EFFICIENT SURFACES for HEAT EXCHANGERS
Fundamentals and Design

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EFFICIENT SURFACES FOR HEAT EXCHANGERS

Methods for the design of efficient heat transfer surfaces for single phase flows, boiling, condensation, and radiation are considered. The results of experimental and analytical studies of the enhancement of heat transfer and the effects of the macro- and microstructure of surfaces on the mechanism and characteristics of heat transfer are systematized. The concept of a real phase interface—a transition surface region—is introduced. Methods of enhancement of heat transfer in different channels of heat exchangers in one- and two-phase coolant flows are considered. Practical recommendations for the choice of methods for heat transfer enhancement, calculations of heat transfer, and hydraulic losses are given.

The book is intended for researchers and engineers involved in the design, production, and testing of heat exchangers in various branches of industry and technology. The volume may be useful for students of thermal engineering, mechanical engineering and thermophysics.

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PREFACE BY THE ENGLISH EDITION EDITORS

Worldwide recognition of the Soviet Union's scientific prowess came in the early 1950's with the discovery of the great progress and achievements of their scientists and engineers, as evidenced by the Russian scholarly literature that had remained almost totally obscured to the West until that time. This realization of important academic and applied strides led to a flurry of translated Russian books and jouma1s. In the field of heat transfer, the heretofore unknown names linked to fundamental research in the thermal sciences began to appear in the translated literature and, in ever-increasing numbers, in Western citations giving rise to the recognition of the high level of Soviet heat transfer.

As in all branches of science and engineering, the tradition associated with a given institution of learning is of great importance to the prestige of the staff itself, both within and outside the walls of the academy, university, institute or laboratory, be they of the fundamental or applied ilk.

The well known authors of this book, E.K. Kalinin, G. A. Dreitser, I.Z. Kopp, and A.S. Myakochin, represented, respectively, the following well known and respected institutions: Moscow Aviation Institute (Technical University), St. Peters- burg State Technical University (former Leningrad Polytechnical Institute), with some of the authors having found their homes today in the United States.

The contacts between the Soviet, post-Soviet Russian and Western heat transfer engineers have been growing and increasing over the years and in 1999, one of us, Arthur Bergles, attended the International Conference on Compact Heat Exchangers and Enhancement Technology for the Process Industry in Banff, Canada (the proceeding of which were published by the other one, Bill Begell). We met with one of his Russian colleagues, Prof. Dreitser who showed him the Russian copy of this book. The conversation turned to the value of the information contained in the monograph and, in a couple of years later, following a great effort in translating, trimming, and editing the work, the present book is being made available to the English-speaking heat transfer engineering community.

There is much good and useful material in this book. It will be valuable for the Western researchers and designers to have the perspective of leading Russian specialists. We found the translation by N. K. Shveyeva to be excellent, and more than the usual care has been taken with clarifying the text and correcting the proof.

We found that while the text contains some extra background material, there is a good deal of useful and original research and results that can be "mined" from the book by engineers involved with the design and research of Efficient Surfaces for Heat Exchangers.

Now the Table of Contents thoroughly reflects the completeness of the coverage found in this monograph.

We are pleased to present the book to heat transfer engineers with the understanding that we have endeavored to eliminate, in this presentation, many of the walls that are always present in trying to breach the language barrier and overcome he difference in approaches to basic research and applied design that exist between the cultures, philosophies, and methods on both sides of the ocean and beyond the Urals.

We believe that we have been, at least partially, successful in minimizing the distance between the these geographies.

Arthur Bergles

Bill Begell

September, 2001

FOREWORD TO THE ENGLISH EDITION

Heat exchangers are the inalienable important units in the majority of complex engineering systems. The specification of requirements for heat transfer surfaces is one of the most significant stages of heat exchanger design. The influence of properties and structure of the surface on the mechanism and efficiency of heat transfer from the solid surface to a liquid or from a liquid to the surface (the most widely used heat transfer systems in heat exchangers) exert a decisive effect on all the stages of the heat transfer. However, the development of a theory describing the laws governing the effect of the surface, and the development of engineering methods for the design of heat exchangers has required a considerable effort.

