ISSN 0040-6015, Thermal Engineering, 2012, Vol. 59, No. 1, pp. 1–12. © Pleiades Publishing, Inc., 2012.
Original Russian Text © I.A. Popov, Yu.F. Gortyshov, V.V. Olimpiev, 2012, published in Teploenergetika.

Industrial Applications of Heat Transfer Enhancement: The Modern State of the Problem (a Review)

I. A. Popov, Yu. F. Gortyshov, and V. V. Olimpiev

Tupolev Kazan State Technical University, ul. K. Marksa 10, Kazan, 420111 Tatarstan, Russia

Abstract—Methods used for enhancing heat transfer in power installations and industrial thermal engineering apparatuses are reviewed. Classification of these methods is given, and the corresponding types of intensifiers are considered.

DOI: 10.1134/S0040601512010119

The technical and economic indicators of thermal power installations are determined to a considerable degree by the parameters of heat exchangers. Such apparatuses have very significant mass and volume. An increase of the capacities of single power installations, which is the main trend in their development, entails a growth in the absolute mass and dimension characteristics of HEs used in these installations. Accordingly, the problem of improving heat exchangers in terms of decreasing their dimensions and mass (metal intensity) and reducing the power required for pumping heat carriers through the apparatus while retaining their thermal capacity is becoming more important and topical.

It is obvious that at present and the future, one of the main ways—most accessible and justified in technical and economic respects—in which the mass of power installations can be decreased and more efficient operation of them can be achieved consists of improving HEs, which can be achieved through the use of efficient methods for enhancing heat transfer.

A huge database on enhancement of heat transfer is presently available in the technical literature. This database contains more than 10 000 technical articles, presentations, and reports, which were published in periodicals and numerous bibliographic reports by A.E. Bergles et al. [1–3], M.K. Jensen and B. Shome [4], in reviews by R. Webb [5, 6], D.P. Shatto and J.P. Peterson [7], A.E. Bergles [8, 9], R.M. Manglik and A.E. Bergles [10], and monographs written by J.R. Thome [11], R. Webb [12], R.M. Manglik and A.D. Kraus [13], and S. Kakac et al. [9]. It should be pointed out that investigations carried out in the former Soviet Union made a considerable contribution in solution of this problem, especially in creating practically feasible methods for enhancing heat transfer. It will suffice to mention the works of V.M. Antuf'ev, V.M. Buznik, G.I. Voronin, N.V. Zozulya, E.K. Kalinin, V.K. Migai, V.K. Shchukin, G.A. Dreitser, E.V. Dubrovskii, and many other scientists.

Studies carried out by I. Newton (1701), J.P. Joule (1861), R. Montgomery (1862), S. Fox (1877), J.P. Serve (1885), L. Serpole (1890), J.M. Witam (1896), R. Roids (1921), M. Jacob (1931), and other researchers became the major milestones in the development of the theory of heat transfer enhancement. The growth of information on this matter is shown in Fig. 1 as the distribution of the number of annual technical publications on this topic (a total of 5676 works had been published by the middle 1995). These publications are the result from implementation of an extensive program of investigations aimed at determining conditions, methods, and devices for achiev-

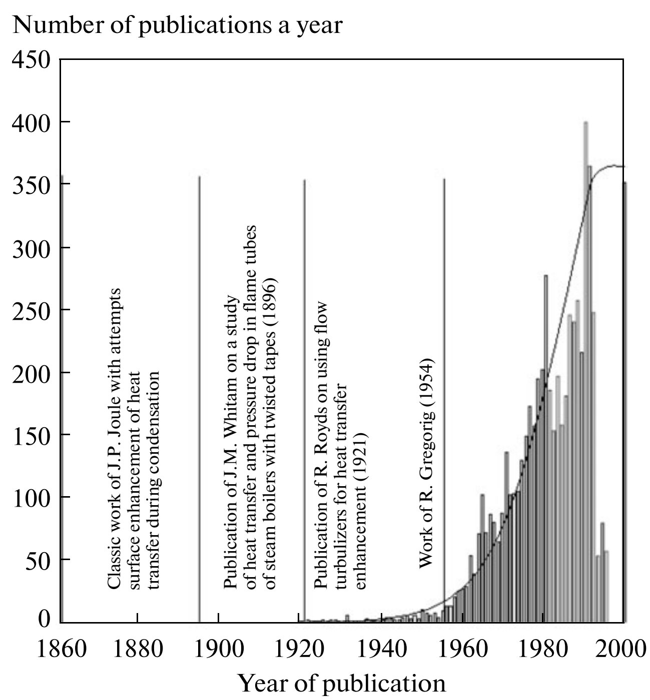


Fig. 1. Growth of information on heat transfer enhancement in the scientific-technical literature published around the world.

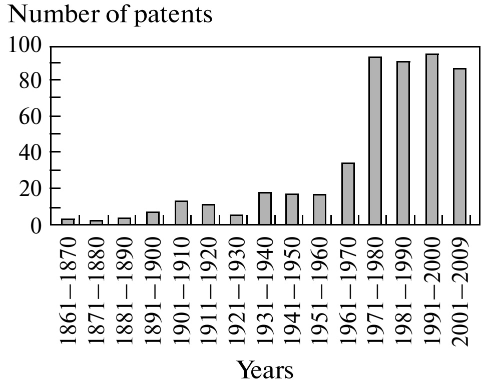


Fig. 2. Worldwide dynamics in issuance of patents on heat transfer enhancement.

ing more intense transfer of heat and mass in technical facilities.

A great number of patents on heat transfer enhancement have become the result from commercialization of methods for enhancing heat transfer, which made it possible to develop these technologies from research works to field industrial applications. Figure 2 shows that interest in this problem increased by many times around the world for the period 1861–2009.

The problem of determining the effectiveness of different methods and devices for enhancing heat transfer is an integral one and fairly difficult due to variety of criteria. A large number of coefficients that take into account economic (expenditures for development, construction, operation, maintenance, etc.) and production factors (suitability surfaces for machine-aided processing, assembling, mounting of devices and other production processes), reliability (compatibility of media and materials, stiffness of structures and their service life), safety, etc. must be taken into consideration in solving this problem apart from relative thermal–hydraulic efficiency of heat transfer intensifiers.

Enhancement methods	Principle of action
Active	Mechanical mixing
	Surface vibration
	Flow pulsation
	Electrostatic fields
	Injection
	Suction of boundary layer
	Jet apparatuses
Passive	Finished surfaces
	Rough surfaces
	Extended surfaces
	Mixing devices
	Flow swirlers
	Coils
	Surface tension devices
	Admixtures for liquids
	Admixtures for gases
Complex	Two or more passive and/or active methods simultaneously

In the majority of cases, the developers of HEs who use methods of heat transfer enhancement pursue the following objectives apart from fulfilling technical specifications and achieving the specified working characteristics of heat exchangers:

(1) Increasing the thermal capacity of existing heat exchanger without changing the power required for pumping heat carriers (or pressure losses) at fixed flowrates of heat carriers.

(2) Reducing the temperature difference between heat carriers for achieving the specified thermal capacity at fixed overall dimensions of a heat exchanger.

(3) Decreasing the mass and dimension characteristics of a heat exchanger while preserving its thermal capacity and pressure losses in its paths.

(4) Decreasing the power required for pumping heat carrier with fixed thermal capacity and retaining the heat-transfer surface area.

Objectives (1), (2), and (4) relate to energy conservation and objective (3) relates to the task of saving resources (reduction of metal intensity and cost). The approach of the authors of this paper to this question is described in [14].

