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Mechanisms of unsteady mixing of heat carrier with its flowrate variation and flow swirling—I. Calculation methods and experimental study of transient processes

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Abstract—The results of experimental and theoretical studies of the unsteady mixing process of heat carrier in a helical tube bundle when heat carrier flowrate is increased and decreased are presented. In experiments, the axisymmetric nonuniformity of a heat release field was modeled and temperature fields of heat carrier were measured at the tube bundle cross-section. Theoretically, the temperature fields were calculated using the two-temperature flow model of a two-phase homogenized medium with a stationary solid phase. Effective turbulent transfer coefficients were determined from comparison of the experimental and predicted temperature fields of heat carrier. New generalizing relations are derived to calculate effective turbulent transfer coefficients used to close a system of equations describing unsteady thermal and hydraulic processes in such tube bundles. The physical phenomena that characterize the specific features of heat transfer from flow swirling in complex-geometry channels for different types of hydrodynamic unsteadiness are considered. Examples of calculation of transient processes, as applied to a vehicular nuclear reactor, are presented. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

The swirling turbulent flow in the complex-geometry channels formed by helical tube bundles [1, 2] enhances heat and mass transfer processes, the unsteadiness effects of the thermohydraulic process making themselves more evident in such channels than in round tubes [3–5].

For the unsteadiness effect on the thermal and hydraulic parameters (temperature, velocity, density, etc.) and their distributions to be taken into account, their time variations must be considered by including the appropriate terms into the equations of energy, motion, continuity and heat conduction, and also the time-dependent heat and mass transfer coefficients must be used to solve a system of these equations. This is because at the first time instants of the unsteady process unsteady heat transfer and mixing coefficients can essentially differ from their quasi-steady values in some way or another depending on the unsteadiness type [3–5].

Despite the fact that at present the unsteady heat and mass transfer problems arouse considerable interest in different fields of science and technology the mechanisms and the nature of unsteady thermal and hydraulic processes are not as yet imperfectly understood. So, in [3–5] the studies of unsteady mixing at sharp variations of heat carrier flowrate and constant heat power were made mainly as the definition of the problem. At the same time the transient operating conditions involving a variation of heat carrier flowrate may be of crucial importance in the serviceability of different heat-engineering installations, e.g. of transport nuclear reactors. So, the nuclear reactor of the space multiple regime propulsion power plant (NPPP) [6] operating under pulsed conditions executes a transition from a propulsion to cycle a power regime and back according to a certain cycle. The heterogeneous reactor of this plant incorporates fuel assemblies where the helical rods similar in shape to helical tubes of heat exchangers considered elsewhere [1, 2] can serve as fuel elements. The helical rods fabricated from a solid solution of refractory metal carbides and uranium-235 allow hydrogen to be heated up to more high temperatures, as against the fuel elements shaped as channels [7]. The advantage of the fuel assemblies composed of helical rods in comparison with those comprising channel-shaped elements is the possibility to partially flatten nonuniformities of the heat carrier temperature field due to mixing which have been formed by a nonuniform heat release field at the cross-section of the rod bundle [1, 2]. Therefore, having regard to the fact that under transient operating conditions the transfer coefficients can several times differ from their quasi-steady values, use of helical rod bundles in the nuclear reactor of the NPPP is all the more preferable.

This article considers the problem of calculating unsteady temperature fields and presents the experimental data on the mechanisms of unsteady thermal and hydraulic processes in the bundle of helical tubes or oval-shaped rods when the heat carrier flowrate is