The analysis and correlation of the results of studies of heat transfer, in which the effects of the surface were considered directly or indirectly and which were conducted by the present authors and researchers in other laboratories in different countries, led off the authors to write the present book devoted to this urgent problem. This monograph was originally published by Energoatomizdat in Moscow in 1999.

The authors are convinced of the usefulness of the detailed and systematically presented results of these studies under various conditions of one- and two-phase flows. Specialists in heat exchange equipment design which is widely used in many branches of modern technology will be interested in this text.

The timeliness of the publication of the first monograph ever concerned with the effect of the surface on heat transfer in English has been coordinated by the authors with the Heat Exchanger Design Handbook (HEDH) published by Begell House Publishers, Inc. Separate aspects of the effect of the surface are directly or indirectly touched upon virtually in all chapters of the five volumes of HEDH. In our opinion, the publication of Efficient Surfaces for Heat Exchangers in the context of the development of the correlations governing heat and mass transfer processes is a logical development of the ideas of HEDH toward comprehensive scientific substantiation and optimization of design-structural and technical-economical solutions. The presented results are especially topical for heat exchanging equipment in the new, highly technological and science-oriented branches of technology.

Following the recommendations of the Editors, the authors have made certain alterations and amendments to the English edition of the book.

The authors express their sincere gratitude to Professor Arthur E. Bergles and William F. Begell for their attention to the work, consideration of scientific and practical significance of the topics covered in the book and willingness to undertake the editing and publication of the book, thus making the results of our extensive studies widely available.

On behalf of the authors

I.Z. Kopp

New York - St. Petersburg, September 2001

PREFACE TO THE FIRST RUSSIAN EDITION

Heat exchangers and other thermal equipment are widely used in different branches of technology: power engineering, chemical, petroleum refining and food processing industries, refrigerating and cryogenic technology, heat engines, transport, aviation and space technology.

One of the promising ways of developing efficient compact heat exchangers is the use of highly efficient heat transfer surfaces and modern methods of heat transfer enhancement in flow channels. Therefore, a good selection of highly efficient heat transfer surfaces is one of the most urgent problems.

The number of publications dealing with heat transfer enhancement is constantly growing. However, results of these studies are often contradictory, the suggested methods of enhancement are not always effective or adaptable to streamlined production. In many cases the choice of the method of enhancement is not substantiated and has a random character.

This explains the slow adaptation of highly efficient heat transfer surfaces which undoubtedly leads to large economic losses and impedes the improvement of products and reduction in the use of metal in their construction.

The authors hope that this book will not only help engineers to reliably select effective heat transfer surfaces in heat exchangers and devices, but also makes it possible to calculate the heat transfer and hydraulic resistance when effective methods of heat transfer enhancement are used.

The present book differs from those published earlier since main attention is here paid to a detailed physical analysis of thermal and hydrodynamic processes occurring in the interaction between coolants and heat transfer surfaces within the framework of the suggested models and to the validation of the choice of most efficient heat transfer surfaces for existing heat exchangers.

The book is the result of systematized analytical and experimental studies in these fields, conducted by the authors over many years. The results of the study of the effect of the entire set of surface properties in heat and mass transfer are considered using the laws governing the heat exchange of surfaces of real solid bodies with gases, liquids, and multiphase flows, as well as modern concepts of macro- and microstructure of heat transfer surfaces. The problems of optimization of heat transfer surfaces with convective flows, vapor generators and converters of solar radiation are considered systematically. Special attention is paid to the studies of heat transfer surfaces to ensure high densities of heat fluxes at high velocities and low pressures and for new types of coolants as well as other urgent problems in the development of new technologies.