In fact, methods of heat transfer enhancement are aimed at reducing the thermal resistance of near-wall layers during convective heat transfer in a heat exchanger and help increase the coefficient of heat transfer with or without increasing the working surface of the apparatus.

Sixteen different methods of heat transfer enhancement were classified in [1–3] and subdivided into passive ones (no external supply of energy is required for enhancement), active ones (requiring some amount of external power supply), and complex ones (see the table).

Different types of tubular heat exchangers for various purposes comprise the overwhelming part (80–90%) of the world and domestic market of heat exchangers. The main advantage of these apparatuses is that they are available for a wide range of working temperatures and pressures, that they can be used in different industry branches and in different kinds of industry and kinds of technical devices and technologies. However, the majority of industry-grade tubular

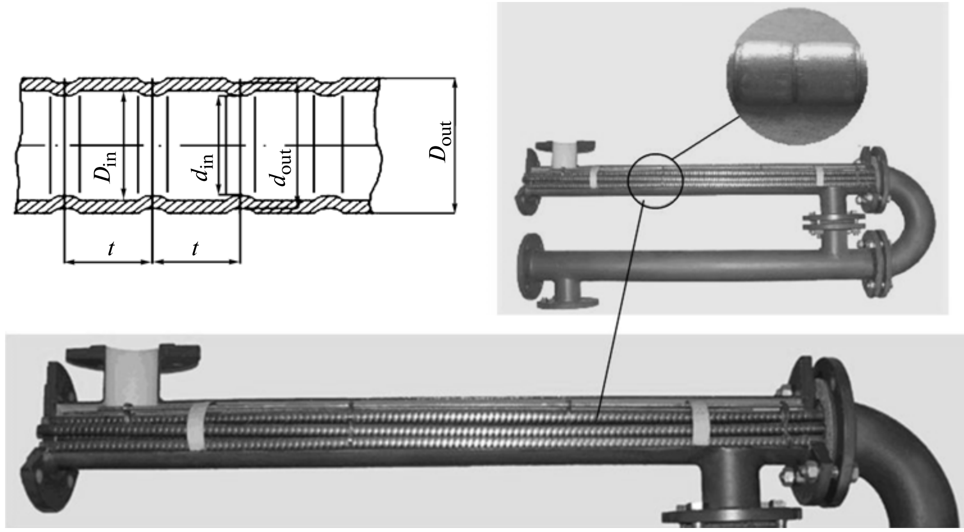


Fig. 3. Type PVV water-to-water heater [produced according to GOST (State Standard) 27590-88 and TU (Technical Specifications) 400-28-132-90 with tubes profiled in the form of annular knurling.

heat exchangers feature rather poor efficiency indicators.

Below, the main methods used around the world in tubular heat-transfer elements of boilers and different types of heat exchangers for enhancing heat transfer in them are considered.

Rough surfaces. Changing the shape of surfaces helps to develop turbulence in flows of coolants (primarily in single-phase flows) without any essential increase in the heat transfer surface. The geometrical characteristics of these surfaces cover a wide range of roughness: from granular (sandlike) roughness to discrete 3D surface indents and/or protrusions. Depending on the geometrical parameters of the used rough surface, heat transfer during turbulent flow is enhanced by a factor of 2.5–3.5, critical heat fluxes during boiling increase by 50–200%, and heat transfer coefficients during condensation increase from 30% to a factor of 5.

The surface intensifiers that are mainly applied in the fire tubes of boilers are made in the form of spiral wire inserts, annular or spiral knurling, and stamps of various shapes, the use of which makes it possible to destroy the boundary layer and turbulize the near-wall layers of gas flow. The following apparatuses can serve as examples of using such tubes: the gas tube boilers produced by Fröling (German) and Babcock Wanson (the United States) in which spiral wire inserts are used, boilers produced by the Hurst Boiler and Welding Co., Inc. (the United States) fitted with fire tubes with spiral protrusions on their inner surfaces, boilers produced by Hoval (Liechtenstein) and Omnimat (Germany) fitted with fire tubes with spherical protrusions, KSVa-1.0 boilers produced by OAO Azovobshchemash (Russia), and VK-22 boilers of ZAO Terminal-P (Russia) fitted with fire tubes with knurled gas flow turbulizers.

Issuance of the GOST (State Standard) 27590-88 (presently GOST 27590-2005) for water-to-water heaters of heat supply systems with profiled tubes (Fig. 3) was the first attempt to organize manufacturing of enhanced heat exchangers in the USSR.

Heat exchangers equipped with profiled tubes are produced by ZAO TsEEVT (Russia) jointly with OOO Gidrotermal' (Russia). The list of products manufactured by these companies includes Type VVPI intensified water-to-water heaters [according to TU (Technical Specifications) 4933-004-47059130-99), Type PMKI intensified multipass shell-and-tube water-to-water heaters (TU 4933-001-58960970-2004), Type PVPI intensified steam-water heaters (TU 4933-002-58960970-2005), Type OVV water coolers, and Type OVM oil coolers.

There are a number of companies that produce heat exchangers with profiled tubes having a spiral knurling on their external surface (Fig. 4). The list of them includes, but is not limited to, the HRS Group Corporation (Spain), the BlueRidge Company (the United States), Energy Transfer MDE (the United States), Thermaline Inc. (the United States), UK Exchangers Ltd. (the United Kingdom), APV (Sweden), MPG Mendener Prazionsrohr (Germany), Britannica Heatex, Ltd (Geat Britain), Waukesha (the United States), INEPEC Group (China), Turbotec Products Inc. (the United States), Doucetti Industries Inc. (the United States), Osaka Steel Tube (Japan), Fintube Technologies (the United States), and Tonglian Stainless Steel Materials Co. (China). Multistart spiral tubes for heat-transfer equipment are commercially available from Raypak (the United states/Canada), Guangzhou Mingfeng Copper Capil-

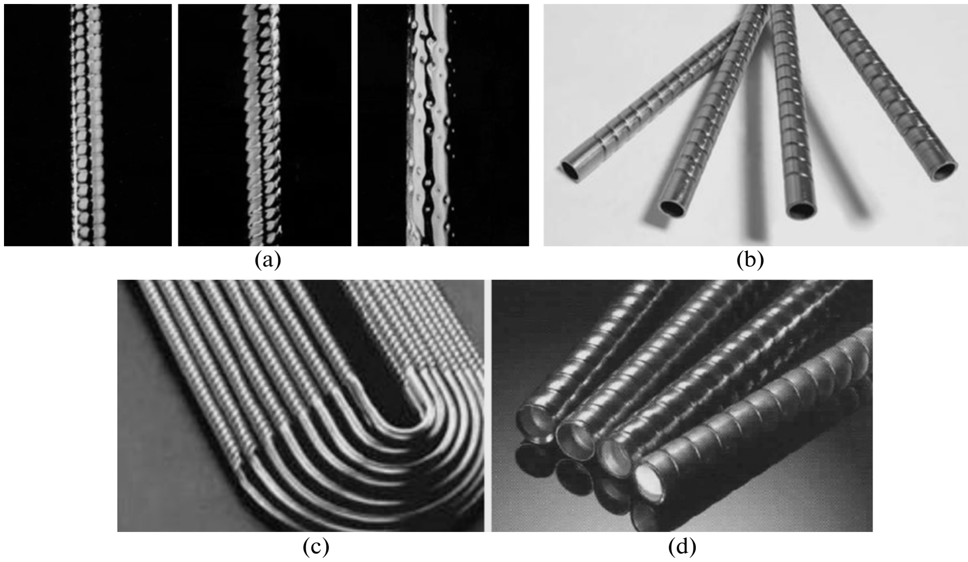


Fig. 4. Profiled tubes with spiral or annular knurling or spherical indents produced by HRS Group (a), Energy Transfer MDE (the United States) (b), MPG Mendener Präzisionsrohr (c), and Turbotec Products Inc. (d).

