Journal of Engineering Physics and Thermophysics, Vol. 65, No. 1, 1993.

INTEGRATED STUDY OF SCIENTIFIC AND APPLIED PROBLEMS ON HEAT TRANSFER ENHANCEMENT IN TUBULAR HEAT TRANSFER APPARATUSES

G. A. Dreitser, N. V. Paramonov, A. S. Neverov,
A. S. Myakochin, I. V. Podporin, L. S. Yanovskii,
A. V. Sergeev, S. G. Zakirov, V. V. Galagan,
F. Yu. Ismailov, T. N. Kravchuk, B. V. Dzyubenko,
V. I. Gomon, and A. G. Tumakov

UDC 536.24

A highly efficient method of enhancing heat transfer in annular swirl-augmented tubes, with gases and liquids flowing in them, under drop and film condensation is developed and investigated.

Decreasing the mass and overall dimensions of heat transfer apparatuses used widely in different fields of technology is an urgent problem. Heat transfer enhancement due to artificial flow swirling is the most promising means to solve this problem.

At the Moscow Aviation Institute a highly efficient method of enhancing heat transfer in tubular heat exchangers has been developed, and extensive experimental studies have been made of the efficiency of the given method in tubes, annular channels, and in gas and liquid in-line flow tube bundles over a wide performance parameter range, as well as during boiling and condensation of heat carriers [1]. The essence of the proposed method is the following. Equidistant annular grooves (Fig.1) are rolled on the outer surface of the heat transfer tube. As this takes place, annular smooth-configuration diaphragms are formed on the inner side of the tube. The annular grooves and diaphragms swirl the flow in the wall layer and promote heat transfer enhancement outside and inside the tubes. The designed annular swirl-augmented tubes can be used in apparatuses operating with gases and liquids during boiling and condensation of heat carriers.

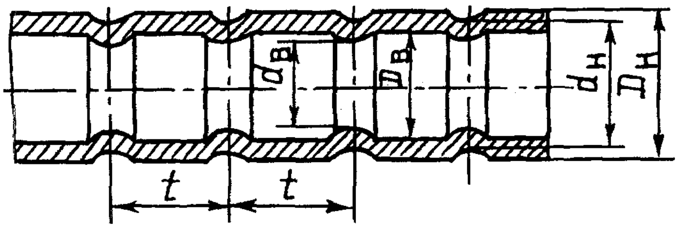
The present article deals with new experimental results on heat transfer enhancement achieved by the proposed method. Studies [1, 2] have been performed at the Moscow Aviation Institute, Tashkent Technical University, Central Institute of Aviation Motor Designing, Scientific Production Association "Central Boiler Turbine Institute," Scientific Research Institute of Sanitary Techniques, Volgodon Branch of the All-Union Scientific Research Institute of the Atomic Engineering Industry and in other institutions. This article also contains the results of introducing this method into different-purpose heat transfer apparatuses.

New Designs of Heat Transfer Tubes. The previous design of the heat transfer tube [1] is considerably improved by using smooth-configuration inserts. As compared to the hydraulic resistance growth, the region of the advancing growth of heat transfer is extended. The same growth of heat transfer and hydraulic resistance is obtained at $Nu/Nu_{sm} = \xi/\xi_{sm} = 2.2$ over a wide Reynolds number range. New data on heat transfer enhancement with water flow in tubes having small insert pitches ($t/D_{in} = 0.2 - 0.4$) are obtained.

Appreciable heat transfer enhancement is provided by using helical annular swirl-augmented tubes [3] (Fig. 2). These tubes, as well as pure helical ones, are assembled into a close-packed bundle. Such a design combines the advantages of helical and annular swirl-augmented tubes. The first tubes provide substantial heat transfer enhancement in the intertube space while the second, inside the tubes. The helical annular swirl-augmented tubes provide an approx. 2.5-3-fold increase of heat transfer coefficient both outside and inside the tubes. This allows high efficiency of heat transfer enhancement in tubular apparatuses at any ratio of heat transfer coefficients outside and inside the tubes.

Moscow Aviation Institute, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 65, No. 1, pp. 25-31, July, 1993. Original article submitted May 19, 1992.

 1062-0125/93/6501-0638$12.50



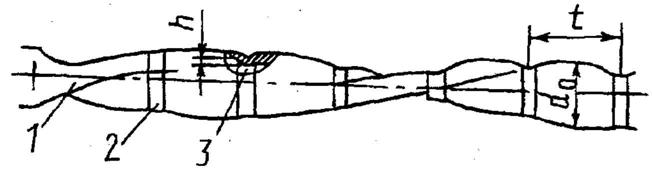


Fig. 1. Annular swirl-augmented tube.