The book is intended for scientists and engineers who are involved in the study and design of heat exchangers and other thermal equipment in various fields of technology (power engineering, machine construction, cryogenic and refrigerating technology, transportation, etc.) and various branches of industry and also for teachers, post-graduate students, and students graduating from polytechnical universities.

The authors will be grateful for any comments and wishes directed to the improvement and comprehension of the problems considered in the book.

The authors

Moscow – St. Petersburg, 1999

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6. METHODS OF CALCULATION AND DESIGN OF EFFICIENT HEAT TRANSFER SURFACES

Nomenclature

a	thermal diffusivity
A	area; flow area; absorptivity (radiation)
b	coefficient of heat absorption
c	heat capacity; concentration
C	resistance coefficient
d	diameter
D	diffusion coefficient; diameter
E	radiation flux; energy
f	frequency; specific area
F	force; area; Helmholtz function $(U - T_s)$
g	acceleration of gravity
h	depth; enthalpy $(U + pV)$
H	height
i	specific intensity
I	intensity of radiation
j	intensity of mass flow
J	mass flow
k	heat transfer coefficient
K	coefficient
l	length; mixing length
L	magnetic of a molecular mean-free path; length
m	mass; mass transfer coefficient
M	molar mass; mass
N	molar flow rate; number
p	pressure
P	power
q	intensity of heat flux
Q	heat flux; quantity of heat; heat rate
r	radius; heat of phase change
R	gas constant; radius
s	specific entropy
S	entropy
t	temperature, ^{o}C $(T - 273.16$ K$)$
T	absolute temperature

u	specific internal energy
U	internal energy
v	specific volume
V	volume
W	work; rate (power)
x	mass void fraction
x, X, y, Y, z, Z	coordinates
z	height
Z	compressibility factor (pv/RT).

Greek symbols

α	heat transfer coefficient; angle
β	coefficient of thermal expansion $(1/\nu)(dv/dt)$
γ	specific heat capacity ratio; angle
δ	diffusivity; thickness
Δ	increment or difference
ε	emissivity (radiation)
η	viscosity
λ	thermal conductivity
μ	coefficient
ν	frequency (radiation); kinematic viscosity (h/r)
θ	dimensionless temperature
ρ	density
σ	surface tension
τ	time.

Dimensionless numbers

Ar	Archimedes number
Bi	Biot number
Ec	Eckert number
Eu	Euler number
Fo	Fourier number
Fr	Froude number
Gr	Grashof number
Ja	Jacob number
Kn	Knudsen number

M	Mach number
Nu	Nusselt number
Pe	Peclet number
Ph	phase change number
Pr	Prandtl number
Re	Reynolds number
St	Stanton number
Sh	Strouhal number
We	Weber number.

Subscripts

abs	absorption, absorbed
ace	acetone
act	actual
activ	activation
active	active
ad	adiabatic
adh	adhesion, adhesive
ads	adsorption
air	air
ash	ash
ash p	ash particle
att	attenuation
ave	averaged
base	base
b.c.	bundle center
boil	boiling
bub	bubble
c	cold
calc	calculated
cap	capillary
cav	cavity
c.ch	combustion chamber
coat	coating
coh	cohesion, cohesive
coke	coke
col	collapse

column	column
con	condensation, condenser, condensate
cont	contact
conv	convection, convective
cor	correlated
corr	corrugated
c.p	combustion product
cr	critical
crest	crest
cyc	cyclic
d	droplet
dep	departure
diff	diffusion
dist	disturbance
dust	dust
dyn	dynamic
e	equivalent
eff	effective
el	electric
env	environment
eq	equilibrium
ev	evaporation
expect	expectation
f	fin
fall	falling
film	film
fl	flow
free	free
furn	furnace
G	gas
gap	gap
gasol	gasoline
gr	growth
h	hot, heated
h.sph	hemisphere, hemispherical
id	ideal
in	inner
ind.f	individual fin
inj	injected

