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INTENSIFICATION OF HEAT AND MASS TRANSFER ON MACRO-, MICRO-, AND NANOSCALES

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The results of theoretical and experimental investigations of heat and mass transfer enhancement on macro-, micro-, and nanoscales in single- and two-phase media, of phase interface vibrations, and of the separation of heterogeneous systems are presented. The research works carried out with the aim of increasing the safety and efficiency of power plants made it possible to develop new methods of heat and mass transfer intensification, formulate new research trends, to create new apparatuses, mathematical models of processes and the engineering methods of their calculations. Propulsion systems of spacecrafts for a piloted mission to Mars and the related methods of heat transfer intensification, the methods of calculation of heat and mass transfer under the conditions of scaling of twisted pipes and pipes with circular diaphragms, and the calculation of the hydrodynamics of multiphase heterogeneous media in a centrifugal field are considered additionally, as well as the results of investigation into the influence of the roughened surface on heat transfer in boiling on a sphere and correlations of the data on the influence of tape twisting on the critical heat loading are presented. The results of comparing the characteristics of tubular and plate-type heat exchangers with heat transfer intensifiers, characteristics of heat transfer apparatuses with twisted tubes, as well as investigations of heat and mass transfer in condensation of steam from escaping flue gases of boilers are given. The book is intended for specialists involved in the development of power plants.

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INTRODUCTION

By the early 21st century, the methods of heat and mass transfer intensification have already been widely applied in the elements of power equipment.

The most popular methods of intensification of heat and mass transfer in the presence of convection are the use of the entry section effect, artificial flow agitation in the wall layer or over the entire flow section by circular or spiral grooves, dimples, finned surfaces, twisted tapes, screws, and coiled pipes [1–8], jet impingement of a heat carrier on a surface, porous and brush inserts [9–13], flow rate fluctuations [14], effect of ultrasonic vibrations [15] and of an electric field [16]. The influence of wall intensifiers of heat removal on laminar-flow heat transfer was investigated in [17].

To intensify heat transfer in boiling, extensive use is made of porous coatings [18–21], since the methods of artificial flow agitation are less efficient here.

The enhancement of heat transfer in condensation is achieved by creating drop condensation, whereas in the case of film condensation, knurling, finning, and alteration of the slope of the surface are employed to enhance heat transfer [22].

Combined methods of heat transfer intensification are based on the use of at least two methods of increasing the heat removal intensity. For example,

- the use of artificial roughness of the surface and of a twisted tape;
- the use of a helical pipe and of porous coating;
- the use of circular knurling and flow twisting in helical pipes.

The enhancement of heat and mass transfer makes it possible to considerably improve the equipment characteristics. For example, heat transfer enhancement in rod bundles with intensifiers-swirlers favored the increase in the boiling-type reactor power. In [23], it is suggested to combine the functions of the spacer grid with the heat transfer intensifier. The axial twisting grids-intensifiers developed and investigated on full-scale rigs were integrated into the first and second blocks of the Ignalina Atomic Power Station. Incorporation of grids-intensifiers into the structure of fuel assemblies made it possible to increase the power of each energy block by a factor of 1.5.

The problems encountered in separation of heterogeneous systems are considered in [24, 25].

Authoritative scientific-industrial centers of specialists in thermophysics and chemical hydrodynamics, who made a noticeable contribution to the outstanding achievements in our country in the above-listed fields, were established in Russia. Among such centers there are the Federal State Unitary Enterprise "Scientific-Research Institute of the Scientific-Production Association "Luch" (Podolsk), Institute of the Problems of Chemical Physics of the Russian Academy of Sciences (Chernogolovka), technical universities "Moscow Aviation Institute," "Moscow Power Engineering Institute," and N. E. Bauman Moscow State Technical University. These are the specialists from these institutions who authored the present publication.

The authors presented the results of the well-known and of their own theoretical and experimental investigations of heat and mass transfer intensification in single- and two-phase media, of phase interface oscillations, and of separation of heterogeneous systems. These investigations were carried out to raise the safety and efficiency of power plants. The investigations carried out made it possible to develop new methods of heat and mass transfer intensification, form new scientific trends, and create new apparatuses of hydrocyclone type, mathematical models of the processes, and engineering methods of their calculation.