Fig. 2. Oval helical transverse annular groove-corrugated tube: 1) tube; 2) grooves; 3) diaphragms.

New designs of heat transfer tubes have been proposed. These have provided high efficiency of heat transfer enhancement under particular conditions. Tubes having relatively high diaphragms and decreased location pitch provide a sharp reduction of foulings outside and inside the tubes in flow of water of evelated hardness. Tubes having step changing height and location pitch of annular diaphragms [4] (Fig. 3) afford optimal heat transfer enhancement when the Reynolds and Prandtl numbers for a heat carrier inside the tube vary substantially. When the liquid is heated along the tube, the Re number increases, the Pr number decreases, the optimal value of d_{in}/D_{in} grows, and the optimal value of t/D_{in} falls.

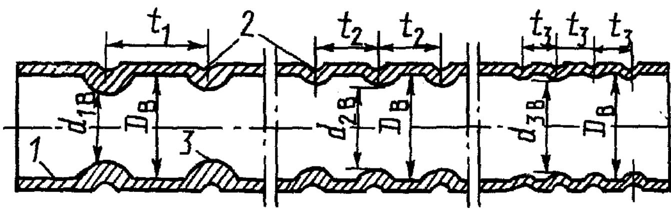
Annular swirl-augmented tubes having arc-shaped annular valleys in the form of a globoid [5] (Fig. 4) on the outer surface between the annular grooves allow additional heat transfer enhancement outside the tubes, as compared to the previous design (see Fig. 1). The smallest globoid diameter is equal to the outer diameter of the annular tube sections. The availability of extra protrusions outside the tube at the junction of the grooves and globoid valleys allows heat transfer outside the tubes to be increased up to $Nu/Nu_{sm} = 2.09$ with increase in resistance $\xi/\xi_{sm} = 2.5 - 2.95$ for $Re = (1 - 8) \cdot 10^4$. The heat transfer coefficient in apparatus incorporating these tubes is increased 2.45 times compared to that containing smooth tubes.

Tubes with convex ridges outside are used in condensers [6] (Fig. 5) if the condensation occurrs outside the tubes. In such heat exchangers the condensate film is easily separated from the tube surface, thus resulting in 2-3-fold heat transfer enhancement in horizontal tubes and 1.6-fold enhancement in vertical tubes. Since in these tubes heat transfer is simultaneously increased, use of these tubes allows an approx. 2.2-fold increase of the heat transfer coefficient in tubular condensers.

Tubes with inclined annular grooves outside and diaphragms inside [7] (Fig. 6) are used in vertical tube-containing condensers. Diaphragmed grooves are located parallel to one another at an angle of $\alpha < 90°$ to the tube axis. The tube design facilitates condensate film separation in the lower parts of each annular groove, thereby decreasing the mean condensate film thickness around the tube periphery. Thus, a 2-3-fold heat transfer enhancement is provided, as compared to a smooth tube.

Heat Transfer Enhancement in Supercritical Hydrocarbon Flow in Tubes. There is interest in this problem when hydrocarbon fuel is used as coolants of heat-stressed elements of vehicle engines. The cold lifetime of these fuels can be greatly increased due to endothermal decomposition reactions, and the availability of the supercritical parameters of a coolant permits a high value of heat transfer coefficient to be obtained. Heat transfer enhancement problems under these conditions have not been studied earlier. Owing to this, numerous experiments have been made. The inner diameter of electrically heated tubes was $D_{in} = 1 - 4$ mm and the tube length was 1 m. Kerosene (trademark RT, $P_{cr} = 2.5$ MPa, $T_{cr} = 666$ K) was used as a working liquid at a pressure of 5.0 MPa. The experiment was conducted for $Re = 10^2 - 3.5 \cdot 10^4$, inlet temperature $T_0 = 373$ K, and heat flux density $q_w = 8 \cdot 10^3 - 8 \cdot 10^5$ W/m^2. Heat transfer in smooth channels is described by the known relations. Under the conditions of high wall temperature ($T_w > 550°C$), partial fuel decomposition occurs, and heat transfer is affected by fuel residence time in the channel.

For deteriorated heat transfer to be suppressed and the wall temperature to be reduced it is recommended that rolled tubes be used for transfer enhancement in the wall region. To do this, stainless steel tibes 4 mm in diameter and 1 m long with rolling parameters were used: $d_{in}/D_{in} = 0.85 - 0.95$; $t/D_{in} = 0.75 - 2.00$.