inl	inlet
int.gap	intercontact gap
kin	kinetic
knurl	knurling
L	liquid
lin	linear
loc	local
long	longitudinal
lum	luminous
m	medium
mat	material
max	maximum
microl	microlayer
min	minimum
mix	mixture, mixing
mouth	mouth
noneq	nonequilibrium
norm	normal
nucl	nucleus, nucleation
o.b	onset of boiling
opt	optimal, optimum
out	outer
outl	outlet
p	pore
pool	pool boiling
pot	potential
pr	protrusion
puls	pulsation
rad	radiation, radiative
rare	rarefaction
red	reduced
refl	reflected
rem	removed
res	residual
rough	roughness, rough
S	solid
sat	saturation
scr	screen
sm	smooth

sp	specific
spac	spacer
spec	specular
spont	spontaneous
spr	spreading
sp.r.f	specific radial force
st	strength
stag	stagnant
str	structure
subc	subcooling
superh	superheating
suppl	supplied
surf	surface
t	turbulent
tr	transverse
trans	transmitted
TSR	transient surface region
tube	tube
V	vapor
w	wall
wat	water
wet	wetted

INTRODUCTION

Heat exchangers – the devices intended for the transfer of heat from one heat carrier to another or to the environment – are most widely used units in all types of energy plants and engines. This equipment makes up the bulk of the production in many branches of industry: power engineering, machine construction, aviation and rocket-space engineering, chemical, petroleum refining, and food processing industries, and also refrigerating and cryogenic technology, systems of heating, ventilation, air-conditioning, and others. In an overwhelming majority of heat exchangers used in all these fields, heat is transferred from a hot heat carrier to a cooler one through a solid body (wall). In this case, a heating agent transfers the heat to one surface, whereas a coolant takes it from the other surface of the wall, i. e., in all cases heat transfer takes place between the heat carrier and the heat transfer surface. Therefore, technical and economical characteristics of heat exchangers of all types and purposes are determined by the soundness in the design and construction of the macro- and microstructure of the heat transfer surfaces.

The theory of heat and mass transfer gives the scientific basis for the selection and design of surfaces in heat exchangers for various purposes. The boundary layer theory, which defines transport processes in the liquid at the boundary with a stable heat-transfer surface, is the basic component of the theory. As applied to a wide class of new problems, especially in nuclear power, aviation, and rocket-space technologies, where high densities of heat fluxes, velocity, and temperature of heat agents can occur, the heat transfer surface acquires an active role in its interaction with the liquid and cannot be considered as a passive, stable, nonvariable medium. In many cases, we observe physico-chemical, thermomechanical, radiative-chemical, and other types of interaction between the liquid and the surface. Without regard for these processes we cannot gain the complete idea of the heat transfer process, i. e., the boundary layer theory is inadequate for describing the mechanism of hydrodynamics and heat transfer under these conditions.

Correlation of various experimental data on heat and mass transfer and hydrodynamics under these conditions with account for achievements in the study of solid surfaces and surface phenomena at the laboratories of universities and companies worldwide, indicates the necessity for qualitatively new modeling and theoretical approach to such problems. The study of multi-layer models of the boundary region of heat transfer forms the basis for the developed theory as applied to the models of the Prandtl boundary layers. In the simplest case the boundary region includes three plane layers: a boundary layer of liquid, an intermediate layer with nonuniformities of the microstructure of the heat transfer surface, and a surface layer of the solid body which involves nonuniform and unsteady structures of the heat transfer surface. In the models studied, the boundary region of heat transfer realizes all nonuniformities of various processes of heat and mass transfer.