NOMENCLATURE

c	heat capacity
d	maximum size of the oval of a tube (rod)
d_{eq}	equivalent diameter
d_{bundle}	bundle diameter, $d_{bundle} = 2r_{bundle}$
D_{eff}	effective turbulent diffusion coefficient
Fr_M	modified Froude number characterizing the inertia-to-centrifugal force ratio for swirled flow
G	mass flowrate of heat carrier
G_1	mass flowrate of heat carrier before disturbing
G_2	mass flowrate of heat carrier after disturbing
K	dimensionless effective turbulent diffusion coefficient
K_{eff}	effective multiplication coefficient in a finite medium
l	length
l^*	mean neutron fission lifetime of atomic nuclei based on the quantity β
Le_T	turbulent Lewis number
N	heat load; reactor power
$N_{fission}$	power resulted from fission of atomic nuclei due to delayed neutrons
N_i	power resulted from fission of atomic nuclei due to the ith group of delayed neutrons
N_o	rated reactor power
$N_{\beta,\gamma}$	power released due to β, γ-decay of fission fragments accumulated during the reactor operation
p	static pressure
Pr_T	turbulent Prandtl number
r	radial coordinate
r_{bundle}	radius of the bundle of tubes (rods)
R	gas constant
Re	Reynolds number
q_V	volume heat release density
s	twisting pitch of tubes (rods)
t	oscillating period; reactor period
T	temperature
ΔT_T	core temperature variation
u	velocity
V	reactor core volume
x	longitudinal coordinate.

Greek symbols

α	heat transfer coefficient
β	effective fraction of delayed neutrons
β_i	fraction of delayed neutrons of the ith group
ε	bundle porosity with respect to heat carrier
λ	thermal conductivity
λ_{eff}	effective turbulent thermal conductivity
λ_i	decay constant of the ith group of delayed neutrons
ν_{eff}	effective turbulent viscosity coefficient
ξ	hydraulic resistance coefficient
ρ	density
$\tilde{\rho}$	reactivity
$\Delta\rho$	variation of the heat carrier density
$\bar{\rho}_r$	β-based efficiency of controlling facilities $\bar{\rho}_r = f(\Phi)$
$\bar{\rho}_T$	temperature effect of fuel reactivity, $\bar{\rho}_T = f(T_s)$
$\bar{\rho}_\rho$	density effect of heat carrier reactivity, $\bar{\rho}_\rho = f(\rho)$
$\bar{\rho}_\Sigma$	total reactor reactivity based on β
$\bar{\rho}_n$	non-controllable disturbances of reactivity
τ	time
τ_1	mean lifetime of one generation of neutrons
τ_r	operation time of the rated reactor
τ_s	time after the reactor shut-down
$\Delta\Phi$	displacement of the controlling facilities from their original position.

Subscripts

m	mean
M	modified
max	maximum
min	minimum
p	at p-const
s	solid phase
un	unsteady.

varied, the flow is turbulent, and the nonuniform heat release field is modeled on the bundle radius. The goal of the present article is also to derive the generalizing relations to be used for calculation of unsteady effective heat transfer coefficients that close a system of equations describing the flow in the bundles of helical tubes or rods.

Of importance is also to reveal the physical grounds of time variations of these transfer coefficients. It is known that the balance among the energy supplied to the turbulent flow, turbulent diffusion of liquid particles, and turbulence energy dissipation is seen only for the steady-mean flow. Such a balance is absent in the unsteady thermohydraulic process. In this case, any energy excess varies turbulence energy. This allows the observed time variation of transfer coefficients to be attributed to the change in the turbulent flow structure.

Unlike the previous studies of unsteady heat transfer in round and flat channels, when the heat transfer coefficient was analyzed within the framework of the one-dimensional flow description, the present article deals both with the temperature fields of heat carrier at the cross-section of the complex-geometry channel and with their time variation in a nonuniform heat release field. The differences of the experimental unsteady temperature fields from those calculated in the quasi-steady turbulent flow enable one to judge the nature of the time variation of the relative turbulence intensity for the considered type of the unsteady process. To evaluate this effect numerically the effective coefficient of turbulent diffusion (thermal conductivity) is used. It is determined experimentally by comparing the experimental and predicted temperature fields for each time moment with the use of the mathematical statistics methods [3–5, 8, 9].

Different types of the hydrodynamic unsteadiness are considered. These are: sharp increase and decrease of flowrate as well as its periodic variation at a constant heat power and simultaneous variations of power and flowrate. Computational examples of transient process, as applied to a transport nuclear reactor, are cited.