This new edition contains the survey of investigations in the field of heat and mass transfer intensification on the macro-, micro-, and nanoscales. The available investigations into heat transfer and hydrodynamics of dimpled surfaces, modeling and visualization of the tornado-like intensification of heat transfer in a channel with hemispherical dimples, modernization of the heat exchangers by using coiled pipes for heat supply are considered in detail.

Consideration is given to the well-known notions on the thermohydrodynamics on the micro- and nanoscales: heat transfer in condensation on macro- and microrough surfaces, heat transfer with boiling on surfaces with porous coatings and protrusions that form a homogeneous relief, heat transfer in the presence of convection in microchannels, the appearance of slipping on the wall in liquid flow over an ultrahydrophobic surface, the influence of molecular layers of surfactants formed on surfaces on the hydraulic resistance of pipelines.

The methods of calculation of heat and mass transfer under the conditions of salt depositions during flow in twisted pipes and in pipes with circular diaphragms, the calculation of the hydrodynamics of multiphase heterogeneous media in a centrifugal field were analyzed, and the results of investigation of the dimpled surface on heat transfer in boiling on a sphere, and of the correlation of data on the influence of a twisted tape on the critical heat loading are presented.

The power plants of spacecrafts for a piloted mission to Mars and the heat transfer intensification methods used in them are considered.

The characteristics of tubular and plate-type heat exchangers with heat transfer intensifiers are analyzed. The results of investigation of heat and mass transfer intensification in condensation of steam from the flue gases of boilers are presented.

The first edition of this book was highly praised by A. M. Prokhorov, Academician of the Russian Academy of Sciences, Nobel Prize Winner; G. G. Devyatykh, Academician of the Russian Academy of Sciences, and G. A. Filippov, Academician of the Russian Academy of Sciences. Academician A. M. Prokhorov noted that the monograph gives an encyclopedic review of the methods of heat and mass transfer intensification on different scales in single- and two-phase media in the elements of power equipment. It describes unique thermophysical and experimental rigs, unconventional detectors, and experimental techniques (developed by the authors) that allow one to carry out, at a high scientific level, thermophysical investigations not only under laboratory conditions but also on pilot plant specimens under full-scale conditions of operation of reactors, electrophysical and laser facilities.

The investigations carried out were aimed at solving the following problems:

- reliable cooling at high heat loadings (1 kW/cm^2 and above) and "delay" in the onset of burnout heat transfer in boiling of a heat carrier in energy-intensive structures;
- thermostating and minimization of thermal deformation of high-heat structures with intensive and nonuniform energy release;
- organization of highly efficient heat transfer processes with the aid of liquid metals;
- creation and testing of the constructions of various heat and mass transfer intensifiers in gaseous and liquid heat carrier flows and in melting of heat accumulating phases;
- a detailed study of the structure of turbulent flows in smooth and rough channels and porous media having different structures;
- development of theoretical models and generalizing dimensionless relations to calculate and predict the heat and mass transfer intensity;
- development and testing of power plants with heat and mass transfer intensifiers;
- conceptual design of prospective power plants with enhanced heat and mass transfer processes;
- raising the efficiency of separation of heterogeneous systems in heat and mass transfer apparatuses.

Due to the close cooperation with leading academic and industrial scientific centers, the method of heat and mass transfer intensification developed by the authors have been introduced into various power plants. This has made it possible to ensure their mass-dimensional and specific parameters, as well as the safety and efficiency at the level of the best world specimens. In particular, the results of the authors' research works were used in designing and creating such unique power plants as gas-cooled nuclear reactors with twisted fuel elements made from refractory metal carbides, liquid metal-cooled thermoemissive nuclear reactor-converters that were tested in space, targets and resonators for accelerating installations, cooled mirrors for high-power laser complexes and infrared radiation detectors, highly efficient hydrocyclones for the chemical, mining, and metallurgical industries, different-purpose compact heat exchangers, evaporators for water desalination, absorption and compression refrigerators, liquid coolers, conditioners, etc. The authors have also made a great contribution to the development of home conceptual designs of inertial thermonuclear reactors with a jet liquid-metal blanket and reactors-lasers with a film nuclear fuel.

The present monograph is a revised and augmented edition of the book "Heat Transfer Enhancement in Power Engineering" published in 2003 [26].

