

**MEASUREMENTS OF
THERMOPHYSICAL
PROPERTIES BY
LAMINAR FLOW METHODS**

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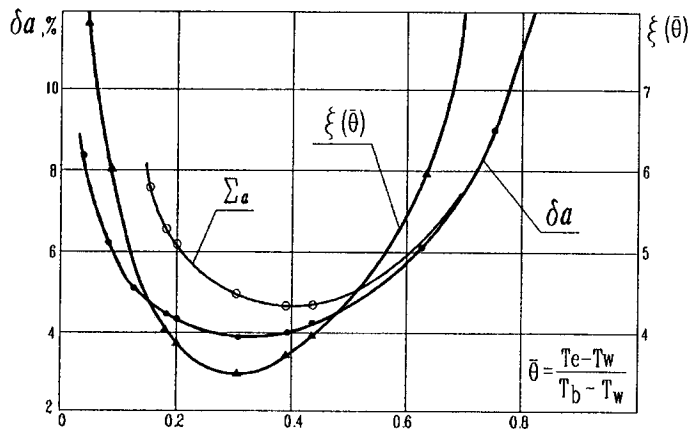
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*Dedicated to the wonderful wives and
partners in our lives who through the
years have blessed us with love, support
and understanding*

*Vera Pavlovna Ponomareva
Ekaterina Borisovna Mishchenko
Sondra Raines Irvine*

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NOMENCLATURE

Latin symbols:

- in figures:

A	- liquid being investigated;
B, C	- liquid heat transfer agents;
ADC	- analog-to-digital converter;
ASSR TPP	- an automated system for the scientific research of the thermophysical properties of liquids;
CD	- control device;
DAC	- digital-to-analog converter;
DRD	- the digital readout device;
FM	- flow rate meter;
MCS	- measuring-computing system;
MP	- microprocessor;
MT	- the measuring tube;
SW	- stopwatch;
SM	- servomechanism;
TPP	- thermophysical properties;
VR	- voltage regulator;

- in equations:

A	- thermal diffusivity tensor;
$a_{r\varphi}, a_{\varphi r}, a_{x\varphi}, a_{\varphi x}, a_{xr}, a_{rx}$	- the extradiagonal components of the thermal diffusivity tensor, A;
$a_{\varphi\varphi}, a_{rr}, a_{xx}$	- the diagonal components of the thermal diffusivity tensor, A;
A_n	- constant coefficients;
a	- thermal diffusivity;
a_w	- the thermal diffusivity of tube wall;
B_n	- constant coefficients;
C	- constant coefficient;
c	- specific heat capacity;
$d = 2R$	- internal diameter of the central tube;
$F(\bar{z}), f(\bar{\theta}), f_n(\bar{R})$	- mathematical functions;
f	- index of the sample geometry

$G(r, \xi, z, \eta), \overline{G}(\overline{r}, \overline{\xi}, \overline{z}, \overline{\eta})$	(f = 0,1,2 correspondingly for flat, cylindrical and spherical systems);
g	- Green's functions in dimensional and dimensionless form;
g	- liquid volume flow rate through the tube;
K, k, k ₁ , k ₂ , k ₃ , k ₄	- gravitational acceleration;
k	- constant coefficients;
L, L ₁ , L ₂ , $\ell_1, \ell_2, \ell_h, \ell_{h1}, \ell_{h2}, \ell_{is}$	- parameter of the power law /8.2/;
m	- lengths of the sections of the measuring tubes;
n	- heat transfer parameter;
P	- parameter of the power law /8.2/;
p	- electrical power, consumed by the electrical heater;
$Pe = \frac{\overline{\omega}d}{a}$	- Laplace transformation parameter;
q, q _w	- Peclet number;
\vec{q}	- heat flux, heating the liquid flow on the heat exchange section of MT;
R	- heat flux vector;
R1, R2, R3	- internal radius of the central tube;
R ₁ , R ₂ , R ₃ , R ₄ , R _i , R _n	- resistances;
r, z	- dimensional coordinates of the boundary surfaces;
$\overline{r} = \frac{r}{R}, \overline{z} = \frac{\pi a z}{2g}$	- the radial and longitudinal coordinates of the heat exchange section;
RK1, RK2, RK3, RK4	- dimensionless radial and longitudinal coordinates of the heat exchange section;
Re	- resistant thermometers;
T	- Reynolds number;
T ₀	- temperature;
T ₁ , T ₂	- the initial value of sample temperature;
T _b , T _e , $\overline{T}_b, \overline{T}_e$	- temperatures on the surfaces of the sample with coordinates $r = R_1, r = R_2$;
(T _e -T _w), (T _b -T _w), (T _e -T _b)	- bulk temperatures of the liquid in the beginning and end of the test section; are the temperature differences,