If the Prandtl theory explains the processes in the liquid, then the modern theory of a crystalline structure of a solid body does not present a unique description of its surface, since the mere presence of the surface (the boundary) is a "defect" of a three-dimensional structure of a crystalline matter. This defect – a break of a periodic crystal lattice – leads to the appearance of geometric, thermal, chemical, and other nonuniformities of the surface. With allowance for the diversity of these nonuniformities and inhomogeneity of physico-chemical properties of the surfaces interacting with different heat agents that are determined by them, under real conditions we deal with complex systems involving many uncertainties. These objective difficulties of the consideration of the problem of the heat transfer surface are complemented by the diversity of the methods of investigation of surfaces of solid bodies, technological processes of the formation of surfaces and their changes under real conditions (deposition and other contaminations, formation of oxide films on the surface, etc.).

All these various and very complex processes are extensively studied by specialists who design heat exchangers. Many works are concerned with the search for the ways to improve the surfaces and the methods of heat transfer enhancement. A large part of these works are devoted to partial problems, the results of many works are contradictory, and the methods suggested in them are not always effective and adaptable to streamlined manufacture. In a number of cases, the choice of the method of enhancement is not substantiated and has a random character. This situation makes a substantiated selection of effective heat transfer surfaces extremely difficult. Certain results of the studies reveal some conservatism as a result of which the possibilities for improvement of heat transfer surfaces for many fields of technology are not realized. In a number of cases use of traditional heat transfer surfaces leads to the substantially overestimated areas of heat transfer surfaces.

One of the special features of the present work is an attempt of applying the methodology of the system approach to the analysis of the role of the surface in the efficiency of heat transfer. The need for this approach is determined by a complex consideration of all factors governing the properties and structure of both the surface itself and the entire boundary surface area where these properties manifest themselves on the available micro- and macrolevels. At present, the methodology of system-structural analysis are actively introduced to various fields of modern science. As applied to the considered problem, the main advantage of this approach is the disclosure of the feasibilities of controlling the quality of the surface and the attainment of the required efficiency of heat transfer.

The advances of science in the investigation of the surfaces of solid bodies, disclosure of interrelation between micro- and macrostructure of surfaces, their behavior in the interaction with flows of liquids and gases, advances in mastering new technological processes of the formation of heat transfer surfaces and the methodology of complex optimization on the basis of a systematic approach, opened the possibilities for the formulation and solution of the problems of optimization of heat transfer surfaces. Nowadays these problems are formulated as comprehensive justification of macro- and microstructure of heat transfer surfaces providing most efficient technical and economic characteristics of heat exchanging equipment that is the most important stage of its design and production.

The problem of enhancement of heat transfer through the effect of the structure of the surface is of decisive importance in nuclear and thermonuclear power engineering, aviation and space technology, and also in solving the problems of transportation engineering, machine construction, environmental protection, electronics, etc. The variety of the methods of investigation, experimental equipment, and traditions of different branches results, in many cases, in unjustified duplication of expensive experimental studies, multiplicity and incoherence of recurrent design recommendations.

A complex general-science approach to an urgent scientific-engineering problem on the basis of use of achievements in different disciplines and technological processes, which is undertaken by the authors, is not only the summary of advances in the considered problem. A comprehensive analysis makes it possible to justifiably define perspectives of the considered new trend in the theory of heat and mass transfer, to facilitate widening and deepening of research and development, hastening of introduction of the results of fundamental and applied studies into practice.

1. MODERN CONCEPTS OF HEAT TRANSFER SURFACES AND THEIR EFFICIENCY

1.1. Characteristics of Efficient Heat Transfer Surfaces

In the description of the process of heat transfer in heat exchangers, the area of a heat transfer surface F is the main factor which relates geometric dimensions and thermal engineering parameters to technical and economic characteristics of the apparatus. The description of F appears to be rather trivial if one considers heat transfer from a heating agent to a heated agent (coolant) through a plane wall (Fig. 1.1a), where F is the same for both agents.