2. THEORETICAL CALCULATION OF TRANSIENT PROCESSES

The results of experimental study of the flow structure obtained for steady-mean isothermal flow [2, 4] can be a basis for constructing flow models in helical tube bundles and for considering theoretically new phenomena seen in turbulent swirling flows in such bundles. As for unsteady nonisothermal flow, these results can be used only assuming that some equilibrium turbulence structure exists, and the hypothesis for the quasi-steady turbulent flow structure is valid. At the same time it is known that in the case of unsteady nonisothermal swirling flow the influence of a number of new physical effects makes itself in time and space variations of turbulence characteristics. The variability of thermohydraulic parameters and thermophysical properties in space and time affecting flow causes the appearance of the pulsations of the quantities characterizing the thermophysical properties associated with temperature and pressure fluctuations as well as their correlations with temperature and pressure pulsations. In this case, when the inertia forces due to flow swirling act on flow of a medium with a variable density, new effects appear under which the nonuniformity of volume force fields can be a reason either for additional turbulization or for flow stabilization. The time variability of the mean value of the medium density results in volume deformation of turbulent vortices and, therefore, affects turbulence characteristics.

Based on the studies of the structure of the steady-mean flow, the flow model was adopted to mathematically describe turbulent flow of gas heat carrier (air, hydrogen, etc.) in a bundle composed of a great number of helical tubes or rods. According to this model, the real flow in the bundle was replaced by the one in a porous massif of a homogenized two-phase medium with a stationary solid phase. Sources of volume energy release q_V and hydraulic resistance $\xi \rho u^2/2d_{eq}$ [2, 4] were distributed in this massif in a certain manner. The two-temperature model was used for the unsteady flow and allowed time and space temperature distributions of heat carrier and solid phase to be calculated. In this case, the hydrodynamic equations were written in the quasi-steady approximation. The system of the equations describing this flow model for the axisymmetric problem, assuming that the disturbances of the parameters responsible for flow are not large and their duration much exceeds the propagation time of a sonic wave along the bundle, is of the form:

$$\rho_s C_s \frac{\partial T_s}{\partial \tau} = q_V - \frac{4\alpha\varepsilon}{d_{eq}(1-\varepsilon)}(T_s - T) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{sr}\frac{\partial T_s}{\partial r}\right) + \frac{\partial}{\partial X}\left(\lambda_{sx}\frac{\partial T_s}{\partial X}\right) \quad (1)$$

$$\rho C_p \frac{\partial T}{\partial \tau} + \rho u C_p \frac{\partial T}{\partial X} = \frac{4\alpha}{d_{eq}}(T_s - T) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{eff}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial X}\left(\lambda_{eff}\frac{\partial T}{\partial X}\right) \quad (2)$$

$$\rho u \frac{\partial u}{\partial X} = -\frac{\partial p}{\partial X} - \xi\frac{\rho u^2}{2d_{eq}} + \frac{1}{r}\frac{\partial}{\partial r}\left(\rho r v_{eff}\frac{\partial u}{\partial r}\right) \quad (3)$$

$$G(\tau) = 2\pi\int_0^{r_{bundle}} \varepsilon\rho u r\,dr \quad (4)$$

$$p = \rho R T \quad (5)$$

The system of equations (1)–(5) allows temperature fields to be calculated from experimental studies of unsteady thermal and hydraulic processes on the models of the bundles of helical tubes (rods) when heated by electric current.

When transient processes were simulated mathematically in the reactor, the heterogeneous nuclear reactor was replaced by the equivalent homogeneous one, to which the diffusion theory was then applied. In this case, the system of equations (1)–(5) had to be supplemented with the equations describing the reactor kinetics with regards to delayed neutrons and temperature and density reactivity effect feedbacks [9].

