Enhancement of condensation heat transfer on surface with macro-, micro- and nanorelief

D V Chugunkov, Yu A Kuzma-Kichta, G A Seifelmyukova and N S Ivanov
National Research University Moscow Power Engineering Institute, Moscow, Russia
E-mail: chugunkovdv@mpei.ru

Abstract. Film and drop condensation are important processes in technics. This article includes the features of macroscale heat transfer intensifiers under film condensation, microscale and nanoscale heat transfer intensifiers under drop condensation. It is noted that condensation heat transfer may be influenced by the wall material. The mechanism underlying this influence is the nonuniform distribution of the wall temperature in the case of a low heat conduction coefficient. Based on the research results, a dependence of the wetting angle from the combined coating consisting of 7 alumina oxide and water repellent is obtained.

1. Introduction
Film and drop condensation are the important processes in the power generation industry, air-conditioning systems, cooling of electronic devices, distillation industry, etc. Enhancement of condensation heat transfer will benefit a wide range of applications. Superhydrophobic surfaces with large contact angle are applied to condensing interfaces aiming to form dropwise condensation to enhance the heat transfer [1-17].

In the case of film condensation the heat transfer is attributed to the action of surface tension on the condensate film. As a result, the film in grooves and its thickness on the remaining portions of the pipe decreases. In contrast to finning, knurling makes it possible to intensity heat transfer on both outer and inner pipe surfaces.

This effect is enhanced through decrease in the relative pitch of grooves, as well as in the case of the wavy profile of a pipe. The variable cross section of the pipe with smooth transitions leads to the collection of the condensate into the grooves. As a result, the thickness of the condensate film on protrusions on the pipe surface and its thermal resistance decreases. The redistribution of the condensate along the pipe length leads to a growth of the average heat transfer coefficient.

The heat transfer coefficients at steam condensation on a horizontal pipe made from brass with knurling was obtained by G.A. Dreitser [1]. It was established that the heat transfer coefficient for a knurled pipe increased more than twice. The increase in the heat transfer coefficient is higher, if the grooves are deeper and their pitch is smaller, as well as the radius of the rounding of the protruding parts of the pipes.

Heat transfer in pipes located vertically is less manifested than in horizontally oriented pipes. The influence of knurling on heat transfer increases with Re_{film} knurling depth, and a decrease in its pitch. When Re_{film} < 400, a decrease in \( t/h \) below 8 was accompanied by a further increase in the ratio of Nusselt numbers for pipes with knurling and without it. This is explained by the retention of condensate in grooves by the surface tension forces.
Visual observations and filming of the steam condensation on a pipe with annular grooves showed that at Re<500–700 the large-scale changes in the condensate film-separation with a frequency of up to 1 Hz in the form of solitons 50–100 mm in length arose. They increased the heat transfer rate. At high Reynolds numbers (Re_{film} > 700) an increased turbulence and vortex formation in the film observed.

With a pipe being slightly tilted (3–5°), heat transfer intensification is enhanced due to the presence of grooves on the surface. This feature was employed in pipes with knurled annular grooves. The grooves were arranged in parallel at an angle to the pipe axis smaller than 90°. The distance between the grooves was equal to their threefold width, with their depth being determined from the expression

\[ G_{\text{cond}} = \text{flow rate of the condensate} \]

where \( G_{\text{cond}} \) is the flow rate of the condensate formed on the pipe surface between two neighboring grooves. Between the grooves fins oriented parallel to the pipe axis are located. This enhances heat transfer.

The condensation heat transfer may depend on the wall material. The mechanism underlying this influence is the nonuniform distribution of the wall temperature in the case of a low heat conduction coefficient. The introduction of the dimensionless complex \( \lambda_w \delta_w / (\lambda_{\text{film}} d_{eq}) \), where \( \lambda_w \) and \( \lambda_{\text{film}} \) are the thermal conductivities of the wall material and film, \( \delta_w \) is the wall thickness, and \( d_{eq} \) is the equivalent diameter of the annular channel, makes it possible to correlate data on heat transfer.