In the present edition, the sections prepared by A. M. Kutepov, I. P. Sviridenko, and V. V. Kharitonov for the first edition have been preserved.

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CHAPTER 1

CHOICE AND JUSTIFICATION OF THE HEAT TRANSFER INTENSIFICATION METHODS

1.1. Macro-, Micro-, and Nanoscale Heat Transfer Intensifiers

1.1.1. *Macroscale Heat Transfer Intensifiers in the Presence of Convection*

The widespread methods of heat transfer intensification in channels with a single-phase heat carrier include artificial turbulization of flow with the aid of annular or spiral grooves, surface finning, coiled or twisted pipes, screw conveyers, twisted tapes [1.1.1–1.1.14], organization of heat transfer in entry sections, and jet impingement of a heat carrier onto the surface [1.1.6].

The efficiency of heat transfer in single-phase media flow is influenced by the flow rate fluctuations; in the case of resonance with the circuit fluctuations, the heat transfer coefficient increases [1.1.7].

Surface with a Regular Roughness

The surface roughness is the deviation of the real surface relief from an ideally smooth one. The height of these deviations can be commensurable with the thickness of the viscous sublayer and of the intermediate layer. Therefore the effect of the surface roughness is concentrated in a relatively narrow wall layer and does not lead to the origination of secondary flows that would involve the entire flow, which is typical of spiral fins, twisted tapes, or screw conveyers.

The surface roughness is characterized by the height and shape of its elements, their number density (their number per unit surface), and mutual arrangement. The flow structure and heat transfer near a rough surface depend on a large number of factors.

The flow in pipes with the roughness formed by densely spaced identical elements — sand grain glued to the pipe surface — was investigated by D. Nikuradze. In this case, the roughness is characterized by a single quantity — the height of the sand roughness element k. Resistance and heat transfer depend only on one additional parameter — the relative roughness k/r.

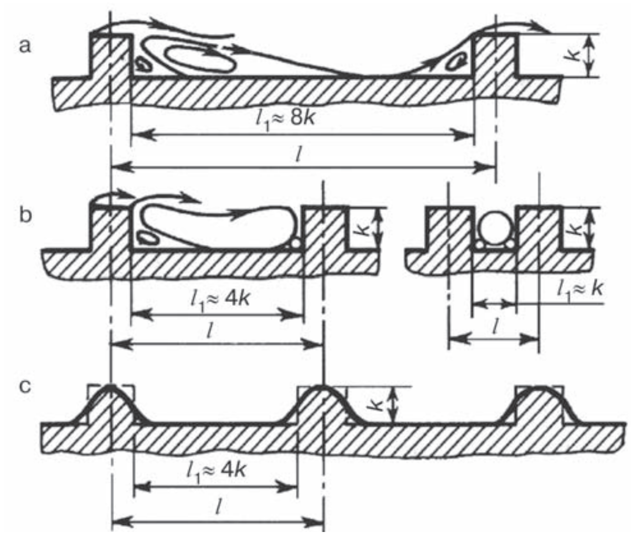

Fig. 1.1. Protrusions with rectangular (a, b) and smooth equally spaced (c) profiles

The height of the roughness element can also be represented in another dimensionless form, using the same length scale (y) as in the universal coordinate $\eta = (V^* y/\nu)$, i.e., the quantity ν/V^*.

Then, the dimensionless height of the sand roughness element takes the form

$$K = V^* k \big/ \nu = \frac{k}{d}\,\mathrm{Re}\,\sqrt{\xi/8} \tag{1.1.1}$$

and it is conveniently compared with such characteristic quantities as the dimensionless thickness of a viscous sublayer $(\delta V^*/\nu) = 5$ or of an intermediate layer $(\delta V^*/\nu) = 30$, where δ is the boundary layer thickness, V^* is the dynamic velocity, and ν is the kinematic viscosity of a liquid.

Heat transfer in a rough pipe can be both higher and lower than in a smooth one. This is determined by the shape, height, and mutual arrangement of the roughness elements and by the Re and Pr numbers.

Protrusions with rectangular and smooth equally spaced profiles are shown in Fig. 1.1.