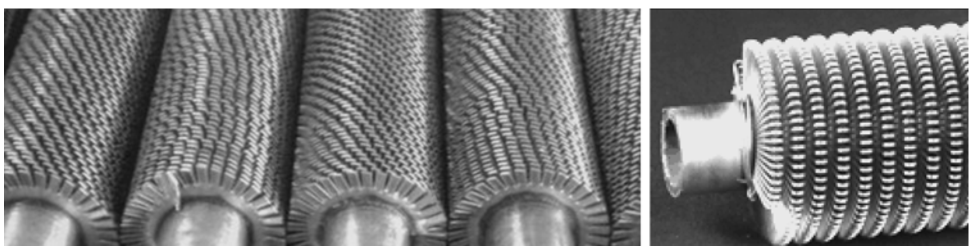


Fig. 5. Externally finned tubes with spiral split and wire fins.

lary Tube Co., Ltd. (China), Vaportec (New Zealand), and Turbotec Products, Inc. Tubes with spherical dimples/protrusions for heat-transfer equipment are commercially available from the HRS Group, Teralba Industries (Australia), and JBT FoodTech (the United States).

The use of **extended surfaces** often called finned surfaces makes it possible to efficiently increase the area of heat-transfer surface. Flat fins have long been used in many heat exchangers. Shapes of finned surfaces have recently been developed that, apart from extending the surface itself, affect the flow making it disturbed, due to which heat transfer is additionally enhanced.

Heat transfer in water-tube boilers is enhanced mainly on the external side of tubes. The surface of tube waterwalls used in the radiant zone is extended by using different types of continuous or split longitudinal finning. The convective parts of boilers (economizers) are made using bimetallic and monometallic tubes with external spiral or annular, pinned or continuous corrugates or split fins made of steel, copper, and aluminum. Such boilers and economizers for them are produced by ZAO Uralkotlomash (Russia), ICI Caldaie (Italy), Viessmann (Germany), Lochinvar (Livan), Laars (the United States), and some other companies. The fire tubes used in gas-tube boilers are finned not only on the gas side, but also on the water side to increase the boiling surfaces. Fire tubes finned on both sides are used in small-capacity boilers, e.g., those produced by Baxi (Italy) and Termomax (Hungary).

Intensified heat-transfer surfaces for boilers and heat exchangers are commercially available from Fintube Technologies Inc., Cain Industries (the United States), the Ordzhonikidze Machinery Construction Works (ZiO) (Russia), Chrystyn Ltd. (the United States), Daikure Co., Ltd. (Japan), Düma GmbH (Germany), Tex-Fin Inc. (the United States), Profins Limited (the United Kingdom), Flamingo Chillers (India), Lu-Ve Group (France), Badrin Industries (India), Heft Engineers (India), Shanghai Shenhua Steel Tube Co., Ltd (China), Wuxi City Qianzhou Seamless Tube Factory (China), Mraz S.A. (Argentina), Elhamd Heatexchangersc Co. (Egypt), Elyon Industry Co., Ltd. (Korea), Dae Ryung Corporation (Korea), Koch Heat Transfer Company LP (the

United States), Pragya Equipments Pvt, Ltd. (India), Shanghai Jinshi Suotai Mechanical & Electric Equipment Co., Ltd. (China), Wellman Hunt-Graham (the United Kingdom), AmerCool (the United States), ΔT-Heat Exchangers (the United Kingdom), Ewha Corporation (Korea), Henok Engineers (India), Wuxi Xin Ming Non-Ferrous Metal Materials, Ltd. (China), Hamoon Mobaddel Co. (Iran), and others (Fig. 5).

Quite a large number of producers continue to place focus on manufacturing tubes with wired finning. In particular, the following companies produce tubes with spiral wire finning on the external and inner surfaces: Concept Engineering International (India), Sun Heat Transfer Technologies (India), Industrial Thermal Engineers (India), Neha Engineering (India), Talab (India), TAAM (India), Gei Industrial Systems Ltd. (India), and Specialist Heat Exchangers (the United Kingdom).

Small-diameter tubes made of materials with high thermal conductivity are finding increasingly wise applications in finned-tube heat exchangers used in refrigerating engineering and air conditioning systems, as well as in usual shell-and-tube general-purpose heat exchangers. Spiral, chevron, annular, 3D, and other protrusions and indents of different types and profiles are applied to their surfaces for heat transfer enhancement (Fig. 6). Wolverine Tube Inc. (the United States), Hitachi (Japan), and Wieland-Werke AG (Germany) are leaders in the manufacture of such heat-transfer tubes. Such tubes are also commercially available from other companies, including, but not limited to, KME Germany AG&Co. (Germany), Shandong Albetter Co., Ltd. (China), Qinngdao Hongtai Metal Co. Ltd. (China), Zhangjiagang Sanwei Machinery Co., Ltd. (China), LP Industrial Co., Ltd. (China), Ningbo Jintian Group Co. Ltd. (China) Norsk Hydro ASA (Norway), Dama Ettehad Co., Ltd. (Iran), Fin Tube Korea Co., Ltd. (Korea), Pune Fin Tube Pvt. Ltd. (India), QAEM Copper Industries (Iran), Sumitomo Metal Industries, Ltd. (Japan), Vallourec Group (France), Dae Ryung Corporation (Korea), High Performance Tube (the United States), and Furukawa Electric Co., Ltd. (Japan).

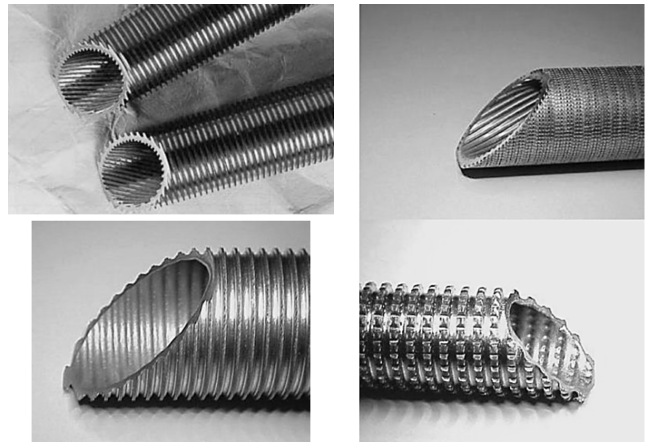


Fig. 6. Heat transfer tubes for evaporators produced by Wolverine Tube Inc.

Agitation devices are essentially inserts that are used first of all during forced convection for improving processes of transfer normal to the heat-transfer surfaces: they “shift” heat carrier from the channel’s heat-transfer surface to the main flow. The main types of mixing devices include porous inserts, ring and ball fills, wire and loop structures, and different kinds of static agitators. The use of such devices allows almost a 10-fold increase of heat transfer intensity to be achieved for single-phase flows of coolants. However, this type of heat transfer enhancement involves a considerably leading growth of pressure drop.

Plate-type turbulizers made of stainless or heat-resistant steel in the form of kinked tapes with different configurations are among widely used heat transfer intensifiers, which implement the principle of agitating (turbulizing) the flow in the flame tubes of small- and medium-capacity gas-tube boilers. Tape turbulizers are used in hot-water boilers produced by Unical (Italy), L.E.S. Incorporated (the United States), Vapor (Finland), Laars Heating Systems (the United States), Electric Furnace-Man (the United States), Baxi, Ferroli S.p.A (Italy), ICI Caldane (Italy), as well as Russian companies Entoros, ACV, Al’yans-Teplo, and others.