Yu.B. Smirnov investigated heat transfer on condensation of a mixture on horizontal finned pipe. Fins and pins on horizontal pipes produced by the method developed at the Bauman Moscow State Technical College.

An increase in the heat transfer coefficient for a pipe with pins, not due directly to the surface extension turned out to be rather great and equal to 1.5 and 1.7 for pressures 0.2 and 0.4 MPa. For a pipe with fins and pins, an interesting feature was revealed lying in the fact that the heat transfer coefficient changes weakly with an increase in the temperature head.

According to the technique of determining the heat transfer coefficient in condensation on horizontal finned pipes of binary vapor mixtures that form immiscible liquids, the extended pipe surface divided into two zones: flooded with the condensate and the unflooded.

In recent years interest is given to the study of surface's wettability on condensation heat transfer. As a result, a wide range of drop sizes arose on the condensing surface (Figure 1). The drop grows until it attains a maximum radius. Thus, a certain drop size distribution function F(R) is established on the condensing surface. Both theoretical analysis and experimental investigation showed that dropwise condensation heat transfer coefficient decreased with the increase of the maximum droplet radius. The maximum droplet radius, droplet rapid motion, droplet size distribution, and then condensation heat transfer performance could be adjusted with special condensing surfaces, such as gradient, superhydrophobic, grooved, hydrophobic-hydrophilic patterned and hybrid surfaces.

![Figure 1. Drop condensation on tube.](image)

As example, the structure of the lotus leaf consists of a combination of two scales: one – 10 nm, the other – 100 nm moreover, the leaf is covered with wax. The combination of the surface relief and wax
coating create the superhydrophobicity of the lotus relief. The drops had the spherical form and rolls off. The effect of the lotus leaf helps to create the hydrophobic coating for drop condensation.

Karlen and Ruleman investigated the drop condensation on microstructure produced as columns with diameter 3 mm from silicon shavings separated by gaps. The wetting angle on such surface was equal 130°.

To remove the drops from condensation surface the microstructure with a wetting gradient was proposed. The wetting gradient was obtained by gradual change of hydrophilic surface width. The drop has different wetting angles in the front and the back. As the hydrophobic layer thickness decreases the drop changes the form.

2. Method for producing nanoparticles
Alumina nanoparticles were obtained by the method [18], which consists in thermal decomposition at a temperature of 1100 °C of a dispersed phase of cellulose and aluminum sulfate.

To obtain nanoparticles of aluminum oxide, cellulose from 100% cotton (GOST 5556-81) was used. A solution of aluminum sulfate was prepared at the rate of 50 g per 400 ml of distilled water. The cotton wool was completely moistened in the solution and placed on a baking sheet. Within an hour, the cotton wool was dried at a temperature of 190 °C in an oven. After drying, hard blocks of cotton wool with deposited aluminum sulfate particles were obtained. The bar was placed in a crucible, where it underwent thermal decomposition at a temperature of 1100 °C.

To form a nanocoating, a colloidal solution of nanoparticles in water with a concentration of 0.01 ± 0.005% was prepared. To equalize the particle size distribution, the solution was intensively mixed and homogenized. When obtaining the coating, the colloidal liquid was applied through a needle onto the surface, which was heated to a temperature of 200 °C. During the boiling of the nanofluid on the surface of the substrate from copper, the liquid phase evaporated, the nanoparticles were deposited on the plate and formed a coating. One layer was the operation of applying a given volume of nanofluid, followed by boiling and deposition of nanoparticles from the solution onto the surface.

Particle sizes were determined using a scanning electron microscope (SEM) TESCAN VEGA 3. The coating shown in Figure 2 is formed by boiling nanofluid with alumina particles on the surface.

![Figure 2](image)

**Figure 2.** A layer of nanoparticles of aluminum oxide on a stainless steel substrate. The characteristic particle size is 100 nanometers. Magnification 5000x.