$$T_w, \bar{T}, \bar{T}_1, \bar{T}_2$$

$$U_b, U_e, \bar{U}, V$$

$$W, \bar{W}$$

$$x, Y_1 = \frac{\pi a L_1}{2g}, Y_2 = \frac{\pi a L_2}{2g}$$

$$z$$

$$\bar{z} = \frac{\pi a z}{2g}$$

$$\tilde{z} = \frac{z}{g}$$

Greek symbols:

$$\beta, \beta = \bar{T}_2 / \bar{T}_1$$

$$\gamma = \frac{d\omega}{dr}$$

$$\Delta\theta = \frac{\Delta T \lambda}{q_w d} = [\theta(1, \bar{z}) - \bar{\theta}(\bar{z})]$$

measured on the MT of the different type;

- temperature of the tube wall;
- deviation of the mean integral value of the wall temperature on the measuring device central tube heat exchange section from the initial temperature T_0 ;

- output signals;
- velocity vector;

- liquid volume, which is gathered in the measuring vessel in time τ ;

- density of internal heat sources;
- dimensionless density of the internal heat sources;

- axis;
- values of dimensionless coordinate

$$\bar{z} = \frac{\pi a z}{2g} \text{ at } z=L_1 \text{ and } z=L_2;$$

- dimensional longitudinal coordinate of the tube;

- dimensionless longitudinal coordinate of heat exchange section;

- ratio of current value of a longitudinal coordinate z to the volume flow rate g ;

- coefficient of volumetric expansion;
- ratio of experimentally measured average integral temperature values of tubes wall sections $[\ell_2, L_2]$ and $[\ell_1, L_1]$;

- shear rate;

- is the difference between the dimensionless temperature $\theta(1, \bar{z})$ of the tube wall and the dimensionless

ΔP ΔT ΔT_{\max}

$$\Delta T = T(R, z) - \bar{T}(z)$$

 $\Delta g, \Delta q_w, \Delta d, \Delta a, \Delta g, \Delta \ell_h,$

$$\Delta(T_e - T_w), \Delta(T_b - T_w)$$

$$\delta a = \frac{\Delta a}{a}, \delta g = \frac{\Delta g}{g}, \delta q_w = \frac{\Delta q_w}{q_w},$$

$$\delta_d = \frac{\Delta d}{d}, \delta \ell_h = \frac{\Delta \ell_h}{\ell_h},$$

$$\delta(T_e - T_w) = \frac{\Delta(T_e - T_w)}{(T_e - T_w)},$$

$$\delta(T_b - T_w) = \frac{\Delta(T_b - T_w)}{(T_b - T_w)}$$

 $\delta \bar{\theta}, \Delta \bar{\theta}$ $\delta_{\mu a}, \delta_{\lambda}$ δ_L $\delta_R = \delta_d$ $\delta_{\Delta P}$ ε bulk temperature $\bar{\theta}(\bar{z})$ of the liquid;

- the pressure difference;

- temperature difference

- the maximum rise of temperature at the distance x from heat source;- difference between dimensional temperature $T(R, z)$ of the tube wall and dimensional bulk temperature $\bar{T}(z)$;- are the absolute errors of the measurement of the flow rate g , heat flux q_w , diameter d , temperature T , thermal diffusivity a , the volume flow rate g , the length ℓ_h of the heat exchange section and temperature difference $(T_e - T_w)$ and $(T_b - T_w)$;- relative errors of $a, g, q_w, d, \ell_h, (T_e - T_w)$ and $(T_b - T_w)$ measurements;- relative and absolute errors of the dimensionless value $\bar{\theta}$ determination;- relative errors of the thermophysical values μa and λ of the liquid measurements;- relative error of the measurement of length L of the section;

- relative measurement error of inner radius of the measuring tube;