The neutron kinetic equations have the following form:

$$1^* \frac{\partial N}{\partial \tau} = (\bar{\rho}_\Sigma - 1)N + N_{fission} \quad (6)$$

$$\frac{\partial N_i}{\partial \tau} = \lambda_i(N - N_i), \quad i = 1, 2, \ldots, 6 \quad (7)$$

$$N_{\text{fission}} = \sum_{i=1}^{6} \frac{\beta_i}{\beta}. \quad (8)$$

The effects of varying the thermal and hydraulic parameters of the reactor core both on the properties of a neutron-multiplying medium and on the reactor power are taken into account by the relation for the reactivity effects:

$$\bar{\rho}_\Sigma = \bar{\rho}_r \Delta\Phi + \frac{\int_V \rho_T \Delta T_s \, dV}{\int_V dV} + \frac{\int_V \bar{\rho}_\rho \Delta\rho \, dV}{\int_V dV} + \bar{\rho}_n. \quad (9)$$

The effect of the β, γ-decay of fission fragments accumulated in the reactor on its energy release is allowed for by Antermayer-Vayls:

$$N_{\beta,\gamma} = 0.1\, N_o[(\tau_s+10)^{-0.2} - 0.87(\tau_s+2{\cdot}10^7)^{-0.2} - (\tau_s+\tau_r+10)^{-0.2} + 0.87(\tau_s+\tau_r+2{\cdot}10^7)^{-0.2}]. \quad (10)$$

The total heat power of the reactor will be equal to the sum: $N+N_{\beta,\gamma}$.

For the system of equations (1)–(10) to be solved, it must be supplemented with the boundary conditions:

$$x = 0: u = u_{bx}(r), p = p_{bx}, T = T_{bx}(r,\tau), T_s = T_{bx}(r,\tau)$$

$$r = 0: \left.\frac{\partial T_s(r,x,\tau)}{\partial r}\right|_{r=0} = 0, \quad \left.\frac{\partial T(r,x,\tau)}{\partial r}\right|_{r=0} = 0 \quad (11)$$

$$\left.\frac{\partial u(r,x,\tau)}{\partial r}\right|_{r=0} = 0$$

$$r = r_{\text{bundle}}: \left.\frac{\partial T_s(r,x,\tau)}{\partial r}\right|_{r=\text{bundle}} = 0 \quad (12)$$

$$\left.\frac{\partial T(r,x,\tau)}{\partial r}\right|_{r=\text{bundle}} = 0, \quad \left.\frac{\partial u(r,x,\tau)}{\partial r}\right|_{r=\text{bundle}} = 0 \quad (13)$$

$$x = 1: \left.\frac{\partial T_s(r,x,\tau)}{\partial x}\right|_{x=1} = 0, \quad \left.\frac{\partial T(r,x,\tau)}{\partial x}\right|_{x=1} = 0. \quad (14)$$

At $\tau = 0$ the temperature distributions $T_s(r,x)$ and $T(r,x)$ are assigned. For the tube bundles the quantities ρ_s, λ_{sr}, λ_{sx}, c_s entering into heat conduction equation (1) are determined by the formula from [4]. The coefficients of heat transfer α and hydraulic resistance ξ are determined according to the recommendations cited elsewhere in [4, 5].

The effective turbulent thermal conductivity λ_{eff} and the effective viscosity coefficient ν_{eff} entering into energy equation (2) and motion equation (3) and used to close the system of equations (1)–(10) must be determined experimentally or theoretically for each of the considered types of unsteadiness. If it is assumed that the turbulent Prandtl and Lewis numbers are equal to unity:

$$Pr_T = \rho\nu_{\text{eff}}c_p/\lambda_{\text{eff}} = 1, \quad Le_T = \rho D_{\text{eff}}c_p/\lambda_{\text{eff}} = 1$$

then it is sufficient to determine from experiment the effective turbulent diffusion coefficient D_{eff} which is:

$$K_{\text{un}} = D_{\text{eff}}/ud_{\text{eq}}. \quad (15)$$

in a dimensionless form. The coefficients λ_{eff} and ν_{eff} at each time moment and at each point of space will be determined by the expressions:

$$\lambda_{\text{eff}} = K_{\text{un}}\rho u c_p d_{eq} \quad (16)$$

$$\nu_{\text{eff}} = K_{\text{un}} u d_{\text{eq}}. \quad (17)$$

The dimensionless coefficient K_{un} in equations (16) and (17) describes the transport properties of the turbulent flow in time but it is invariable for the entire flow region at a fixed time moment τ. The parameters ρ, u and c_p entering into equations (16) and (17) depend on both time and position of a design cell in space when thermal and hydraulic processes are modeled numerically in bundles of helical tubes or rods. In what follows, at each time moment of the unsteady process temperature, velocity and concentration fields are assumed to be similar, which follows from the conditions $Pr_T = 1$ and $Le_T = 1$. Moreover, it is assumed that at each fixed time moment the transfer coefficients λ_{eff} and ν_{eff} depend on the derivatives of some effective mean values of temperatures and velocities in the swirling flow where turbulence diffusion and its convective transfer with a mean flow velocity [2, 4] are substantial.

Therefore, based on the hypothesis for similarity and the mathematical formalism, the proposed method to close equations (1)–(10) by using the experimental coefficients λ_{eff} and ν_{eff} is approximate and requires no strict physical grounds. This closing procedure was substantiated experimentally in [3–5, 8, 9]. By this closing procedure it is assumed that some equilibrium turbulence structure (equilibrium of coarse turbulent vortices with an averaged velocity field) exists at each time moment or the problem must be similar, although obviously such requirements are not formulated.

The system of equations (1)–(10) subject to both boundary conditions (11)–(14) and the experimental closing dependences of the coefficient K_{un} on the determining similarly numbers was solved by the numerical methods.

Equations of heat conduction (1) and energy (2) were solved by the variable-direction method [4]. The numerical analogs of the equations were written in an implicit form and were solved by the sweep method. Gasdynamics equations (3)–(4) were solved by the sweep method using Simuni's substitutions. These solutions were then matched through state equation (5) and the iteration cycles [4]. Neutron kinetics equations (6)–(8) were solved by Ya. V. Shevelev's proposed linear interpolation method. The process convergence was controlled by a heat carrier temperature, whose error did not exceed 0.5%. The time step was chosen according to Curant's stability condition:

$$\Delta\tau/\Delta x \leqslant 1/(|u|+a) \tag{18}$$

where a is the sonic velocity and Δx is the design step along the x-coordinate.

3. TRANSIENT PROCESSES IN THE NUCLEAR REACTOR OF THE VEHICULAR POWER PROPULSION PLANT

As an example of using the developed theoretical flow model governed by the system of equations (1)–(10) subject to the appropriate initial and boundary conditions (11)–(14) as well as the proposed approximate closing procedure for this system, consider the numerical simulation of a transient process when the power of the nuclear reactor of the multiple-regime power propulsion plant [6] increases at a transition from a power to a propulsion engine regime. At the same time heat carrier (hydrogen) flowrate increases with growing power. In calculations, the limitations on heat fluxes and temperatures of fuel helical rods were allowed for. This process must be performed rapidly and with a maximum efficiency of hydrogen flowrate. Furthermore, a maximum magnitude of input reactivity and a rate of its input (minimum allowable period of reactor going up) permitting the nuclear reactor safety to be achieved are the important limitations. Indeed, according to Nordheim's equation establishing a link between the reactivity $\tilde{\rho}$ and the reactor period t_r:

$$\tilde{\rho} = \frac{K_{\text{eff}}-1}{K_{\text{eff}}} = \frac{\tau_1}{t_r K_{\text{eff}}} + \sum_{i=1}^{6} \frac{\beta_i}{1+\lambda_i t_r} \tag{19}$$

in the neutron–spectrum reactor close to the fast one (lifetime $\tau_1 \approx 10^{-5}$ s), the reactivity input exceeding the effective fraction of delayed neutrons causes the chain reaction to run away and the prompt neutron reactor to go up. In equation (19) the reactor period

$$t_r = \frac{1}{(1/N)(\mathrm{d}N/\mathrm{d}\tau)} \tag{20}$$

is the time, for which the neutron density (or power) increases e times.