3. Effect of coating from alumina oxide nanoparticles and water repellent investigated on the wetting angle
In work the effect of coating from alumina oxide nanoparticles and water repellent investigated on the wetting angle. The test section is covered with alumina nanoparticles. Nanoparticles (average size 100 nm) deposit on the heating surface during evaporation of colloidal solution (nanoliquid) based on
deionized water. Colloidal solution and water repellent were applied through a needle. The wetting angle was measured for sections with different coating consisting of different number layers from nanoparticles.

Static wetting angle is measured by method of lying drop (Figure 3). Wetting angle measurements were made for samples in three different points. Ten measurements of wetting angle on the left and right side of the drop were made for each point. Chosen drop volume was 0.0041cm$^3$ in order to compare results with known data. Contact angle is influenced by various factors. In paper influence of coating was considered.

![Figure 3. Drop on nano-coated surface.](image)

It was established that the wetting angle decreases with increase of number layers from nanoparticles and the wetting angle increases for surface that was processing additionally through water repellent. The combined coatings consisting of alumina oxide nanoparticles layers and water repellent were produced and the wetting angles measured (Figure 4).

![Figure 4. Dependence of wetting angle from number of layers of combined coating consisting from alumina oxide particles and water repellent.](image)
Conclusions

Heat transfer enhancement by macro-, micro-, and nanorelief of surface at film and drop condensation on tube was considered.

The effect of coating consisting from alumina oxide nanoparticles and water repellent on wetting angle was investigated. The wetting angle was measured for sections with different number of layers from alumina oxide particles and water repellent.

It was established that the wetting angle increases in case of combined coating consisting from alumina oxide nanoparticles and water repellent with increase the number of layers.

Acknowledgments

This work was supported by the Ministry of Education and Science of Russia. (Cipher of the scientific theme FSWF-2020-0021).

References

[1] Kalinin E K, Dreizer G A, Kopp I Z, Myakochin A S 1998 Effective heat transfer surfaces. Energoatomizdat
[2] Kuzma-Kichta Yu A and Leontiev A I 2018 Journal of Enhanced Heat Transfer 25(6) 465–565
[3] Dzyubenko B V, Kuzma-Kichta Yu A, Leontiev A I, Fedik I I, Kholpanov L P 2016 Intensification of Heat and Mass Transfer on Macro-, Micro-, and Nanoscales 564
[4] Kuzma-Kichta Yu A, Sedlov A S, Vasin V A 2012 Energosaving and water conditioning 6 120
[5] Ruleman E, Fujii T, Uehara H, Kurata Ch 1972 Int. J. Heat Mass Transfer 15(2) 235–46
[6] Bansal G D, Khandekar S 2009 Journal nanoscale and microscale thermophysical engineering 184–201
[7] Shang H M, Wanf Y, Takahashi K, Cao G Z 2005 Journal of material science 4 141–5
[8] Miljkovic N, Enright R 2013 “Nanoletters” L24-28
[9] Kuzma-Kichta Yu A, Zhukov V M, Lavrikov A V, Shustov M V 2013 Heat Process in Technik 5 217–23
[10] Solodov A P, Isachenko V P 1967 THT 5:6 1032–9
[11] Isachenko V P, Solodov A P, Mal'tsev E V, Yakusheva A V 1984 THT 22:5 924–32
[12] Nusselt W 1916 Zeitschrift des VDI 60(27) 541–6, 568–75
[13] Corradini M L 1984 Nuclear Technology 64(2) 186–95
[14] Gebauer T, Al-Badri A R, Gotterbarm A, El Hajal J, Leipertz A, Fröba A P 2013 Int. J. Heat Mass Transf. 56(1–2) 516–24
[15] Briggs A, Sabarattam S 2003 Int. J. Energy Res. 27 301–14
[16] Hu H W, Tang G H, Niu D 2016 Applied Thermal Engineering 100 699–707
[17] Tang G H, Hu H W, Zhuang Z N, Tao W Q 2012 Appl. Therm. Eng. 36 414–25
[18] Kuzma-Kichta Yu A, Ivanov N S, Lavrikov A V, Kiselev D S Patent No. 2665524