When heating and heated agents have different properties, then, even in this simplest case, efficiencies of heat transfer from one and the same area of the surface with heating and heated agents are different. This follows from the equations of heat transfer and heat balance. If a shape of the heat transfer surface is other than plane (e. g., a tube wall (Fig. 1.1b) or it is rough (has protrusions) on one side (Fig. 1.1c)), then the areas of heat transfer surfaces of heating (hot) and heated (cold) agents will be dissimilar.

For the simplest case of heat transfer through a smooth plane wall, the expression for the area through which heat Q from a hot agent with a flow rate G_h to a cold agent with a flow rate G_c is transferred has the form

$$F = Q/k\,(t_h - t_c)\,, \tag{1.1}$$

where k is a mean coefficient of heat transfer through the surface F and t_h and t_c are mean temperatures of hot and cold agents, respectively.

For an element of the area of the heat transfer surface dF, the expression for the amount of heat is written in the form of the relation of local values

$$dQ = k\,(t_h - t_c)\,dF\,, \tag{1.2}$$

from which, by integration for the specified scheme of flow of heating and heated agents (cocurrent, countercurrent, crosscurrent, etc.), we find the vari-

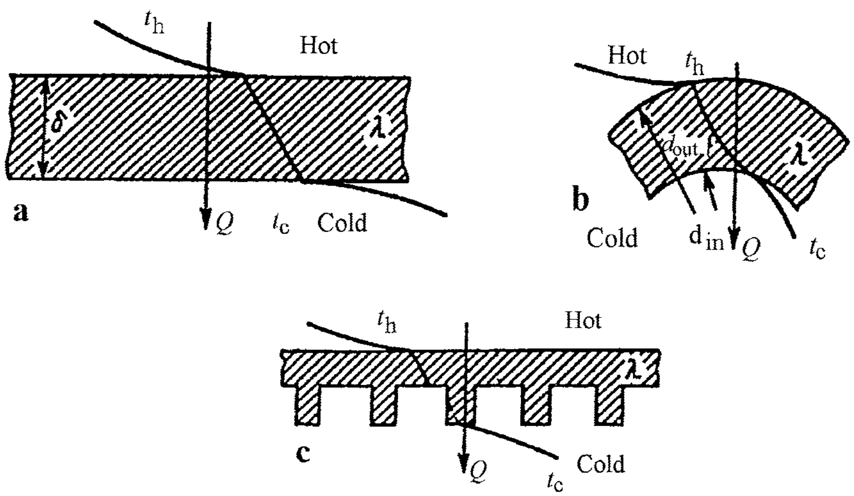

Fig. 1.1. Types of heat transfer in heat exchangers from heating (Hot) to heated (Cold) agent: a) through a plane wall; b) through a cylindrical wall (in tubes); c) through a wall with one-sided finning.

ation of t_h and t_c along the direction of their motion in the heat exchanger and, consequently, the temperature differences which define F.

The expression for the calculation of the coefficient of heat transfer k depends on the shape of the surface through which heat is transferred. For the case of heat transfer through a plane uniform wall, when F is the same for all components of the total thermal resistance, a mean value of the coefficient of heat transfer is

$$k = 1/(1/\alpha_h + \delta_w/\lambda_w + 1/\alpha_c)\,, \tag{1.3}$$

where $1/\alpha_h$ is the thermal resistance of heat transfer from the hot agent, $1/\alpha_c$ is the thermal resistance of heat transfer to the cold agent, δ_w/λ_w is the thermal resistance of heat conduction of a wall with thickness δ_w and thermal conductivity λ_w, and α_h and α_c are the coefficients of heat transfer of the surface with hot and cold agents, respectively.

In the majority of practical problems, the determination of F requires the actual dependences of local temperatures along the motion of hot and cold agents be taken into account [1.1–1.3].