Agitation devises are frequently installed in heat exchangers carrying viscous liquids, e.g., oils in power installation cooling systems. A laminar flow mode is commonly takes place in such system, which is characterized by low heat transfer coefficients); therefore, there is an acute need here for heat transfer enhancement. For example, enhancement of heat transfer on the oil side in FanEx F700 air oil coolers produced by ITT Industries (the United States) is achieved by chaotically filling hollow metal balls in the tubes, due to which a parabolic profile of velocity during oil flow typical for laminar flow is changed and layers of liquid are mixed. Enhancement of heat transfer in the T-Rex transformer air-oil coolers produced by Termofin (Canada) is achieved by applying spiral protrusions inside the externally finned aluminum tubes by extrusion. A solution used in the heat exchangers produced by Maaf Pump Systems Textron (Switzerland) for heating high-viscous media consists in furnishing the apparatuses with channels containing segments of a twisted tape welded to each other to form a continuous surface, the lengths of which correspond to the twisting pitch (a 180° turn of the tape). During welding, the segments are placed with turning them by 90°, due to which more efficient mixing of working medium is achieved. The relative twisting pitch of the static mixer is selected from the optimality conditions for each medium or mixture having different viscosities. Such

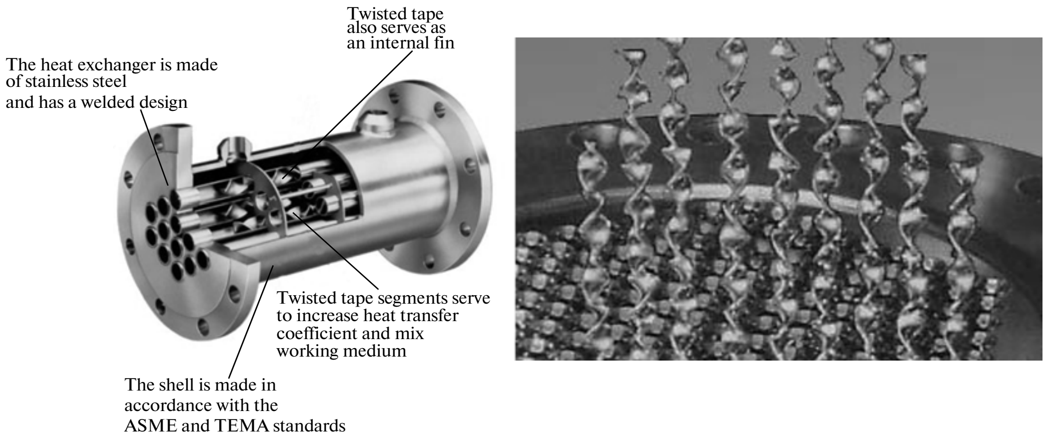


Fig. 7. The Kenics heat-and-mass transfer shell-and-tube apparatus produced by Chemineer, Inc. with inserts made as a set of short twisted tapes.

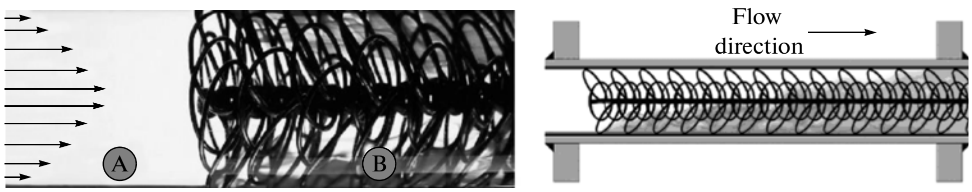


Fig. 8. The HiTran matrix (wire) intensifiers produced by Cal Gavin Ltd. A is a hollow tube and B is a tube with an insert.

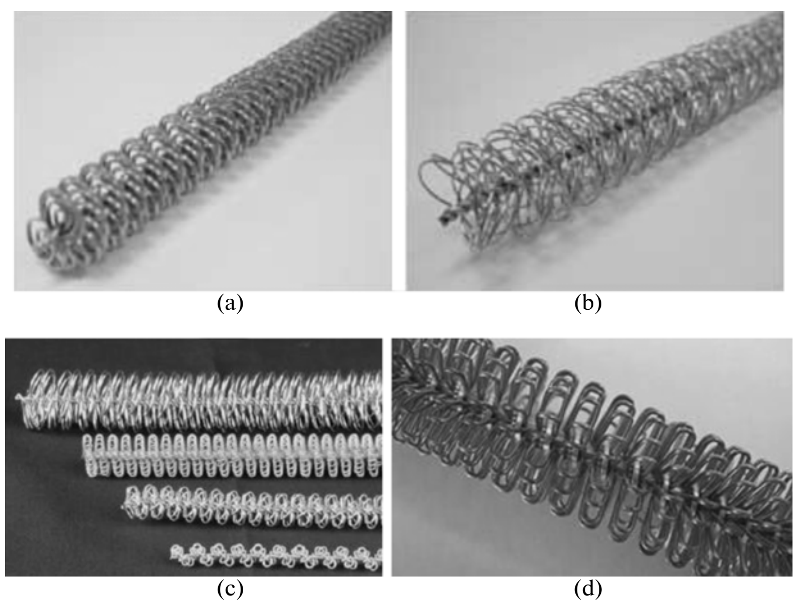


Fig. 9. Wire-matrix turbulizing inserts produced by Midland Wire Cordage Ltd. (a) and (b), Concept Engineering International (c), and Specialist Heat Exchangers (d).

turbulizers are used in heat exchangers produced by the Chemineer Co. Inc. (the United States) (Fig. 7), which also produces tubular heat exchangers with static mixers in the form of petal turbulizers, systems of crossed groove tapes and pins.

Cal Gavin Ltd. (the United Kingdom) produces apparatuses for air cooling and condensation of working media used in industrial processes, as well as shell-and-tube heat exchangers for different purposes, including condensers and evaporators constructed on

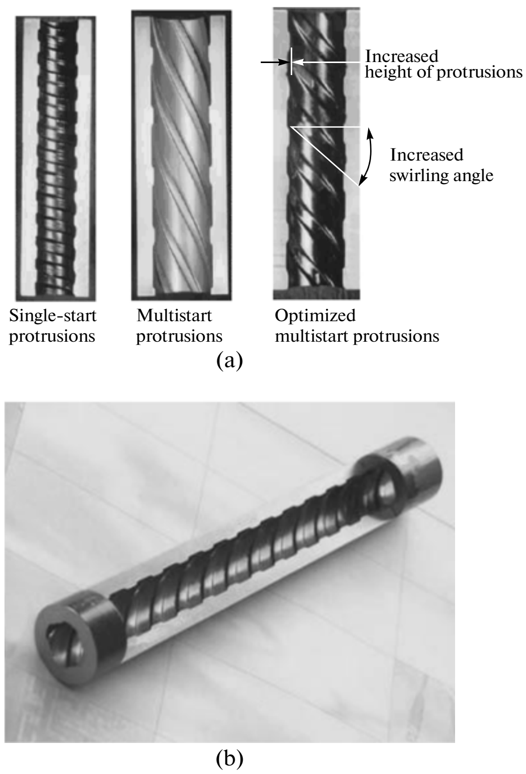


Fig. 10. Profiling shapes of inner surfaces in the tubes for power-generating boilers produced by the Babcock & Wilcox Company and Siemens AG (a) and Foster Wheeler North America Corp. (the United States) (b).