The roughness with rectangular protrusions is characterized by the height of its elements k, pitch l, and by the width of the trough l_1. The figure illustrates the pattern of flow along a wall with rectangular elements. As a result of flow separation behind an asperity, a vortex zone appears, whose extension to the reattachment point amounts to about $8k$ (see Fig. 1.1a). Downstream this zone, the velocity field analogous to that in a smooth pipe is formed. Before the next asperity, a small vortex region of length $(1–2)k$ is also formed. If the distance between the asperities is equal to about $4k$, the vortex zone occupies the entire trough (see Fig. 1.1b). The separation of flow on the roughness protrusions leads to the enhancement of turbulent transfer near the upper boundary of the vortex zone and in the vicinity of the reattachment point. As a result, heat transfer in these zones is improved. The stagnant zones in the troughs lead to a decrease in the heat transfer rate, sometimes to a level lower than in smooth pipes.

Thus, along the length of a trough the heat transfer rate is distributed nonuniformly. It is lower in the stagnant zones, maximum near the reattachment point, whereas far from the protrusion, where the influence of the vortex zone becomes weaker, it decreases again. The length of the trough corresponding to the maximum of the heat transfer rate average over the surface amounts to (10–12)k.

The efficient height of the roughness element is commensurable with the wall layer thickness in which most of the thermal resistance is concentrated and which depends on the Pr number. Thus, at Pr numbers equal to 1, 5, and 50 the relative roughness height k^* is equal to 250, 50, and 10, respectively.

With efficient characteristics of the artificial roughness the heat transfer coefficient can be increased two or three times. However, it is important that the increase in the heat transfer rate could be accompanied by a not very large increase in hydraulic resistance. Therefore, the elements of two-dimensional roughness with sharp edges are not efficient. Powerful vortex zones appearing behind them and the high resistance of the shape lead to high energy losses. More suitable are the roughness elements with smooth outlines (see Fig. 1.1c) displaying lower energy losses. In pipes with smoothly outlined roughness protrusions at the optimum ratio l/k, an increase in the heat transfer rate is accompanied by a smaller increase in the hydraulic resistance than in the case of the roughness with sharp edges.

In the case of a large enough relative roughness, a certain contribution to the increase in the heat transfer rate is made by the "finning effect," i.e., an increase in the surface area of the rough wall as compared to the smooth one, provided, of course, that the roughness elements have a good thermal contact with the wall. In the case of the so-called applied roughness, for example, a wire located near the wall and not soldered to it, the "finning" effect is absent.

There are empirical and semi-empirical relations for calculating the heat transfer rate in rough pipes. The semi-empirical relations are based on two-, three-, and even four-layer models of flow along a rough wall. For each layer, empirical relations for the coefficient of turbulent transfer are adjusted.

To calculate heat transfer in pipes with natural and artificial uniform roughness, whose elements have different shapes (wires, spheres, pyramids, cylinders, etc.) and are closely spaced, so that the flow between them is determined by their dimensions and shape, the following equation was suggested in [1.1.8]:

$$\mathrm{Nu} = \frac{\sqrt{\xi/8}\ \ \mathrm{RePr}}{2.12\ \ln\left(r/k\right) + 0.55(\mathrm{Pr}^{2/3} - 0.2)(K)^{1/2} + 10 - \dfrac{3.2}{(1 - k/r)^2} + 6.6\sqrt{\xi/8}}\ , \tag{1.1.2}$$

where Nu = $\alpha d/\lambda$ and α is the heat transfer coefficient related to the surface of a smooth pipe of diameter $d = 2r$ measured in a trough.

The resistance coefficient for the sand roughness is defined by D. Nikuradze formula. The height of the sand roughness equivalent to the assigned actual roughness is found from tables or experimentally. Equation (1.1.2) is valid for $100 \le K \le 4000$, i.e., for the regime with complete manifestation of roughness at rather high Re numbers in the ranges of k/r from 0.005 to 0.18 and Pr numbers from 0.7 to 9. For the indicated conditions, independently of the shape of roughness elements, the deviation of the measured Nu numbers from the predicted ones does not exceed 10%. Although the equation was derived for the boundary condition of the first kind, it can also be used for the boundary condition of the second kind.

1.1.2. *Hydrodynamics and Heat Transfer in Helically Profiled Pipes*

A helically profiled pipe represents a pipe, with a rectilinear axis, on the walls of which helical protrusions are made. The screw knurling can have a different number of starts. Figure 1.2 shows a pipe with two-start knurling. Inside the pipe with a helical groove, an asperity twisting a flow is formed.

