INTERCHANNEL HEAT-CARRIER MIXING WITH PERIODIC FLOW-RATE VARIATION OVER TIME IN SPIRAL-TUBE BUNDLES

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The nonsteady results of investigating the nonsteady heat-carrier mixing in bundles of spiral tubes with periodic variation in air flow rate by heat diffusion from a central group of electrically heated tubes are outlined. The frequency and amplitude of flow-rate oscillation influence the variation in heat-carrier temperature and effective turbulent-diffusion coefficient. The transition from steady thermal conditions to conditions with regular periodic variation in the temperature and the relative coefficient of heat-carrier mixing for the given type of nonsteady hydrodynamic conditions is considered.

INTRODUCTION

Nonsteady thermal processes are realized in startup, transient, and emergency conditions of heat-exchanger operation. The nonsteady transfer coefficients may differ significantly here from their quasi-steady values, and depend on the rates of variation in the nonsteady boundary conditions. In the channels of complex shape formed by bundles of spiral tubes, the nonsteady conditions have a greater influence on the transfer coefficients than in circular tubes [1]; this is associated with the characteristics of turbulent flow in such channels. Nonsteady mixing of the heat carrier in spiral-tube bundles with variation in the rate of thermal loading and constant heat-carrier flow rate was investigated in sufficient detail in [1].

The mixing processes with variation in heat-carrier flow rate over time and constant thermal load were investigated in [2, 3]. With sharp decrease in heat-carrier flow rate, increase in the effective turbulent diffusion coefficient $K_N = D_{tN}/ud_e$ is seen initially, with subsequent gradual approach to the quasi-steady value K_{qs}. Taking account of nonsteady effects by means of the relative mixing coefficient

$$\varkappa = K_N/K_{qs}, \tag{1}$$

the influence of the determining parameters (Fo_b, Fr_M, G_2/G_1) in this coefficient may be described by dependences obtained in [2]: when $Fo_b = 0\text{-}0.514 \cdot 10^{-3}$ and $Fr_M = 57\text{-}220$

$$\varkappa = [2.95 \cdot 10^{-4} (G_2/G_1)^{-11.94} + 0.993](1 + 927\,\mathrm{Fo}_b), \tag{2}$$

when $Fo_b = 0.514 \cdot 10^{-3}\text{-}1.4 \cdot 10^{-2}$, $G_2/G_1 = 0.605\text{-}0.765$, and $Fr_M = 57$

$$\varkappa = [2.95 \cdot 10^{-4} (G_2/G_1)^{-11.94} + 0.993](2.57\,\mathrm{Fo}_b^{-0.0437} - 2.11), \tag{3}$$

and when $Fo_b = 0.514 \cdot 10^{-3}\text{-}0.9 \cdot 10^{-2}$, $G_2/G_1 = 0.579\text{-}0.611$, and $Fr_M = 220$

$$\varkappa = [0.645\,(G_2/G_1)^{-0.818} + 0.04](0.398\,\mathrm{Fo}_b^{-0.165} + 0.13), \tag{4}$$

where

$$\mathrm{Fo}_b = \frac{\lambda_b \tau}{c_{pb} \rho_b d_h^2}; \tag{5}$$

$$\mathrm{Fr}_M = s^2/dd_e. \tag{6}$$

The influence of Fr_M is seen in the increase in κ with decrease in Fr_M and in that the approach to the quasi-steady value K_{qs} is extended to larger Fo_b with decrease in Fr_M.

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With decrease in G_2/G_1, for a bundle with given Fr_M, there is increase in the nonsteady dimensionless effective diffusion coefficient K_N for the given Fo_B and prolongation of the transition to K_{qs}.

In the case of sharp increase in the heat-carrier flow rate, different laws of the variation in κ as a function of Fo_b, Fr_M, and G_2/G_1 are observed. Thus, initially, there is a sharp decrease in κ with subsequent smooth transition to $\kappa = 1$ at a time $\tau \sim 10$ sec as follows [3]

$$\varkappa = A\,\mathrm{Fo}_b^n + C, \tag{7}$$

where A, n, C are functions of G_2/G_1. Equation (7) holds when $Fo_b \geq 8 \cdot 10^{-3}$ and $\kappa \lesssim 1$.