In a steady state of heat transfer without regard for heat losses to the environment, the heat flux in the heat exchanger Q is equal to a decrease in the enthalpy of the hot agent $G_h \Delta i_h$ and an increase in the enthalpy of the cold agent $G_c \Delta i_c$:

$$Q = -G_h \Delta i_h = G_c \Delta i_c \tag{1.4}$$

or

$$Q = G_h (t_{h\,inl} - t_{h\,outl}) = G_c (t_{c\,outl} - t_{c\,inl}) , \tag{1.5}$$

where t_{inl} and t_{outl} are the enthalpies of the agents at the inlet to and outlet from the heat exchanger (or the considered section).

Since $\Delta i = \bar{c}_p \Delta t$, we can write

$$Q = G_h \bar{c}_{ph} (t_{h\,inl} - t_{h\,outl}) = G_c \bar{c}_{pc} (t_{c\,outl} - t_{c\,inl}) , \tag{1.6}$$

where $\bar{c}_{ph}$ and $\bar{c}_{pc}$ are mean heat capacities of the agents within the considered ranges of temperatures.

Then we can write Eq. (1.4) as

$$-G_h \bar{c}_{ph} \Delta t_h = G_c \bar{c}_{pc} \Delta t_c . \tag{1.7}$$

With the use of expressions for total heat capacity of mass flow rates of the agents

$$C_h = G_h \bar{c}_{ph} \quad \text{and} \quad C_c = G_c \bar{c}_{pc} , \tag{1.8}$$

which are also referred to as "water equivalents", a change in the thermal head for the case of cocurrent parallel simultaneous motion of the heating and heated agents is

$$d (t_h - t_c) = -(1/C_h + 1/C_c)\, dQ . \tag{1.9}$$

Having substituted dQ from (1.2), we obtain

$$d (t_h - t_c) = -(1/C_h + 1/C_c)\, k\, (t_h - t_c)\, dF . \tag{1.10}$$

Integrating this equation from 0 to F and assuming C_h, C_c, and k being constant

$$-mk \int_0^F dF = \int_{(t_h - t_c)_{inl}}^{(t_h - t_c)_{outl}} \frac{d (t_h - t_c)}{t_h - t_c} , \tag{1.11}$$

we obtain the expression for the dependence of the required area of the heat transfer surface on the thermal heads at the inlet to and outlet from the heat exchanger for cocurrent flow:

$$F = -\frac{1}{mk}\ln\frac{(t_h - t_c)_{outl}}{(t_h - t_c)_{inl}}, \tag{1.12}$$

where $m = (1/C_h + 1/C_c)$.

The solutions for countercurrent flow of the agents are obtained similarly.

For cross and multipass flows of agents in the heat exchanger loops, the solution for the heat transfer area is obtained in a more complex way: by dividing the entire flow scheme into portions or by numerical methods. For the cases of heat exchangers with the same agents (water–water, air–air, sodium–sodium, etc.) the necessary area of the surface on the side of the hot agent F_h can approximately be taken equal to the area of the surface of the cold agent F_c, i.e., for these individual cases the version of two-sided equal area of the heat transfer surface $F_h = F_c$ is preferable.

In the case when the values of the coefficients of heat transfer α_h and α_c are substantially different, in order to attain an optimal ratio of F_h and F_c one can use the characteristics of the surface itself, its macro- and microstructure, and also design engineering solutions which provide optimization of the ratio of F_h and F_c at the expense of their arrangement in the heat exchanger and use of new technologies affecting the surface by special types of treatment or deposition of coatings which change the area of the surface.

Proceeding from the above, in the general case we characterize the efficiency of the heat transfer surface in the heat exchanger by the degree of approximation to optimal design solutions as to the choice of materials and properties of surfaces, their arrangement and macro- and microstructure.

As applied to individual problems, use is made of different definitions of the efficiency of the heat transfer surface. For example, for a version of regular finning of the surface, the efficiency denotes the ratio of the actually transferred amount of heat Q_{act} to its calculated value Q_{calc}, which might have been transferred if the temperature of the entire surface was constant and equal to the temperature of the fin base (with infinite thermal conductivity of fins).