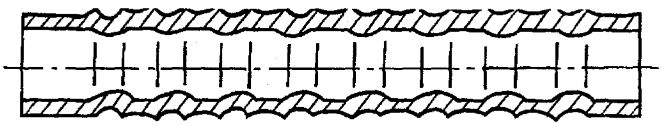


Fig. 3. Annular variable height and pitch swirl-augmented tube: 1) tube; 2) grooves; 3) annular diaphragms.

Fig. 4. Annular swirl-augmented tube having outside arc-shaped annular ridges between grooves.

As a result of the studies conducted, the Re range in which use of rolled tubes is most profitable has been found, i.e., the range where $(Nu/Nu_{sm})/(\xi/\xi_{sm}) > 1$. The effect of the rolling parameters d_{in}/D_{in} and t/D_{in} on heat transfer enhancement has been defined. It is shown that for Re < 1000 in laminar flow $Nu/Nu_{sm} < 1$. It is shown that heat transfer enhancement is the most efficient way to suppress deteriorated heat transfer (Nu/Nu_{sm} attains 5.0). It is found that the rolling profile affects not only hydraulic resistance but also heat transfer. Greater enhancement effects are achieved when supercritical hydrocarbon fuels are used rather than other heat carriers.

During the flow of hydrocarbon fuels, coke foulings are formed on the channel walls and these disrupt the heat transfer process. Rolling affects coke fouling ambiguously. On the one hand, the wall temperature decreases and, on the other hand, the oxygen delivery rate to the hot wall increases. Deoxidizing fuels are efficiently used to prevent coke foulings.

The ranges of the working parameters over the test section are: pressure 0.3-1 MPa (oil), 3-5 MPa (fuel and individual fuels); temperature 283-293 K (oil), 283-373 K (fuel hydrocarbons); mass flow velocity 240-400 $kg/(m^2 \cdot sec)$, 1415-9000 $kg/(m^2 \cdot sec)$ (fuel and hydrocarbons); maximum heat flux density $q_w = 10^6$ W/m^2.

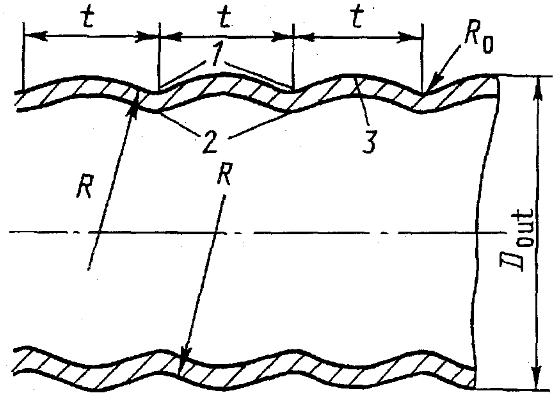
Time variations of local thicknesses and roughness, and of fouling permeability in laminar and turbulent flows are revealed. It is shown that, as rolling takes place, the fouling structure on a smooth surface changes: first, separate spherelike small-size agglomerates are formed on the wall; second, a continuous fouling layer originates and then, as it thickens, its external part becomes permeable. Such a structure is found to greatly affect heat transfer. Heat transfer in the transient Re number range is enhanced, thereby noticeably (up to 300°C) reducing the wall temperature.

It is established that, as heat transfer is enhanced the fouling rate first increases compared to a smooth channel and then, vice versa, decreases and becomes an order of magnitude less than in a smooth channel. Such an influence of heat transfer enhancement on the fouling rate is common in different hydrocarbons: both individual and fuel oils in which the fouling formation is conditioned by dissolved oxygen oxidation processes.

The rolling parameters are determined, which for different hydrocarbons leads to foulings being formed not in the diffusional but now in the kinetic deceleration region. By the electron microscope method it is found that, unlike a smooth tube, the foulings on the surfaces of tubes rolled by the method developed at the Moscow Aviation Institute are formed nonuniformly: in the diffusional deceleration region foulings are mainly formed on the leeward side of microprotrusions, and flow separates. In the kinetic deceleration region foulings are formed on the windward side and in the vicinity of the apex of the macroprotrusions.

Based on the radical-chain mechanism of carbon oxidation, a method is proposed for the calculation of fouling formation and heat transfer in wall flow swirl-augmented channels.

Heat Transfer Enhancement in Crossflow Past Annular Grooved Tube Bundles. A study is made over the range of $Re = 10^3 - 8 \cdot 10^4$ in water and air flows. Experiments are made in staggered tube bundles with the following values of S_1/D_{in} and S_2'/D_{in}: 1) 1.35, 1.35; 2) 1.2, 1.2; 3) 1.1, 1.1 and in an in-line flow tube bundle with S_1/D_{in} = 1.2 and S_2/D_{in} = 1.2. The tube bundles were assembled so that the grooves on all tubes were located in one section and were displaced half a pitch in the adjacent transverse pitches. In both cases it was shown that for pure crossflow past tube bundles the annular grooves did not provide a substantial growth of heat transfer and hydraulic resistance.