As a result of the heat carrier twisting, the thermal resistance to convective heat transfer through a boundary layer decreases. Due to this, heat transfer is intensified, but simultaneously the hydraulic resistance increases. Helically profiled pipes in heat exchangers transfer much more heat than circular smooth pipes. Such pipes make it possible to create self-cleaning heat-transfer surfaces and to sustain the heat transfer coefficient constant.

Figure 1.3 presents the image of velocity fields which was obtained in [1.1.9].

The velocity field was reproduced from measurements taken at 78 points of the outlet section of a helically profiled pipe. The pitch of the two-start screw knurling in the pipe is 640 mm, the radius of the protrusion (for the inner surface of the pipe) is 10 mm. The length of the test section of the pipe is 4817 mm. The velocity field was measured at an average flow velocity of 22.2 m/s, which corresponds to the Reyn-

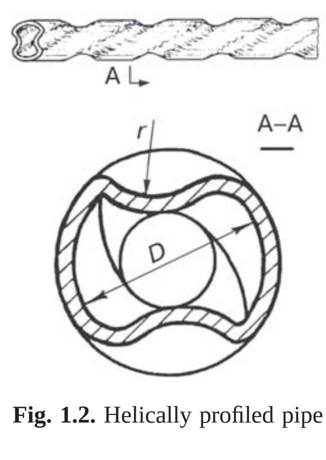

Fig. 1.2. Helically profiled pipe

NOMENCLATURE

C_p	pressure and friction related to double velocity head
D	diameter of a depression, m
f	frequency of volumetric fluctuations downstream of a depression, s^{-1}
H	channel height
h	depth of a depression, m
L	length of cylindrical insert
Nu	Nusselt number
Pr	Prandtl number
r	radius of edge rounding
Re	Reynolds number
Re_D	Reynolds number for a depression, $V_\infty D/\nu$
Re_{x0}	Reynolds number upstream of a depression, $V_\infty x_0/\nu$
Sh	Strouhal number, fD/V_∞
S_x	pitch between depressions in longitudinal direction, m
S_z	pitch between depressions in transverse direction, m
Tu	intensity of pulsations, %
V_∞	flow velocity upstream of the test section, m/s
x	distance from the forward edge of the plate, longitudinal coordinate, m

Greek symbols

γ	number density of dimples
δ	boundary-layer thickness, m
Δ	depth of a dimple
ν	kinematic viscosity of a flow, m^2/s
ξ	coefficient of hydraulic losses
φ	angle of inclination of a trench-like depression

Subscripts

0	flow parameters upstream of a depression
00	flow parameters on a plane plate
pl	plane, plate

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1.2. Flow Twisting in Pipes and Bundles of Fuel Elements and Pipes

1.2.1. *Heat Transfer Intensification with the Aid of a Twisted Tape*

In twisting a flow by a tape, in the cross section there occur overflows from the periphery to the center due to the pressure gradient (Fig. 1.73). The liquid from the boundary layer penetrates (shown by arrows) into the flow core. These motions lead to the appearance of four vortex regions that favor the enhancement of exchange and, together with the action of the centrifugal forces, decrease the boundary-layer thickness. Moreover, vortex mixing leads to the onset of a turbulent flow at smaller Re numbers.

Thus, the increase in the heat transfer rate on flow twisting with the aid of a tape is attributed to the following:

- the increase in the wall velocity;
- the flow rearrangement and the appearance of secondary flows and vortices;
- the increase in the flow turbulence.

The flow can also be twisted with the aid of wall swirlers. In using plate spiral swirlers, turbulence in the wall layer increases due to the flow twisting and detachment. The optimum dimensions of plate swirlers are: l/d = 3.5–4, h/d = 0.2.

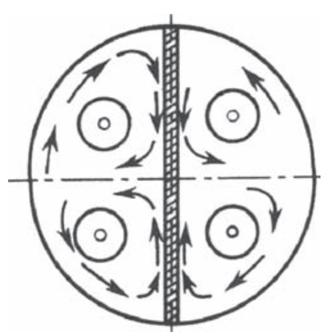

Fig. 1.73. Scheme of formation of secondary flows in a pipe with a twisted tape