As well as the nonsteady hydrodynamic conditions associated with sharp decrease or increase in heat-carrier flow rate with constant thermal load, periodic variation in the heat carrier over time may be observed in various heat exchangers. In this case, the laws for the effective coefficient K_N may differ from Eqs. (2)-(4) and (7), and may be a function of the frequency (period) and amplitude of harmonic oscillation of the flow rate. Since there are no data on transient processes with periodic flow-rate variation, it is necessary to determine the transfer characteristics for nonsteady hydrodynamic conditions of this type. The interchannel heat-carrier mixing in a bundle of spiral tubes with periodic variation in air flow rate over time is investigated experimentally.

1. EXPERIMENTAL METHOD

The influence of periodic variation in heat-carrier flow rate over time on the transfer coefficients is investigated on an experimental apparatus described in detail in [1, 3]. The periodicity of the variation in heat-carrier flow rate over time is the result of variation in the cross-sectional area of the channel using a diaphragm controlled by an electric motor with reducing gears by means of a crankgear mechanism (Fig. 1). The frequency of variation in heat-carrier flow rate is determined by the rate of rotation of the electric motor, which is established by means of a special regulator. The automated system controlling the experiment and the collection and analysis of the experimental data at a certain point switches on a device which produces periodic variation in heat-carrier flow rate with specified frequency in specified intervals. Simultaneously, experimental data are collected, and the thermal load applied to the central heated part of the spiral-tube bundle is maintained

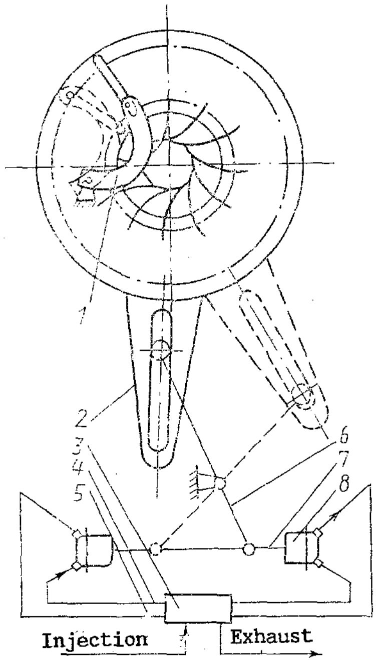

Fig. 1. Device for changing the flow rate: 1) opening and closing cross section of lobe channel; 2) clamp; 3) distributive pneumovalve; 4) pipeline for fresh air supply; 5) pipeline for air exhaust; 6) lever; 7) coupling rod; 8) pneumatic chamber.

TABLE 1. Parameters Realized in Experiments with Spiral-Tube Bundle When $Fr_M = 57$ in the Case of Periodic Variation in Heat-Carrier Flow Rate

t, sec	N, kW	G_{max}, kg/sec	G_{min}, kg/sec	$G_{\tau=0}$, kg/sec	$\frac{G_{max}}{G_{min}}$
20	7,0	0,3108	0,1938	0,1938	1,625
20	7,8	0,3064	0,1898	0,3064	1,614
20	5,7	0,2754	0,1591	0,1591	1,731
20	5,8	0,2726	0,1629	0,2726	1,673
20	8,8	0,303	0,184	0,253	1,647
20	8,0	0,303	0,183	0,258	1,656
13	7,7	0,305	0,181	0,259	1,685
13	7,4	0,307	0,179	0,186	1,715
13	7,8	0,305	0,178	0,298	1,713
48	8,3	0,323	0,192	0,263	1,682
50	8,4	0,323	0,191	0,321	1,691
46	8,4	0,323	0,194	0,197	1,665
68	8,5	0,321	0,196	0,264	1,638
68	8,5	0,322	0,195	0,321	1,651
65	8,1	0,322	0,197	0,198	1,626

constant by applying power to the regulator. On heating the central group of 37 spiral tubes, the method of heat diffusion from linear sources is used to determine the effective turbulent-diffusion coefficients at different times, by comparing the experimental and theoretical temperature fields of the heat carrier [1].

The experiments cover a range of variation in heat-carrier flow rate G = 0.15-0.32 kg/sec, $Re = 5.9 \cdot 10^3 - 1.2 \cdot 10^4$, and thermal power N = 2.5-8.5 kW. The period of variation in heat-carrier flow rate is within the range t = 4-70 sec, and the ratio of maximum and minimum flow rates varies in the range $G_{max}/G_{min} = 1.2-1.73$ ($G_{min}/G_{max} = 0.62-0.83$). The basic parameters of the experiment for a bundle with $Fr_M = 57$ are shown in Table 1.