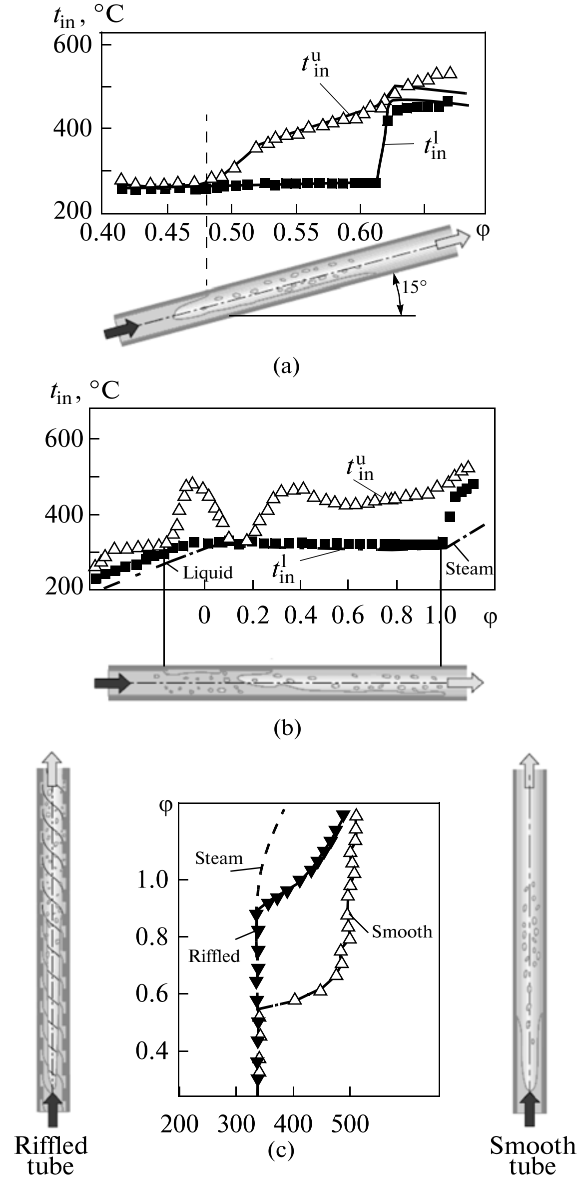


Fig. 11. Influence of gravity forces on heat transfer in inclined (a), horizontal (b), and vertical (c) tubes of steam boilers produced by Siemens AG. t_{in}^u and t_{in}^l are the temperatures of the inner tube surface's upper and lower parts, φ is void fraction, p is pressure, ρw is mass flowrate, q is heat flux density, and d_{in} is the tube inner diameter; p (MPa), ρw [kg/(m^2 s), q (kW/m^2), and d_{in} (mm): (a) 5, 1000, 400, and 24.3; (b) 10, 500, 300, and 24.3; and (c) 15, 500, 300.

the basis of matrix (wire) intensifiers of the HiTran series (Fig. 8). Type HiTran matrix intensifiers produced by Cal Gavin, Ltd. (United Kingdom) allow heat transfer to be increased by as much as a factor of 10 as compared with usual tubes.

Wire-matrix turbulizing inserts for heat-transfer tubes and apparatuses (Fig. 9) are commercially available from Midland Wire Cordage, Ltd. (United Kingdom), Concept Engineering International, Sun Heat Transfer Technologies, Hayden Products LLC (the United States), Specialist Heat Exchangers, Talab and TAAM, Hamoon Mobaddel Co., and others.

Devices swirling flow in channels facilitate the occurrence and development of secondary circulation in flow. These devices can be made as spiral tapes, screws, or twisted tubes. Forms of flow inlet into the channel (tangential to the axial direction) also differ from one another. Such devices are used both for single-phase and two-phase flows. According to the data available from the literature, heat transfer is in this case enhanced by as much as a factor of 1.8–5. For flows of boiling coolants, critical heat fluxes can be increased by as much as 100%. The Babcock & Wilcox Company, which is a pioneer in boiler construction, produces intensified tubes for vertical tube waterwalls used in power-generating boilers. Their effectiveness at low mass flowrates and different pressures depends on the geometrical characteristics of the tube inner surface. Multiple-start spiral protrusions made on this surface allow the flow to be essentially turbulized and are indispensable for increasing critical heat fluxes due to achieving enhancement of heat-transfer processes and better wettability of the surface. However, pressure losses in such tubes are quite essential, and the method of producing them is rather costly. Tubes with multi-

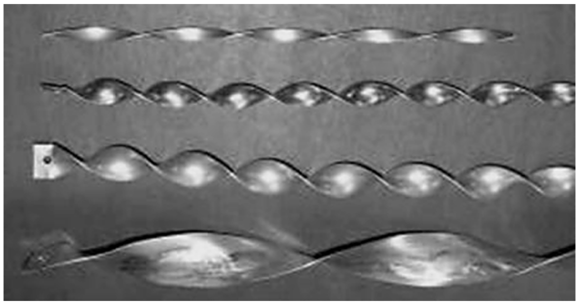


Fig. 12. Heat transfer intensifiers in the form of twisted tapes produced by Brown Fintube Company (the United States).

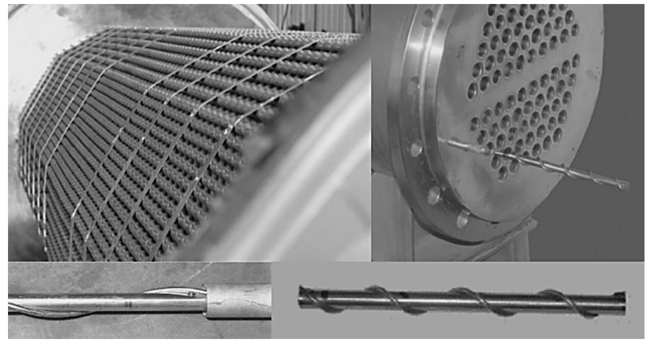


Fig. 13. Screw-type intensifiers and external wire winding on the tubes of heat exchangers produced by the Brown Fintube Company.

start spiral protrusions feature smaller pressure losses and are simpler to manufacture. However, turbulization in such tubes is insufficient for achieving the required enhancement of heat transfer. In addition, the occurrence of nucleate boiling burnout is not prevented during operation at high heat fluxes in boilers and with reduced average mass flowrate of water.

Specialists of Siemens AG (Germany), who used the results of previous work carried out by Babcock & Wilcox as a basis, optimized the characteristics of tubes with inner protrusions to achieve higher critical heat fluxes at low flowrates of water. It has been obtained from these works that increasing the height of protrusions and their twisting angle results in higher turbulization of flow in the near-wall region. An example of intensified tube for a power-generating boiler produced by the Foster Wheeler North America Co. (the United States) jointly with Siemens AG is shown in Fig. 10.

The advantages of intensified tubes are shown on the example of water evaporation modes in vertical, inclined, and horizontal waterwalls of steam boilers (Fig. 11). We see that boiling crisis (burnout) is accompanied by a sharp buildup of temperatures, due to which tubes can be burnt through or become thermally distorted. It should be noted that in horizontal and inclined tubes burnout on surfaces begins at different distances from the beginning of a tube, which aggravates its thermal distortion and can lead to a tube failure.

Application of intensified tubes in power-generating steam boilers makes it possible to achieve the required thermal power with essentially smaller flowrates of coolant (water) and, hence, with smaller power requirements for pumping. Intensified tubes with inner spiral indents are installed in power generating boilers produced by Mitsubishi Heavy Industries, Ltd. (Japan). It should be pointed out that the use of rifled tubes makes it possible to achieve smaller contamination of internal heat-transfer surfaces.

Tubes with inner spiral protrusions and grooves for power-generating boilers are commercially available from Eurotube GmbH (Germany), Suzhou Seamless Steel Tube Works (China), Shengde Seamless Steel Tube Co., Ltd. (China), Jiangsu Xuanli Group Co., Ltd., and others.