Calculations were made when the positive reactivity varied linearly up to $\sim 0.9\ \beta$ with velocity $\Delta\beta/s$, as applied to the channel–vessel nuclear reactor with a thermal neutron spectrum (lifetime $\tau_1 = 10^{-3}$ s), for the mean lifetime of one generation of neutrons with regard to the presence of delayed neutrons:

$$\bar{\tau}_1 = \sum_{i=1}^{6} \beta_i t_i + \tau_1 \approx 0.1\ \text{s} \tag{21}$$

and the quantity

$$\beta = \sum_{i=1}^{6} \beta_i \approx 0.0075$$

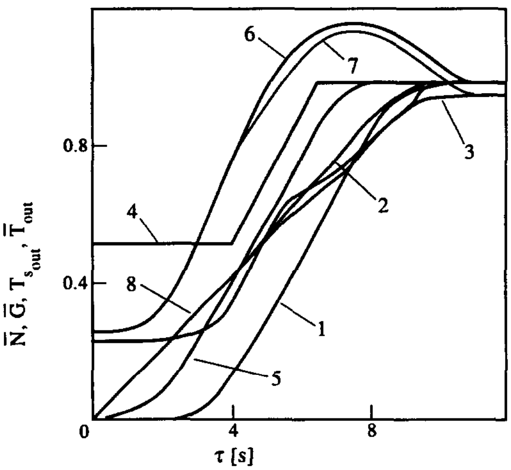

Fig. 1. Transient process in the nuclear reactor at different initial power levels and time variations of heat carrier flowrate: (1–4) variations of dimensionless $\bar{N}$, $\bar{T}_{s_{out}}$, $\bar{T}_{out}$ and $\bar{G}$ at the initial power level $N_{\text{initial}} = 200$ kW; (5–8) at $N_{\text{initial}} = 1$ mW.

when uranium-235 served as fissible substance. The hydrogen flowrate varied linearly in time and goes out of its rating value (Fig. 1) for 3 s. Figure 1 plots the time variation of the dimensionless power $\bar{N} = N/N_o$, flowrate $\bar{G} = G/G_o$, solid phase temperature $\bar{T}_{s_{out}} = (T_{s_{out}}/T_{s_{out}})_o$ and heat carrier temperature $\bar{T}_{out} = (T_{out}/T_{out})_o)$, based on their rating values under the propulsion operating conditions: $(T_{out})_o \approx 2900$ K, $N_o = 300$ MW. It is seen that a transition from the starting power level of the power regime (200 kW) to that of the propulsion one (300 MW) occurs for 9 s and a temperature of $\sim$2900 K is reached in 10 s after displacing the controllers. The solid phase temperature does not exceed the allowable one. The time variation of reactivity due to the displacement of the controllers and with regard to the temperature and density effects of reactivity occurs smoothly with some inflection at $\tau = 9$ s [9]. Different variations of the hydrogen flowrate (Fig. 1) were varied to decrease the time of achieving rating parameters with respect to the heat carrier temperature. It is seen that a required value of the temperature T_{out} can be attained in 5 s after the onset of the transient process if the gas flowrate varies linearly, starting with the time moment $\tau = 0$. However, in this case, the temperatures of the solid phase and hydrogen are approximately 15% in excess of their rating values.

4. EXPERIMENTAL PROCEDURES OF STUDYING TRANSPORT FLOW PROPERTIES

Figure 2 is the schematic of the experimental setup for studying the unsteady heat transfer process with a time variation of heat carrier. Unlike the previous devices considered in [3, 4], the distinctive feature of the present setup is the use of special facility 17 for varying flowrate in time which provides small inertia of the system. Operating as a camera diaphragm, this