- relative error of the pressure difference ΔP measurement;- systematic errors of measurements of thermal diffusivity a and thermal

$$\varepsilon_n, \psi_n(\bar{r})$$

$$\theta = (T - T_b)\lambda / (q_w 2R)$$

$$\bar{\theta}(\bar{z}) = 4 \int_0^1 \theta(\bar{r}, \bar{z}) \bar{r} \left[1 - (\bar{r})^2 \right] d\bar{r}$$

$$\bar{\theta}, \bar{\theta}_i = \frac{T_{ei} - T_w}{T_b - T_w}$$

$$\theta_{opt}$$

$$\bar{\theta}_e = \frac{T_e - T_w}{T_b - T_w}$$

$$\bar{\theta}_f$$

$$\bar{\theta}(\bar{z})$$

$$\Lambda$$

$$\lambda$$

$$\lambda_{r\varphi}, \lambda_{\varphi r}, \lambda_{x\varphi}, \lambda_{\varphi x}, \lambda_{xr}, \lambda_{rx}$$

$$\lambda_{\varphi\varphi}, \lambda_{rr}, \lambda_{xx};$$

$$\mu$$

$$\mu \cdot a$$

$$\mu_{ef} = k\gamma^{n-1}$$

$$\nu$$

$$\xi_1 = \frac{\ell_1}{L_1}, \xi_2 = \frac{\ell_2}{L_2}$$

$$\xi, \eta$$

$$\bar{\xi} = \frac{\xi}{R}, \bar{\eta} = \frac{a\eta}{2\omega R^2} = \frac{\pi a\eta}{2g}$$

conductivity λ ;

- eigenvalues and eigenfunctions of the Sturm-Liouville boundary value problem;

- dimensionless temperature;

- dimensionless bulk temperature;

- dimensionless bulk temperature;

- the optimal dimensionless temperature value;

- is the dimensionless bulk temperature of the liquid at the end of the measuring tube;

- actual value of the dimensionless temperature;

- function which determine the change of the dimensionless bulk temperature;

- thermal conductivity tensor;

- thermal conductivity;

- extradiagonal components of the thermal conductivity tensor Λ ;

- the diagonal components of the thermal conductivity tensor Λ ;

- dynamic viscosity;

- complex thermophysical parameter;

- apparent viscosity of the Non-Newtonian liquid;

- the kinematic viscosity;

- ratio of the geometrical coordinates, determining the positions of resistance thermometers RK1, RK2 on the heat exchange section of the measuring tube;

- integration variables;

- dimensionless coordinates;

ξ_n, ψ_n $\bar{\xi}(\bar{W}, \bar{\theta})$ ρ ρg σ τ τ_H τ_0 $\Phi(\beta), \Phi_1(\beta)$ φ $\varphi(\bar{z})$ $\psi_n(\bar{r}), \psi_i(\bar{R})$ $\Omega = (T_w - T_e) / (T_e - T_b)$ $\bar{\omega} = \frac{4g}{\pi d^2}$ $\bar{\omega} = \frac{n}{n+1} k \left[R \left(\frac{R \Delta P}{2Lk} \right)^{\frac{1}{n}} \right]^n$ ω_0 $\omega_0 = \left[\frac{3n+1}{n+1} \right] \bar{\omega}$ $\omega_z(r)$ $\omega(r)$

- characteristic values and functions of the Sturm-Liouville boundary value problem;

- is the inverse function of the initial function $\bar{\theta} = \varphi(\bar{W}, \bar{z})$;

- density of the sample material;

- mass flow rate of the liquid;

- stress tensor; tangential or shear stress;

- time;

- is the relaxation time;

- time of filling the tank with capacity V;

- mathematical functions;

- axis of cylindrical coordinate system;

- is the mathematical function;

- eigenfunctions of the Sturm-Liouville boundary value problem;

- the dimensionless parameter;

- average velocity of liquid flow in the tube;

- is the average flow velocity of the sugar solution through the central tube at the differential pressure ΔP , applied over the heat exchange section of length L;

- maximum velocity of liquid flow;

- is the maximum non-Newtonian liquid flow velocity;

- velocity profile;

- profile of the velocity of flow of the liquid or gas, which, for fully developed flow in a tube, is given by Poiseuille's formula;

INTRODUCTION

Because of modern conditions of shortages of power and materials resources, there are societal demands to increase effectiveness of technological processes. The best way to approach this problem [1, 2] is the use of computer aided design systems which permit the evaluations and comparison of many design variables. In technical processes which involve the flow of liquids, mathematical models are utilized in which the thermophysical properties (TPP) of the liquids appear as independent parameters in the problems. Thus, the need arises to develop efficient and accurate methods to measure these thermophysical properties which consist of thermal conductivity, thermal diffusivity and specific heat.