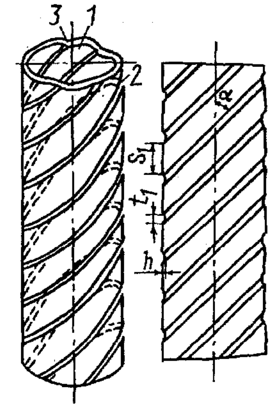


Fig. 5. Tube having outside convex protrusions: 1) annular grooves; 2) annular smooth-geometry diaphragms; 3) convex tube protrusions.

Fig. 6. Tube having inclined grooves and diaphragms: 1) tube; 2) grooves; 3) protrusions.

Heat Transfer Enhancement during Condensation of Pure Vapors and Vapor Mixtures on a Single Horizontal Tube. Tubes with $D_{in} = 25$ mm and 1 m long having outside rolling parameters d_{out}/D_{out} and t/D_{out} equal to 1) 0.872 and 0.2, 2) 0.9 and 0.2, 3) 0.912 and 0.3, 4) 0.876 and 0.4, and 5) 0.91 and 0.4, respectively, were studied.

For film condensation of pure vapors of water, acetone, and extraction benzine irrespective of the thermophysical properties of the heat carrier, the availability of annular grooves results in a substantial 1.8-2.2 fold heat transfer enhancement for tubes Nos. 1, 2, 3 of 2.8-3, 2-2.5, and 1.8-2.2, respectively.

The study of the condensation of binary vapors of different composition miscible (water-acetone) and immiscible (water-extraction benzine) liquids on annular-grooved tubes was accompanied by condensation visualizations. For water-acetone mixture condensation, depending on the mixture composition there exist three regimes of condensate falling down the cooling surface: film, drop and transient film-drop (plumes). When even a small amount of a volatile component (acetone) is added, the film flow is disturbed, and drops start forming. Increasing acetone concentration X_A is the cause of stable drop condensation. Major drop formation has been observed at $X_A = 17\%$. At $X_A > 54\%$ the drop regime changes to the plume regime, and at $X_A \geq 77\%$ the film regime starts.

For mixture condensation the thermal heat transfer resistance R denotes the thermal condensate film resistance R_c and the diffusional thermal resistance R_D when heat is supplied to the condensation surface. The ratio R_c/R_D grows with increasing temperature head between the vapor and wall. Use of annular grooves has allowed R_c to be decreased 1.4-1.75 times and R_D, approx. 1.5 time.

During condensation of a water-extraction benzine vapor mixture on the wall to be cooled, first, benzine vapors are condensed in the form of the film and then water vapors in the form of drops on this film at benzine concentration $X_b < 62\%$ or in the form of a film at $X_b > 62\%$. Use of annular grooves decreases R_c 2.2-2.3 times and R_D, 1.6-1.8 times. During condensation of immiscible liquid vapors the enhancement intensity is higher than that during condensation of immiscible liquids (water-acetone).

Foulings in Tubes with Annular Diaphragms. In [1, 2] it is shown that use of tubes with annular grooves outside permits foulings to be greatly decreased when these are streamlined by water with elevated bicarbonate hardness (up to C = 20 mg·eqv/liter). Similar studies have been performed in water flow of elevated hardness in tubes with annular grooves inside. Experiments are performed for water heating with C = 10 and 20 mg·eqv/liter, temperature of 20-30°C, $Re = (3.5 - 25) \cdot 10^3$, and time up to 360 h in tubes having the following diaphragm parameters: 1) $d_{in}/D_{in} = 0.91$ and $t/D_{in} = 0.5$; 2) 0.91 and 0.25; 3) 0.935 and 0.5. The thermal resistance of the fouling layer in diaphragmed tubes is 3-4 times smaller than in smooth tubes. These foulings are the smaller the larger the height and the smaller the diaphragm location pitch. Characteristically, for diaphragmed tubes the heat transfer coefficient decreases no more than by 10% for 100 h of operation, and the hydraulic resistance not practically does not change. During this time the hydraulic resistance increases by 20% for a smooth tube.

Thus, the experiments performed prove that foulings outside and inside rolled tubes are much smaller than in smooth tubes, and their growth obeys an asymptotic law. Use of tubes with annular grooves allows stable operation of heat exchangers, with no special cleaning of their surfaces.