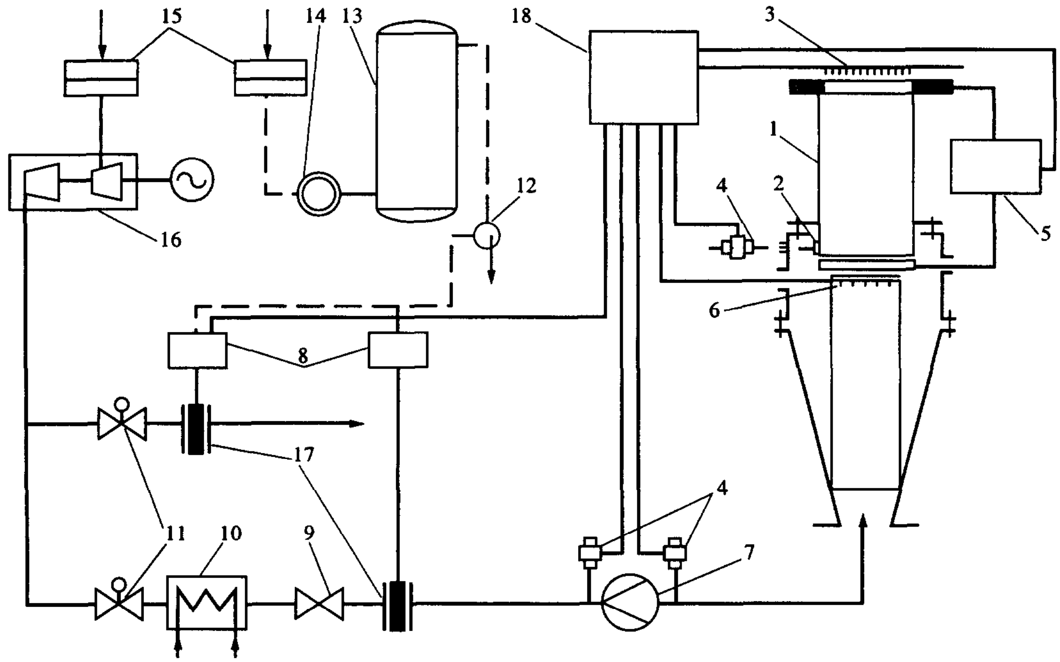

Fig. 2. Schematic of the experimental setup. (1) test section; (2) pressure take-off; (3) coordinate mechanism comprising a thermocouple comb; (4) pressure transducer; (5) d.c. generator; (6) thermocouples; (7) flow nozzle; (8) pneumatic drive; (9) gate: (10) refrigerator; (11) automatic-controlled gates; (12) reducer; (13) receiver; (14) compressor; (15) filter; (16) turbocompressor; (17) facility for varying flowrate; (18) automatic control and measurement system.

facility alters the area of the useful cross-section of the pipeline. This facility is placed in front of standard nozzle 7 that meters air flowrate. Facility 17 operates as follows. An electric signal of the automatic control and measurement system of device 18 via the amplifier enters the electromagnetic valve of pneumatic distributor 8, to which compressed 0.6 MPa air is supplied. Compressed air from the pneumatic distributor enters one of two spring energy accumulator-equipped chambers depending on the considered type of unsteadiness associated with increasing or decreasing flowrate and displaces the chamber rod. This rod transports a force via the arm to rotate diaphragm blades in a required direction. To model a periodic time variation of flowrate, altering the area of the useful channel cross-section by the diaphragm was provided by the d.c. gear-equipped motor and by the crank- and connecting-rod assembly instead of pneumatic chambers. A frequency of varying heat carrier flowrate was determined by the speed of the electric motor that was set by a special controller. Air was used as heat carrier. The time lag of the system measuring the unsteady air flowrate by means of the controlling computer was found experimentally and constituted no more than 0.1 s (complete time lag of a signal from the moment of its supply to the response of facility 17 up to fixing a quantity to be measured).