The flows of real technological liquids in many cases consist of dispersion systems (suspensions, emulsions or liquid-gaseous mixtures). Effective values of TPP in dispersion systems can be measured only in a flow process. Conventional methods and apparatus of thermophysical measurements are based on the assumption that the liquid being investigated must be in a motionless or «quasi-solid» state in process of measurement. (There must be no convection heat transfer). Therefore these methods and apparatus are not applicable to measure the effective TPP of liquids under flow conditions.

Research experience has shown that one of the most appropriate methods for the measurement of TPP of such technological liquids are methods of laminar flow. The merits of such methods are both the possibility of continuous in time measurements of TPP of liquids in the process of flow through measuring devices and the possibility of experimental investigations of the dependence of liquids thermal conductivity on shear rate in non-Newtonian flows. This second advantage has especially great meaning in connection with published articles during last decade in the heat transfer scientific-technical literature. These articles are devoted to theoretical investigations of the effects of anisotropy of heat transfer in convective liquids flows. But experimental data indicating anisotropy of thermal conductivity during such liquid flows has not been published up to now.

The problems of automatization of measuring operations and experimental data processing is an important aspect of the development and use of the laminar flow methods of TPP measurements. The solution of this problem permits us to obtain the necessary information about the character and the value of the changes of TPP during an experiment and to use this information to create liquids with specified TPP.

The aim of this book is to present to the reader information about laminar flow methods and information about measuring devices based on these methods. The methods and devices considered in this book have the following

merits as compared to conventional methods and devices of thermophysical property measurements:

a) the ability to perform measurements of thermophysical properties of liquids continuously in time in flow process of scientific and engineering experiments and in real technological processes.

b) to experimentally determine the dependence of the second diagonal components of tensors of thermal conductivity and thermal diffusivity of liquids on shear rate.

c) to automate with sufficient simplicity the processes both to control the experiments and to process experimental information with the use of simple computers.

A brief review of classical measurement methods of thermophysical properties is given in the first chapter.

The second, the third and the fourth chapter are devoted to the theoretical basis of methods of laminar flow and devices.

The fifth chapter is devoted to the analysis of sources of measurement errors of TPP with use of the described methods and devices.

The design of measuring devices and the composition of experimental apparatus are considered in the sixth chapter.

The results of calculated and experimental evaluations of errors of liquid TPP measurements are discussed in the seventh chapter.

The results of experimental measurements of liquids TPP are presented in the eighth chapter. The results of using these methods for monitoring of changes of liquid's TPP in scientific experiments or real technological process are also given in this chapter.

The results of theoretical and experimental investigations which supplement and substantiate the contents of the main chapters of the book are considered in the appendix.

This book is intended for engineers and scientists, for senior students and post-graduates specializing in the area of thermophysical investigations.

**CHAPTER
ONE**

**REVIEW OF METHODS FOR THE
MEASUREMENT OF THERMOPHYSICAL
PROPERTIES OF LIQUIDS**

Research investigations, previously performed by the authors, have indicated that the following demands are placed upon the methods, instruments and automatic systems of scientific research intended for the experimental determination of the thermophysical properties of flows of technological liquids, which change as a result of chemical, physical, microbiological and other factors in technological processes or scientific experiments [39, 52, 53]:

1) In connection with the experimental measurement of the thermophysical properties of liquids directly in a technological process, scientific or engineering experiment, the measurement method must be such, that it is possible to have a duct flow measuring device, suitable for installation in pipe-lines of different experimental, semi-industrial and industrial devices.

2) Because the flow characteristics of the liquids under study are non-reproducible in most cases, the possibility of obtaining the maximum information about the thermophysical properties during a single experiment must be provided. Thus, it is desirable to provide continuous measurements of all the liquid thermophysical properties (thermal diffusivity, thermal conductivity and heat capacity).

3) It is necessary to obtain information about the changes of thermophysical properties directly during the experiment, so that the experimenter can actively influence the experimental process in order to obtain the required results. For example, it is necessary, that the mathematical models for calculating thermophysical properties are simple enough to allow the automatic analysis of primary measured information directly in the experimental process.