Twisted spiral tapes are most frequently used in the flame tubes of gas-tube boilers (Fig. 12). These tapes are one of the oldest types of means for enhancing heat transfer in tubes and were proposed and studied in works of J. Witam as far back as 1896.

Industrial boilers produced by Kalvis (Lithuania), Ferroli S.p.A. (Italy), TARM (the United States), ZAO Agroresurs (the Ukraine), and others are examples of such boilers. Enhancement of heat transfer in flame tubes produced by Olymp Werk Telfs GmbH (Austria) is achieved through the use of welded segments of tape twisted in opposite directions. The length of each segment corresponds to the twisting pitch.

A set of modern and efficient technical solutions has been implemented in a KV-3.0G hot-water gas-tube boiler produced by OAO GSKB (Belarus). Tubes with a three-zone heat transfer are used here. In the first (high-temperature) zone this tube has smooth surface, and the initial inlet part of this zone operates with minimal heat transfer. In the second zone (the zone of medium temperatures), the tube surface has a specially knurled (discretely roughened) part. A more than a factor of 2 higher coefficient of heat transfer as compared with the smooth tube is achieved here. In the third (low-temperature) zone, a spiral insert is used apart from knurling, due to which the total level of heat transfer enhancement enhanced by a factor of 3 or more. A stable level of heat loads is maintained over the entire tube length due to high heat transfer intensity.

Enhancement of heat transfer in flame tubes on the side of flue gases through the use of knurled turbulizers, tape, or spiral swirlers has been implemented in

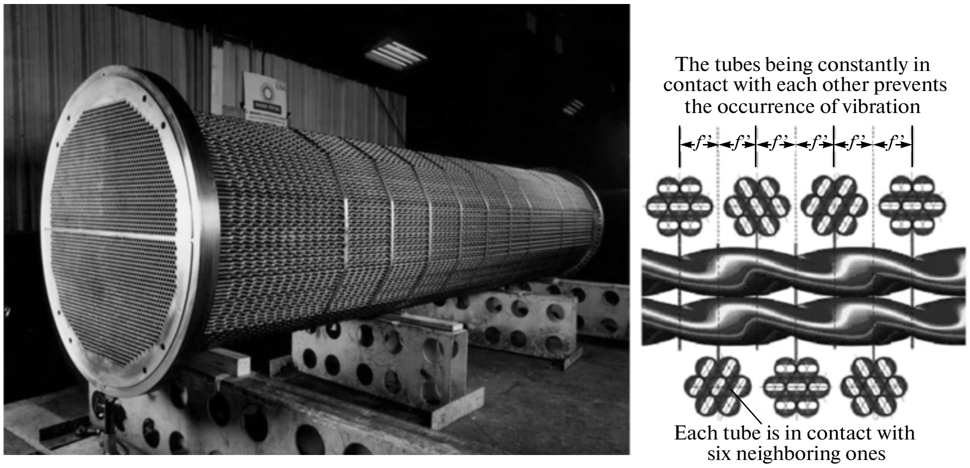


Fig. 14. Heat-transfer matrices of shell-and-tube heat exchangers equipped with twisted tubes produced by the Brown Fintube Company and the layout of adjacent tubes in a bundle of twisted tubes.

the designs of Type KSVa steel hot-water boilers produced by OOO PK Promkomm (Russia).

The Brown Fintube Company (the United States), which belongs to the Koch Heat Transfer group of companies (the United States), proposes to use tubes fitted with inner intensifiers made of twisted tapes in heat exchangers intended for heating, cooling, and condensation of working media.

Exact Exchanger Incorporated (the United States), Nitram Energy Inc. (the United States), and Energy Transfer MDE (the United States) specialize in producing air coolers and air oil coolers, tubular heat exchangers, and boilers with helically twisted tapes inserted over the entire length of the tubes.

Intensifiers in the form of spiral wire inserts in tubes are widely used in boiler units. Boilers produced by Fröling and Babcock Wanson are fitted with flame tubes in which spiral wire inserts are used as heat transfer intensifiers, and the hot-water boilers produced by Hurst Boiler & Welding Co., Inc. (the United States) are fitted with flame tubes having spiral protrusions on the inner surface.

The spiral wire inserts produced by Spirelf System (the United States) are intended for enhancing heat transfer in shell-and-tube heat exchangers serving as heaters and evaporators and operating at temperatures of up to 360°C with carrying liquids or two-phase flows. The use of inserts produced by Spirelf System allows up to an 80% enhancement of heat transfer to be achieved inside the tubes as a result of higher flow turbulization.

Flow swirling, which helps to enhance heat transfer in the smoke tubes of flame-tube boilers, can also be organized using screw inserts. Built-in screw-type heat transfer intensifiers made of stainless or heat-resistant steel are used in steam and hot-water boilers produced by LVAR (Italy), YGNIS (France), ICI Caldaie (Italy), Kaukora Oy (Finland), and others.

Screw-type intensifiers for heat exchangers are commercially available from Brown Fintube (the United States). In addition, it is proposed to wind wire on the external side of tubes used in constructing shell-and-tube heat exchangers (Fig. 13). Such a solution allows advantages typical for twisted tubes to be achieved: support partitions are no longer needed, the shell space is contaminated to a lesser extent, and more intense heat transfer is achieved in it.

The main advantage of intensifiers made in the form of twisted taped, screw inserts, and spiral wire inserts is that they are easy to install in and dismantle from heat-transfer channels if the latter have to be cleaned.

Brown Fintube produces shell-and-tube heat exchangers with twisted tubes (Fig. 14), which are widely used in power engineering applications as water–water heaters, machinery oil coolers, steam-

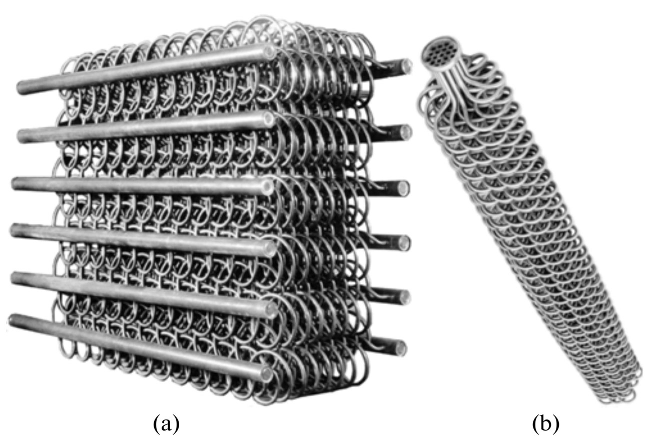


Fig. 15. Heat-transfer matrices made of interlaced coils for the heat-recovery boiler of GPA-Ts16 and GTK-10-4 gas turbine (a) and OV-03 heat exchanger (b).