Highly Efficient Heat Exchangers. Experimental data of [1] and the present article were supported by tests of industrial heat exchangers. In single-phase exchangers the heat power was increased by 60-80% while in condensers, up to 2.2 times.

New designs of water-moderated, water-cooled heaters of atomic power plants are manufactured and tested. Possible use of the developed designs for ∅ 133, 325, 1200, and 1800 mm heaters is substantiated. Three models of ∅ 325 mm rolled, helical, and helical-rolled tube-equipped heat exchangers have been tested. Increases of 1.62-, 1.9-, and 2.6-fold in the heat transfer coefficient are obtained, respectively. Groove rolling results in a 2-fold increase of the hydraulic resistance inside the tubes and practically none outside them. The Volgodon Branch of VNIIAM has developed technical proposals for using grooved tubes in the heat exchangers of the V-1000 reactor unit.

New designs of water-moderated, water-cooled heaters of heating systems using in-line flow annular groove-containing tube bundles are manufactured and tested. A tube design is included into GOST 27590-88 "Water-Moderated, Water-Cooled Heaters of Heating Systems. General Specifications" and has found use in heat exchangers manufactured by the Scientific Production Association "Biotekh" (Varna, Bulgaria). Replacing smooth tubes by rolled ones has allowed the thermal capacity of heat exchangers to be increased 1.8 time, and five exchangers have been left instead of eight.

New designs of tube-to-tube heat exchangers, as well as of 7- and 19-tube containing apparatuses for heat treatment (pasteurization) and cooling milk systems are designed and tested. Tubes having annular grooves, helical, and helically rolled tubes are utilized.

The thermal power of apparatuses increased more than 1.5 time. Under pasteurization conditions foulings decreased and the continuous operation time increased several times.

Annular groove tubes are used in convective bundles of fire-tube bundles, waste gas heat recovery units of industrial furnaces, and heat exchange apparatuses of the food and chemical industry, whose overall dimensions and metal consumption have been decreased 1.4-2.2 times. When waste dust gases flow inside these tubes the dust foulings are much smaller than in smooth tube.

CONCLUSIONS

1. A highly efficient method of enhancing heat transfer in tubes with annular grooves has been developed and studied. Use of these tubes allows substantial heat transfer enhancement with liquid and gas flow in tubes with surface and film boiling, drop and film condensation on the outer surface of the horizontal and vertical tubes, as well as significant reduction of salt foulings on the inner and outer tube surfaces.

2. Tests of commercial heat transfer apparatuses equipped with such tubes indicate their high efficiency and the possibility of decreasing the heat transfer surface 1.5-2 times as compared to apparatuses with smooth tubes.

NOTATION

D_{in}, D_{out}, inner and outer tube diameters; d_{in}, annular diaphragm diameter; d_{out}, annular groove diameter; S_1, S_2, S_2', transverse, longitudinal, and diagonal tube bundle pitches; t, swirler location pitch; X_A, X_B, content of acetone and benzine in the mixture; ξ, hydraulic resistance coefficient; Nu, Pr, Re, Nusselt, Prandtl, Reynolds numbers. Subscripts: sm, smooth; cr, critical.

REFERENCES

1. É. K. Kalinin, G. A. Dreitser, and S. A. Yarkho, Heat Transfer Enhancement in Channels [in Russian], Moscow (1990).

2. É. K. Kalinin, G. A. Dreitser, N. V. Paramonov, et al., Heat and Mass Transfer, No. 2, Minsk International Forum, Heat/Mass Transfer in Power and Chemical Engineering Devices: Problem Paper, Minsk (1988), pp. 19-35.
3. L.-V. Ashmantas, Yu. V. Vilemas, G. A. Dreitser, and Yu. S. Voskresenskii, A heat transfer helical tube: Inventor's Certificate 1386843 (USSR): MKI F 28 F 1/02.
4. V. I. Gomon, P. G. Ostapushchenko, G. A. Dreitser, and É. K. Kalinin, A heat transfer tube: Inventor's Certificate 1223016 (USSR): MKI F28 F 1/02, 1/6.
5. G. A. Dreitser, S. A. Yarkho, M. P.Ignatiev, and F. P. Kirpichnikov, A heat transfer tube: Inventor's Certificate 1374029 (USSR): MKI F28 F 1/42.
6. G. A. Dreitser, É. K. Kalinin, A. S. Neverov, et al., A heat transfer tube: Inventor's Certificate 1307211 (USSR): MKI F28 F 1/42.
7. G. A. Dreitser, V. K. Migai, A. V. Mikhailov, et al., A heat transfer tube: Inventor's Certificate 1474435 (USSR): MKI F28 F 1/42.