4) It is important to provide the necessary measurement precision, at the level of modern requirements to the methods and devices used for measuring the thermophysical properties of liquids.

5) If the liquids have internal heat sources, which occur from energy dissipation because of viscous friction, chemical reactions or other reasons, it is necessary to foresee the possibility of their influencing the measurement results. In some cases the measurement of the influence of these internal heat sources may be of interest to an engineer developing new technological processes.

§1.1 Basic Information About the Traditional Methods of Thermophysical Measurements

In references [3-26] the methods of thermophysical property measurements can be divided into two large classes : steady state and transient methods.

Steady state methods in their traditional sense [3-26] are based, in most cases, on the mathematical modeling of the heat transfer process in the test sample with the help of the one-dimensional heat conduction equation

$$\frac{d}{dr} \left[r^f \frac{dT(r)}{dr} \right] = 0, \quad R_1 < r < R_2,$$

with boundary conditions [27 - 33] :

$$\lambda \frac{dT(R_1)}{dr} = q = \text{const}, \quad T(R_2) = T_2 = \text{const},$$

where r is the transverse coordinate of the one-dimensional sample; R_1, R_2 - coordinates of the boundary surfaces of the sample; T - temperature; f - index of the sample geometry ($f = 0, 1, 2$ correspondingly for flat, cylindrical and spherical systems); λ - thermal conductivity of the sample material; q - heat flux, transferred to the sample on the surface with coordinate $r = R_1$; T_2 - temperature, assumed constant on the surface of the sample with coordinate $r = R_2$.

The thermal conductivity λ is usually defined taking into consideration the value of the temperature $T(r)$, measured at one of the inner points of the sample with coordinate $R_1 \leq r < R_2$.

Steady state methods were used for the first time to define thermal conductivity for both solid and liquid materials in the last century and at present are considered classical [3]. The following are the drawbacks [3 - 26] of these methods: they require a long time to reach the necessary steady state condition, they permit only periodic measurements (each of them takes a long period of time), they require taking special measures to prevent convection from occurring inside the liquid samples under study, they are not suitable for direct measurement of thermophysical properties of transient heat transfer, for

example, thermal diffusivity $a = \lambda / c\rho$ or thermal activity $b = \sqrt{\lambda c\rho}$, where c is specific heat capacity and ρ - density of the sample material. In this class of traditional steady state methods, we could not envisage any methods suitable for continuous measurements of the thermophysical properties of technological liquids.

Transient methods [3] are usually based on the mathematical modeling of the heat transfer in one-dimensional samples by the differential equation of unsteady heat conduction [27 - 33]

$$\frac{\partial T(r, \tau)}{\partial \tau} = a \frac{1}{r^f} \frac{\partial}{\partial r} \left[r^f \cdot \frac{\partial T(r, \tau)}{\partial r} \right], \quad \tau > 0, \quad R_1 < r < R_2, \quad a - \text{thermal}$$

diffusivity,

with initial condition [27 - 33] $T(r, 0) = T_0 = \text{const}$,

and boundary conditions [27 - 33], for example:

$$\lambda \frac{\partial T(R_1, \tau)}{\partial r} = q_1(\tau), \quad T(R_2, \tau) = T_2(\tau),$$

where τ - time; T_0 - the initial value of sample temperature; $q_1(\tau)$, $T_2(\tau)$ - functions, defining the laws of changes of heat flux and temperature on the boundary surfaces of the sample with coordinates $r = R_1$ and $r = R_2$; other definitions were given above.

On the surfaces $r = R_1$ and $r = R_2$ any combinations of boundary conditions of the first, second and third kind [30] may be given. If the sample under study is in thermal contact with a standard material, then on the contact surface, boundary conditions of the fourth kind [30] are additionally given.

Transient methods may be divided into three large groups [3]:

1) Methods based on the laws of the initial condition of the transient heat transfer process in the sample. For this group of methods, a strong dependence of the results of the measurements on the given initial conditions is typical. Examples of such methods are the method of an instantaneous heat source and impulse methods [3, 20]. These methods are the quickest and they are useful for the purposes of time dependent measurement of the thermophysical properties.

2) Methods, based on the laws of the regular or developed region of transient heat transfer processes in the sample. The results of measuring thermophysical properties using these methods do not depend on the given initial distribution of temperature in the sample under study. Examples of such methods are methods of regular modes of the first, second and third kind [3 - 25]. For this group a considerable experiment duration, close to that of steady state methods, is typical.