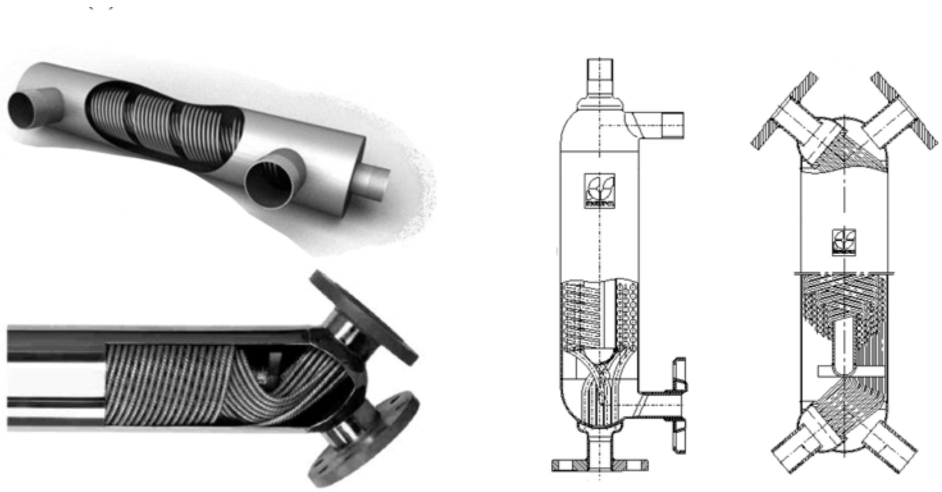
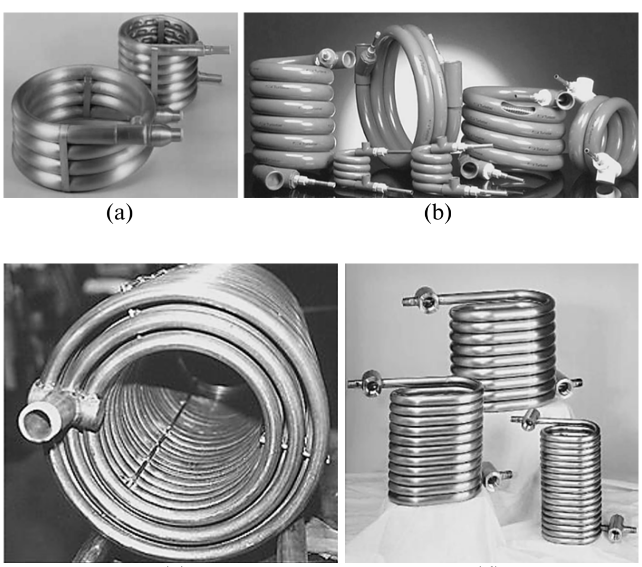


Fig. 16. Heat exchangers with spiral tubes produced by Sycespol Co. (Canada) and Heseco (Germany).

turbine condensers, and evaporators. The use of twisted tubes having ellipsoidal cross section makes it possible to do without partitions of their heat-transfer matrix, which are usually installed to reduce tube bundle vibration and organize cross flows of heat carriers. Each tube is supported by two adjacent tubes (see Fig. 14); at the same time, space for coolant flow is available over the entire tube length. Such a solution eliminates vibration of tubes, which is one of the main problems encountered during operation of heat exchangers. Flow swirling is induced by intense secondary currents in tubes and in the shell space and helps to considerably increase heat-transfer coefficients on both sides (even for flow of viscous liquids and/or at low velocities), thus helping to achieve higher thermal efficiency of the heat exchanger. A changeover for using twisted tubes makes it possible to save 20–50% of the heat-transfer area and, as a consequence, up to 20–30% of the heat exchanger net cost.



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

Fig. 17. Coaxial coil heat exchangers produced by Wieland-Werke AG (Germany) (a), Turbotec Products, Inc. (the United States) (b), JFD Tube & Coil Products (the United States) (c), and Exergy LLC (the United States) (d).

Coils. A heat-transfer device can be made more compact by twisting tubes around an axis. Flow swirling in a coil channel entails the occurrence of secondary currents, or Dyne vortices, which help to obtain heat-transfer coefficients during flow of single-phase coolants and boiling. According to the data available in the literature, the factor by which heat transfer in coils is enhanced may vary from 30% to a factor of 3 for flow of single-phase and boiling coolants depending on the coil geometry. The extent to which critical heat fluxes increase during flow of boiling coolants is 150–600%.

Coil tubes are widely used for reducing the overall dimensions of hot-water boilers operating on gas and solid fuel.

Coils with a small bending radius have found use in heat exchangers and heat-recovery boilers (Fig. 15) produced by OOO Anod–Heat-Transfer Center (Russia).

Such designs have the following main advantages:

(i) They feature high-efficient heat transfer both in the shell and tube spaces. In the first case, this is achieved by partially swirling the flow, and in the second case, owing to mass forces acting on heat carrier in the direction away from the coil wall, which give rise to secondary currents and enhance heat transfer).

(ii) With such designs, it becomes possible to optimize flow pass sections and, accordingly, coolant velocities, as a result of which the optimal (specified) thermal–hydraulic parameters are obtained for different media and operating conditions.

(iii) Heat-transfer elements can be united into intermediate modules (smaller-diameter tubes can be used).

(iv) A countercurrent media flow arrangement can be applied.

(v) Self-compensation of temperature expansions can be organized, due to which reliable operation is ensured during thermal cycling stresses, as well as during thermal and hydraulic shocks.

Such heat exchangers are commercially available from SEC Heat Exchangers (Canada). Vertical shell-and-tube HEs equipped with helically knurled coil tubes are produced jointly by Sycespol Co. (Canada) and Heseco (Germany) (Fig. 16).

Wieland-Werke AG (Germany), which manufactures tubes with means for outer and inner enhancement of heat transfer, also produces coil heat exchangers and elements on the basis of tubes with external and internal finning: condensers, coaxial heat exchangers-evaporators, etc. (Fig. 17a), and Turbotec Products Inc. (the United States) produces coaxial titanium heat exchangers on the basis of discretely roughened tubes (Fig. 17b). By using flow swirling and modifying the boundary layer, the required length of tubes in a heat exchanger can be reduced very considerably and its mass can be decreased by 40–50%. Similar tube-in-tube coil heat exchangers intended for use as condensers, water coolers and heaters, and evaporators are also offered by JFD Tube & Coil Products (the United States) (Fig. 17c) and Exergy LLC (the United States) (Fig. 17d).

Russian and foreign designers of small- and medium-capacity industrial and house-holding gas-tube boilers mandatorily furnish them with heat-transfer intensifiers (flow turbulizers). Thus, imported industrial hot-water boilers with a capacity of 0.01–12.0 MW equipped with different types of heat transfer intensifiers (flow turbulizers) supplied to the Russian market come from the following producers: Loos (Austria); ACV (Belgium); Buderus, Viessmann, Wolf, Standart-Kessel, and Omnical (Germany); Biasi, Feroli, Garioni Naval, Lamborgini, I.Var, ICI Caldae, Riello, Unical, and Roca (Italy); Daikon (Japan); Baxi, De Dietrich, and Ygnis (France); PT Grand Kartech (Indonesia); Vapor (Finland); Rendamax (Holland); Kiturami (Korea); Thermax (India); Erensan (Turkey); and Laars (the United States). There are also a number of Russian producers of boilers with heat transfer enhancement, of which the following ones are worthy of mention: OOO Teplov, OOO Remex, OOO Biiskenergomash, PG Generatsiya, OAO ZiOSAB, and some others.

Other types and methods of heat transfer enhancement. Among these, passive methods (implying the use of structured surfaces and admixtures for liquids and gases), as well as active and combined methods should be pointed out.

Structured surfaces are used for enhancing heat transfer during pool boiling of liquids. The roughness of such surfaces has almost no effect on heat transfer during forced convection of coolant. The following surfaces should be pointed out here: surfaces obtained by mechanical processing or grooved, molded, or low-finned ones; multilayer surfaces made of stamped or perforated coatings; surfaces with thin-wire winding or wire meshes incorporating nonwetting coatings and abrased surfaces or artificial surface porosity. The enhancement of boiling heat transfer on such surfaces can vary from 30% to a factor of 15.