An important fact which determines the trends of further analysis is that in our approach the efficiency of a real heat transfer surface is considered and estimated with an account for interaction with a real agent. In this sense, efficiency can be estimated only for a specific heat exchanger with specific operating parameters of agents.

In order to consider heat transfer problems analytically, in most cases we can get by with a two-dimensional description of the surface in the plane (x, y) with sufficient accuracy; however, in search for possible ways of heat transfer enhancement we inevitably refer to more complex models of processes and a three-dimensional description of the surface. Several approaches to the description of surfaces in the coordinate space are used. The simplest of them are the following:

in the form of the function of deviations relative to (x, y)

$$Z = f(x, y) ; \tag{1.13}$$

in the form of equations

$$F(x, y, z) = 0 , \tag{1.14}$$

and in the form of parametric relations

$$\left.\begin{aligned} x &= x(u, v) \\ y &= y(u, v) \\ z &= z(u, v) \end{aligned}\right\} , \tag{1.15}$$

where u and v are the parameters passing a certain region in the plane (u, v). In the latter case, the area of the surface is determined by the double integral

$$F = \int_V \int_U [x_u y_v - x_v y_u] \, du \, dv , \tag{1.16}$$

where V is the region in the plane (u, v) which corresponds to the region U in the plane (x, y).

Quantitative methods of the determination of an actual area of three-dimensional surfaces F are considered in the monographs dealing with the geometry of surfaces [1.4–1.6]. In [1.6], the simplest curves and surfaces, regular point systems, various plane configurations, kinematics and topology of different types of surfaces are considered on a systematic basis. In particular, a rigorous definition of the curvature of the surface for the cases of points with convex and saddle curvature is given.

It is characteristic for the point with a saddle curvature that the tangential plane, which is tangent to the surface at this point, does not intersect surfaces in the nearest neighborhood of the considered point but lies entirely on one side of the surface (at this point (e. g., the point of a sphere or an ellipsoid) the surface can be laid on the table plane).

At the point of passing of the saddle curvature, the horizontal tangential plane crosses the crest (e. g., from the left or from the right) and the slopes are directed forward and backward from the saddle point. The everywhere saddle-like curved surface represents an unparted hyperboloid or hyperbolic paraboloid.

The center of curvature at the point P lies on the normal to the surface passing through the point P. Upon revolution of the plane, which passes through the normal to the surface, about the normal, the center of curvature will move along the normal and describe the pattern of the properties of the curvature at this point of the surface. In the case of an elliptic point P, the centers of curvature lie on the normal on one side from P. Minimum and maximum radii of curvature are termed the principal radii of curvature R_1 and R_2, their reciprocal values are called the principal curvatures ζ_1 and ζ_2, and the direction of tangents are named the directions of curvature which at the right point are perpendicular to each other.

At the modern level of knowledge other practically important characteristic shapes of real surfaces of heat transfer can be described similarly.

1.2. Macrostructure of Heat Transfer Surfaces

In a general form, a macrostructure of the heat transfer surface is characterized by the presence (or absence) of any purposeful changes of the geometry due to technological operations (corrugation, impact extrusion, finning, pinning, etc.) on the surface. When they are absent, the surfaces are said to be technically smooth. The characteristic of the macrostructure of technically smooth surfaces is confined to deviations of the shape from calculated values (e. g., for round tubes, these are ellipticity across the section and a "barrel-like" shape along the length, and other deviations of the shape of the flow area and the outer shell).

Waviness of a technically smooth surface is characterized by smooth periodic deflections relative to the plane with a pitch of 0.08 to 240 mm along one of the axes in this plane. Actual deflections from the plane for technically smooth surfaces obtained by modern methods, which exceed 250 mm, are termed the error of shape. For plane heat transfer surfaces obtained by stamping, actual deflections lie within the waviness. For mechanically treated surfaces, the macrostructure is maintained within the specified limits.

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