [50], hydrophobic and hydrophilic surfaces were the same polymer, which changed its properties from hydrophobic to hydrophilic and back upon reaching a certain temperature. A total of four coatings were studied: the fluorine-based coating with hydrophobic properties, a polymer with the temperature of properties change from hydrophobic to hydrophilic equal to 108° C, a sample consisting of 50% polymer and 50% fluorine-based hydrophobic coating, and a sample consisting of 80% polymer and 20% fluorine-based hydrophobic coating.

As a result, the coating consisting of polymer showed an increase in the heat transfer intensity during boiling, and the heat transfer coefficient for a coating consisting of 100% polymer showed an increase in the heat transfer coefficient of up to 1.3 times, compared to the sample without coatings. The change in the heat transfer coefficient depending on the heat flux for an uncoated specimen and a specimen with a polymer coating is shown in Fig. 18 [50].

a)

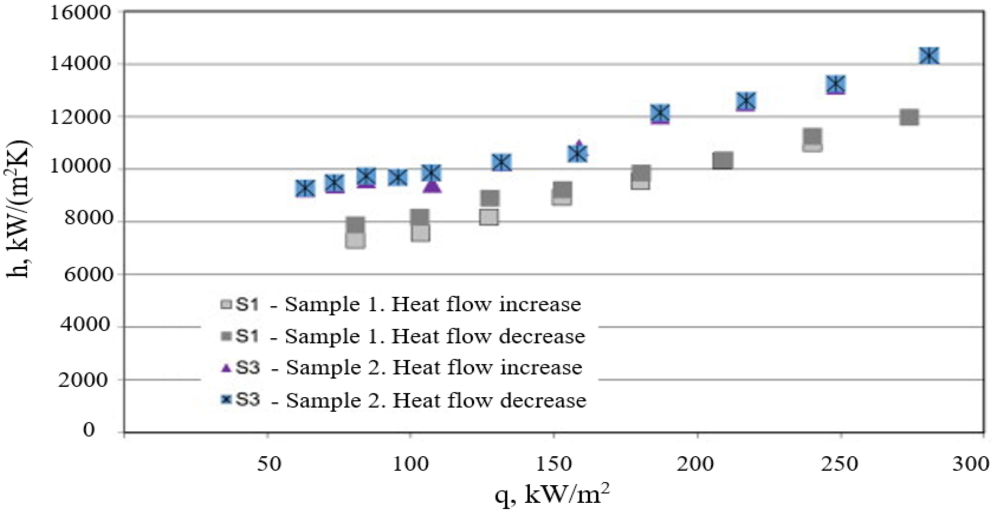


Fig. 18 The change in the heat transfer coefficient depending on the heat flux for an uncoated sample (sample No. 1) and a polymer-coated sample (sample No. 2)

The method of intensifying the heat transfer studied in [51]–[53] is based on creating a biphilic surface with both hydrophobic and hydrophilic properties. The surface studied in [51] was a combination of copper substrate strips with hydrophilic properties and a hydrophobic coating during heat transfer. Upon condensation of the heat carrier on the coatings, various condensation conditions (film and drop) were observed, respectively.

IV. DISCUSSION

Thus, various surfaces perform different functions in the process of heat exchange; drop condensation occurs on hydrophobic surfaces, intensifying heat transfer; hydrophilic surfaces act as transport for the fluid, collecting drops from the hydrophobic surface and preventing a layer of condensate from forming on it, which in turn will represent additional thermal resistance. A schematic representation of such a surface is shown in Fig. 19.