By using solid additives to gas flows and gas additives to liquid flows, a 40–400% enhancement of heat transfer can be achieved, and critical heat fluxes can be increased by a factor of 2.5–3.5. Nanoparticles have recently been increasingly more frequently considered as additives to liquids and gases. Reviews of investigations in this area can be found in [15–17]. Use of liquids with additives of nanoparticles (nanoliquids) allows boiling heat transfer to be enhanced by 20–40% even with low concentration of these additives. Increasing the concentration of nanoparticles in liquid entails a drop of heat transfer by 10–30%. The increase of critical heat fluxes during boiling of nanoliquids makes 300–450%. Increasing the concentration of nanoparticles up to 4% causes heat transfer in single-phase flows to increase by 1–3%. The maximal increase of heat transfer by a factor of 3–4 was observed in laminar flows of water (NWCHT/H_2O). The maximal increase of heat transfer for turbulent flow of water reached 25–30% (Al_2O_3/H_2O).

Conditions arise in technical devices, including power-generating ones, during their operation that may lead to enhancement of heat transfer; such conditions are classified as active methods of enhancement. For example, rotation of surfaces causes the coefficient of heat transfer to increase up to 350%, and pulsation and vibration of surfaces may cause it to increase from 54% to a factor of 20. Critical heat fluxes during boiling on vibrating surfaces increase up to 10%, and so does heat transfer during condensation. Application of electromagnetic fields allows heat transfer to be increased up to 100%, and application of ultrasonic vibration allows heat transfer during free convection to be increased by 30–200% and that during boiling, by 50%.

According to A.E. Bergles, in the case of using complex methods, coefficients of heat-transfer can be increased due to the effect of each method for its enhancement.

A detailed analysis of methods for enhancement of heat transfer and examples of their industrial applications are given in [18, 19].

Thus, the presented review of practical methods for heat transfer enhancement in modern power-generating, industrial, and house-holding boilers and heat-transfer equipment testifies that they have received the widest development outside of Russia. In Russia, methods of heat transfer enhancement are used rather rarely except different types of fined surfaces. To improve the situation, efforts should be taken for making methods of heat transfer enhancement more popular on the basis of carrying out a further analysis of experience gained around the world, studying the feasibility of using heat transfer intensifiers in existing heat-transfer and power-generating equipment, and constructing new models of equipment with solutions for enhancing heat transfer laid down in the project.

In our opinion, ways for making the thermal power industry in Russia more efficient are seen in introducing domestically produced heat-transfer equipment and using a great number of results from scientific research works and experience gained from using heat transfer enhancement outside of Russia. In so doing, the main goals pursued by enhancement must be taken into consideration, namely, advanced increase of heat transfer as compared with the growth of pressure for ensuring energy efficiency (achieving higher efficiency) and/or efficient use of resources (minimizing mass and dimension characteristics and metal intensity) of heat-transfer equipment. The science of heat-transfer enhancement, in its turn, must be developed in the direction of working out designs of optimal intensifiers and development of breakthrough technologies for intensifying heat transfer from an analysis of the effect different types of intensifiers exert on the boundary layer.

REFERENCES

1. A. E. Bergles, V. Nirmalan, G. H. Jukhan, and R. L. Webb, *Bibliography of Augmentation of Convective Heat and Mass Transfer. Report HTL-31. ISU-ERI-Ames-84221* (Heat Transfer Laboratory, Iowa State University, Ia, Ames, 1983).

2. A. E. Bergles, M. K. Jensen, E. F. C. Somerscales, and R. M. Manglik, *Literary Review of Heat Transfer Enhancement Technology for Heat Exchanges in Gas-Fired Applications. Report GRI 91-0146.* (Gas Research Institute, Chicago, 1991).

3. A. E. Bergles, M. K. Jensen, and B. Shome, *Bibliography on Enhancement of Convective Heat and Mass Transfer. Report HTL-23* (Heat Transfer Laboratory, Rensselaer Polytechnic Institute, NY, Troy, 1995).

4. M. K. Jensen and B. Shome, *Literature Survey on Heat Transfer Enhancement Techniques in Refrigeration Applications. Report ORNL/Sub/91-SL794* (Oak Ridge National Laboratory, TN, Oak Ridge, 1994).

5. R. L. Webb, A. E. Bergles, and G. H. Junkhan, *Bibliography of U.S. Patents on Augmentation of Convective Heat and Mass Transfer. Report HTL-32. ISU-ERI-Ames-84257* (Iowa State University, Ia, Ames, 1983).

6. R. L. Webb, "Enhancement of Single-Phase Heat Transfer," in *Handbook of Single-Phase Convective Heat Transfer*, Ed. by S. Kalkas, R. K. Shah, and W. Aung (Wiley, New York, 1987), Chapt. 17.

7. D. P. Shatto and G. P. Peterson, "A Review of Flow Boiling Heat Transfer with Twisted Tape Inserts," J. Enhanced Heat Transfer **3** (4), 233 (1996).

8. A. E. Bergles, "Techniques to Enhance Heat Transfer," in *Handbook of Heat Transfer*, 3rd ed., Ed. by W. M Rohsenow, J. P. Hartnett, and Y. I. Cho (McGraw-Hill, New York, 1998), Chapt. 11.

9. *Heat Transfer Enhancement of Heat Exchangers*, Ed. by S. Kakac, A. E. Bergles, F. Mayinger, and H. Yuncii, (Kluwer Academic, 1999).

10. R. M. Manglik and A. E. Bergles, "Swirl Flow Heat Transfer and Pressure Drop with Twisted-Tape Inserts," Advances in Heat Transfer **36**, 183 (2002).

11. J. R. Thome, *Enhanced Boiling Heat Transfer* (Hemisphere Publishing, New York, 1990).

12. R. L. Webb, *Principles of Enhanced Heat Transfer* (Wiley, New York, 1994).

13. R. M. Manglik and A. D. Kraus, *Process, Enhanced, and Multiple Heat Transfer* (Begell House, New York, 1996).

14. Yu. F. Gortyshov, I. A. Popov, V. V. Olimpiev, et al., "Thermal–Hydraulic Effectiveness of Prospective Methods for Enhancing Heat Transfer in Channels of Heat-Transfer Equipment," in *Enhancement of Heat Transfer*, Ed. by Yu. F. Gortyshov (Center for Innovation Technologies, Kazan, 2009) [in Russian].

15. V. I. Terekhov, S. V. Kalinina, and V. V. Lemanov, "The Mechanism of Heat Transfer in Nanoliquids: The Modern State of the Problem (a Review), Part 2: Convective Heat Transfer," Teplofiz. Aeromech. **17** (2), 173 (2010).

16. V. I. Terekhov, S. V. Kalinina, and V. V. Lemanov, "The Mechanism of Heat Transfer in Nanoliquids: The Modern State of the Problem (a Review), Part 1: Synthesis of Nanoliquids and Their Properties," Teplofiz. Aeromech. **17** (1), 1 (2010).

17. Yu. A. Kuzma-Kichta, A. V. Lavrikov, and D. F. Tsurikov, "Boiling of Nanoliquids," in *Proceedings of the Internal Conference "Heat Tubes for Space Applications, FGUP Lavochkin NPO, Moscow, 2009.*

18. I. A. Popov, Kh. M. Makhyanov, and V. M. Gureev, "Physical Principles and Industrial Application of Heat Transfer Enhancement," in *Enhancement of Heat Transfer,* Ed. by Yu. F. Gortyshov (Center for Innovation Technologies, Kazan, 2009) [in Russian].

19. B. V. Dzyubenko, Yu. A. Kuzma-Kichta, A. I. Leont'ev, et al., *Enhancement of Heat and Mass Transfer on Macro-, Micro-, and Nanoscales* (FGUP TsNIIAtominform, Moscow, 2008) [in Russian].