Unsteady mixing of heat carrier was studied experimentally by the method of heat diffusion from line heat sources (zone heating method). This method was realized in a bundle of 151 helical tubes when the central group (zone) composed of 37 helical oval tubes was heated electrically. These tubes were electrically insulated from non-heated ones. The bundle was 0.5 m long. Experiments were conducted on tubes, whose wall thickness was 0.2 mm and the maximum oval size was $d = 12.3$ mm. The tube twisting pitches were $s = 12\ d$ and $s = 6.1\ d$. The number $Fr_M = s^2/dd_{eq}$ characterizing the swirling intensity of the flow under study was 220 and 57. The tubes were manufactured of stainless steel 12X18H10T. Heat carrier temperature fields were measured at the outlet cross-section of the bundle by means of a comb containing 10 chromel–alumel thermocouples made of the 0.1 mm dia wire and mounted on the coordinate-screw mechanism at the centres of the bundle cells at the points with the coordinates $r/r_{\text{bundle}} = 0.073$; 0.128; 0.193; 0.265; 0.334; 0.408; 0.479; 0.625; 0.770 and 0.916. The air temperature at the bundle inlet was measured by three thermocouples. In some experiments, the wall temperature was measured by the thermocouples welded to the inner surface of the tube at the cross-sections $x/l = 0.7$, 0.8, 0.9 and 0.95 at $r/r_{\text{bundle}} = 0.078$, 0.109, 0.132, 0.170 and 0.187. The time lag of the chromel–alumel 0.1 mm diameter wire thermocouples was 0.04–0.1 s.

In experiments with constant heat release, the heat supply to the heated part of the bundle was kept constant by the power controller. The automatic system, comprising the measuring-computational complex IVK-2, d.c. generator, pressure transducer, generator power controller, turbocompressor, facility of varying flowrate, and the information processor [3, 4], was used for automatic control of experiment, data acquisition and processing.

To conduct experiments with simultaneous variations of heat carrier flowrate and heat power, the initial values of the generator power and heat carrier flowrate were mixed. Furthermore, the information processor sent a signal of the start of the IVK-2 which at given time moments sent signals that controlled the facility of varying flowrate and the power controller which varied flowrate and set finite heat power. Temperatures and pressures to be measured were converted into electric signals that were amplified and recorded by the information processor. The latter converted the analog signals into the digital ones and conveyed them into the INK-2 for further processing and storage.

Experiments with time acceleration of the heat carrier flow were conducted in the flow parameter range: $N = 5.2$–8.7 kW; $Re_1 = (5.57$–$8.46)\cdot 10^3$; $G_2/G_1 = 1.12$–1.77 and $Fr_M = 57$ and 220.

Experiments with time deceleration of the heat carrier flow were performed on the helical tube bundles with the same numbers $Fr_M = 57$ and 220 at $N = 5.2$–8.6 kW; $Re_1 = (8.93$–$11.92)\cdot 10^3$ and $G_2/G_1 = 0.605$–0.890. The flow parameters realized in experiments with a periodic variation of the heat carrier flowrate were varied over the following ranges: $N = 4.7$–8.8 kW; $G_{max}/G_{min} = 1.28$–3.75; $\Delta G/G_m = (\pm 12.2$ to $\pm 65)\%$; $t = 4$–68 s and $Fr_M = 57$ and 220.

Experiments with simultaneous variations of heat carrier flowrate and heat power were made over the following range of the flow parameters: $N_1 = 0$–11.9 kW; $N_2 = 0$–12.9 kW; $Re_1 = (2.58$–$12.45)\cdot 10^3$; $G_2/G_1 = 0.492$–4.59.

The developed methods and the designed experimental setup allowed unsteady mixing of heat carrier in bundles of helical tubes to be studied with a sufficient accuracy. The investigation results and their analyses are reported in Part 2 of the present article.

5. CONCLUSIONS

(1) The empirical method for closing a system of the equations describing flow and heat transfer in complex-geometry channels is developed and is based on both the hypothesis for a local similarity of transfer processes and the mathematical formalism to solving the unsteady thermohydraulic problem.

(2) Applicability of the developed computational–experimental approach to solving unsteady problems is substantiated by agreement between the predicted values of transient process parameters and the experimental ones for different types of hydrodynamic unsteadiness on the models using the method of heat diffusion from a group of line heat sources.

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