3) Methods, based on the use of laws of all stages of transient processes of heat transfer in the samples under study (the initial and developed stages). Examples of such methods are methods [23 - 26, 167, 170, 181, 218], based on the use of temporal integral characteristics and space-temporal integral characteristics of temperatures and heat fluxes. For these methods, a considerable experiment duration is also typical.

Transient methods on the whole are less prolonged in comparison with steady state methods and in some cases do not require the preliminary maintaining of the samples at a certain temperature. In addition they often make it possible to avoid heat flux measurements, don't place exact demands upon the thermal protection of the samples and allow the measurements of all the thermophysical properties (α , λ , c_p , b) in one experiment. Because of the difficulties in obtaining given temporal temperature modes and the necessity of using complex systems of automatic control [24, 52, 161, 162] and data acquisition, transient methods have come into use only in the last decades [4, 9, 10, 23, 25].

Traditional steady state methods and most transient methods may be used to measure thermophysical properties of liquids only in a periodical mode. The only exceptions are some methods of regular mode of the third kind [9], suitable for uninterrupted measurement of the thermophysical properties of liquids using immersion-type transducers. These methods are based [9, 38, 177, 178] on the measurement of steady-state temperature pulsations of quick-response metallic transducers (a stripe of foil or wire), placed in the medium under study which is heated by an alternating current. A considerable advantage of this method consists in the fact that free convection in the volume of the liquid under study practically does not influence the measurements results because of the small thickness of the layer (fractions of a millimeter), in which the temperature wave is fully absorbed. However, according to the results of one investigation [38], if forced convection appears with a liquid speed greater, than 0.015 m/sec, a large additional error is introduced in the results of measurements, which is impossible to take into account. Thus, it did not seem appropriate to use this method in the development of devices for the measurement of the thermophysical properties of liquids, including the study of the thermal conductivity dependence on shear rate. No other information is apparently available on other methods based on the laws of transient heat transfer, which could be used for the development of devices for measurements of liquid thermophysical properties undergoing continual change.

For the above steady state and transient methods there is a common supposition that in the volume of liquid under study of its thermophysical properties any free or forced convection is fully absent. In other words, the traditional methods of thermophysical property measurements are based [39] on

the supposition, that the liquid sample is in “quasi-solid” state (there is no convection heat transfer). This supposition is the main reason, preventing the use of traditional steady state or transient methods for measuring the thermophysical properties of technological liquids and for the study of the dependence of thermal conductivity of liquids on shear rate.

In some investigations [6, 10, 24, 27, 39-53], there is information about methods of thermophysical property measurements, free from the above mentioned drawbacks. The common characteristic of these methods is that they allow the measurement of thermophysical properties of liquids in a laminar flow process and that is why some of them in reference [6] were called laminar flow methods.

§1.2 Methods of Thermophysical Property Measurement With Liquid Laminar Flow in a Tube

Methods of laminar flow, based on the laws of heat transfer for liquid laminar flow in a tube, are usually based [6, 10, 24, 27, 39 - 45, 52 - 77] on the mathematical modeling of the heat transfer process in steady-state laminar flow of liquid or gas as described by the steady state energy equation for hydrodynamically fully developed flow, i.e. the Graetz problem

$$\omega(r) \frac{\partial T(r, z)}{\partial z} = a \frac{1}{r^f} \frac{\partial}{\partial r} \left[r^f \frac{\partial T(r, z)}{\partial r} \right], \quad /1.1/$$

$$z > 0, \quad 0 < r < R,$$

with the initial condition [34-36]

$$T(r, 0) = T_b = \text{const} \quad /1.2/$$

and the boundary conditions [7, 11, 24, 39-41, 52], for example:

$$\text{for } r = 0 \quad \frac{\partial T(0, z)}{\partial r} = 0, \quad /1.3/$$

$$\text{for } r = R \quad T(R, z) = T_w = \text{const}, \quad /1.4/$$

where r, z - radial and longitudinal coordinates of the flow of liquid or gas; $r = 0$ and $r = R$ - coordinates of the tube center and the surface, containing the laminar flow (the value R may change [39-53] within the limits $0 < R \leq \infty$); $\omega(r)$ - profile of the velocity of flow of the liquid or gas, which, for fully developed flow in a tube, is given by Poiseuille's formula [6, 10, 24, 39-41, 52]:

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