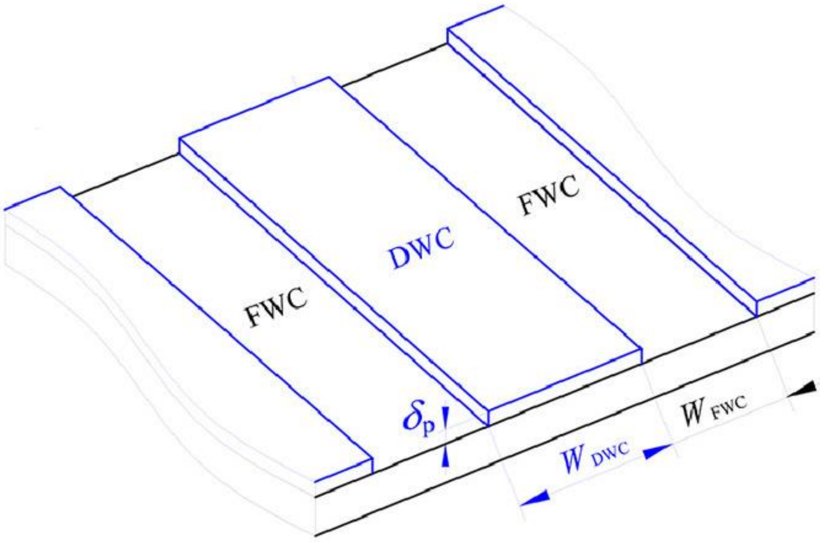


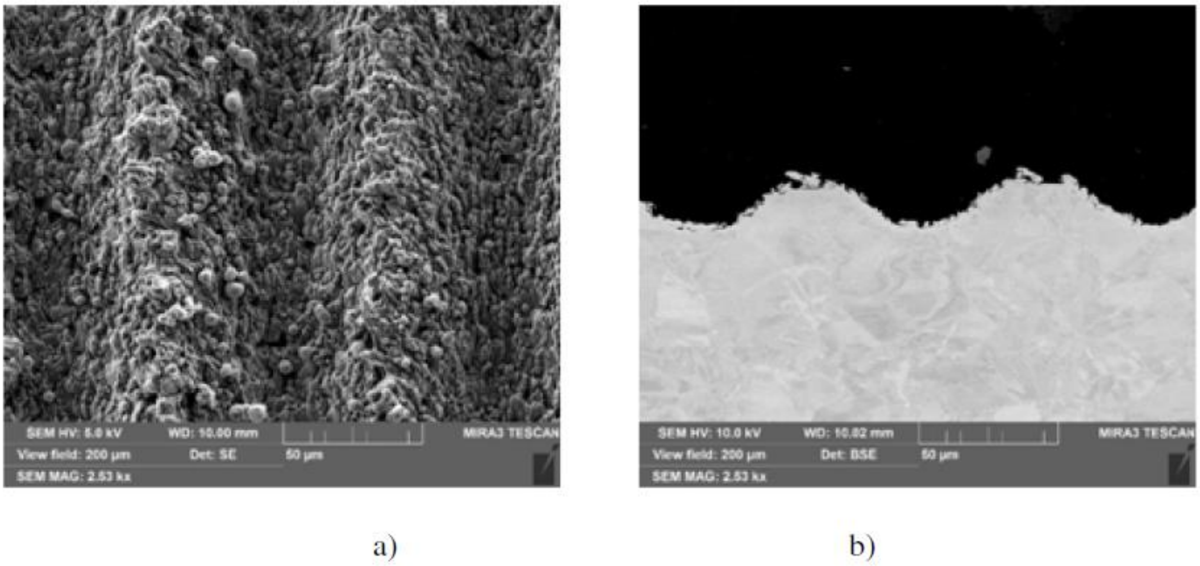
Fig. 19 Schematic representation of a combined hydrophobic and hydrophilic surface, where FWC is the film condensation area, DWC is the drop condensation area, W_{dwc} and W_{fwc} are the widths of the hydrophobic and hydrophilic surfaces, respectively, and δ_p is the thickness of the hydrophobic layer

With that, depending on the width of the hydrophobic layer, both intensification and reduction of the heat transfer coefficient may be achieved; with the optimal width of the hydrophobic surface, the increase in the heat transfer coefficient may be up to 140% [51].

In [54], the main conditions for obtaining hydrophobic materials and coatings, as well as the features of the superhydrophobic state of hard surfaces, are considered. It is noted that for achieving high contact angles on surfaces, roughness is required in addition to reducing the surface energy. To obtain a superhydrophobic coating, a method based on the use of laser technology is chosen, which is the most promising due to the high speed of texturization of the surfaces of solid bodies and the possibility of creating a formed relief with sufficiently accurate required geometric parameters.

It has been found that in order to obtain a superhydrophobic surface shown in Fig. 20 [55], it is necessary to simultaneously meet the following conditions: texturization of the micro/nanoscale relief on the surface with the geometric parameters that ensure stable heterogeneous conditions, and decreasing surface energy at the solid to gas interface to the level that is lower than the level at the solid to fluid interface.

In analyzing the process of hydrophobic surfaces formation using laser equipment, it has been found that after processing, various metal surfaces with the time of exposure had acquired hydrophobicity instead of initial hydrophilicity. In that case, for brass surfaces, the transformation was presumably based on the sorption of carbon compounds with nonpolar C-C/C-H bonds from the air. As a result of experimental studies [54], hydrophobic brass surfaces with contact angles of 145 – 146° were obtained. It has been found that the maximum contact angles were achieved after exposure to an emulsion of surfactants immediately after laser treatment. Besides, when applying a hydrophobic agent to a modified surface, the minimum layer thickness that ensures uniform and complete surface coverage should be achieved.



a)

b)

Fig. 20 Electron microscopic images of the surface (a) and the polished cross-section (b) of a modified brass specimen at the same scale

V. CONCLUSION

Various modern methods of increasing the efficiency of heat exchangers have been considered. The most promising way to intensify the heat exchange processes in a single-well system for subsoil deep thermal energy pickup and transportation is changing the wettability (hydrophilization and hydrophobization) of the functional surfaces. This method results in a slight increase in the hydraulic resistance with sufficient intensification of the heat exchange processes. This method may be implemented based on using both surfactants and laser surface modification.

ACKNOWLEDGMENTS

The results of the work have been obtained with the financial support of the Ministry of Education and Science of the Russian Federation within the framework of grant of the President of the Russian Federation for state support for young Russian scientists No. MK-2409.2019.8 (Agreement No. 075-15-2019-331 dated 13.06.2019).

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