Experiments are conducted on bundles of 151 spiral tubes of oval cross section (length 0.5 m). The tubes (wall thickness 0.2 mm) have a maximum dimension of the oval d = 12.3 mm and a spiral spacing s = 12d and 6.1d ($Fr_M = 57$ and 220). The temperature field of the heat carrier is measured in the output cross section of the bundle by means of a manifold of 10 Chromel—Alumel thermocouples with a wire diameter of 0.1 mm placed by means of a coordinate mechanism at the center of cells with $r/r_h = 0.073$, 0.128, 0.193, 0.265, 0.334, 0.408, 0.479, 0.624, 0.770, and 0.916. Air is used as the heat carrier. Typical graphs of the variation in air flow rate over time are shown in Figs. 2 and 3.

2. RESULTS AND ANALYSIS

Experimental results for the temperature field of the heat carrier in a bundle with $Fr_M = 57$ when the period of flow-rate variation $t \approx 20$ sec and the amplitude is characterized by the ratio $G_{max}/G_{min} \approx 1.62$ ($G_{min}/G_{max} \approx 0.62$) are shown in Fig. 2. In the case of transition from steady conditions with the minimum flow rate $G_{min} = 0.19$ kg/sec to periodic conditions with $G_{max}/G_{min} \approx 1.62$ (Fig. 2a), the heat-carrier temperature is less than in steady operating conditions of a spiral-tube bundle and in two periods ($\tau = 2t = 40$ sec) the temperature variation takes on a regular character typical of harmonic oscillations with the same period t = 20 sec.

The minimum of the temperature-variation curve is shifted in phase by approximately 0.25t along the axis τ relative to the maximum of the curve $G = G(\tau)$; this is due to thermal inertia of the spiral-tube walls. For this case, the relative effective diffusion coefficient $\kappa = K_N/K_{qs}$ decreases by 30% in the first moments after the appearance of flow-rate perturbation, in accordance with Eq. (7) for flow acceleration with N = const. Then, with decreases in flow rate, κ increases, reaching a maximum at $G = G_{min}$ ($\kappa = 1.2$). Subsequently, κ varies periodically over time; its maxima correspond to minima of the heat-carrier flow rate G_{min}, while minima of κ correspond to G_{max}.

To determine κ, the experimental temperature field of the heat-carrier is compared at each instant with the theoretical temperature field in the output cross section of the spiral-tube bundle for the experimental process parameters. The theoretical temperature field of the heat carrier is determined by the method proposed in [1, 2].

On transition from steady conditions with maximum flow rate $G_{max} = 0.31$ kg/sec to con-

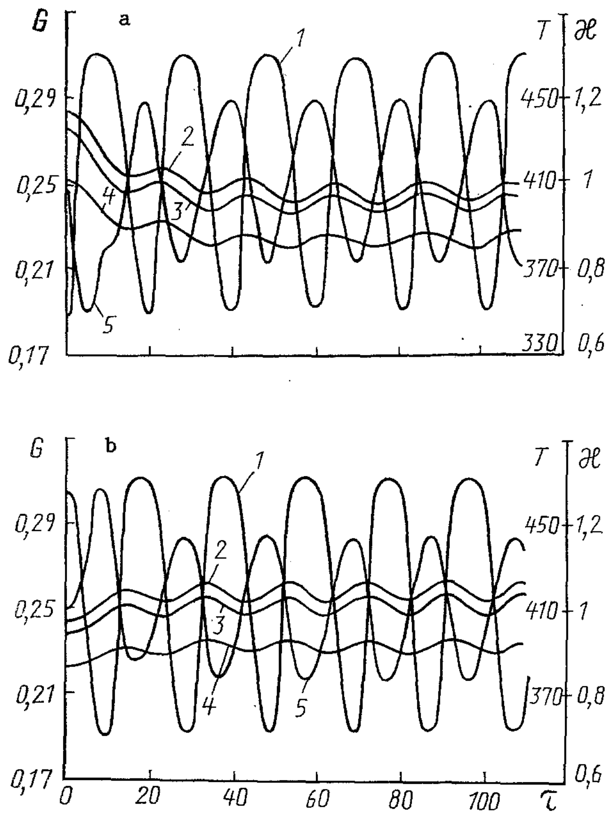

Fig. 2. Variation in heat-carrier flow rate and temperature and in the relative diffusion coefficient over time when N = 7.1 kW, G_{max}/G_{min} = 1.625, and t ≃ 20 sec (a) and when N = 7.7 kW, G_{min}/G_{max} = 0.62, and t = 20 sec (b): 1) G = G(τ); 2-4) temperature for r/r_h = 0.073, 0.193, and 0.334; 5) κ = κ(τ). G, kg/sec; T, K; τ, sec.

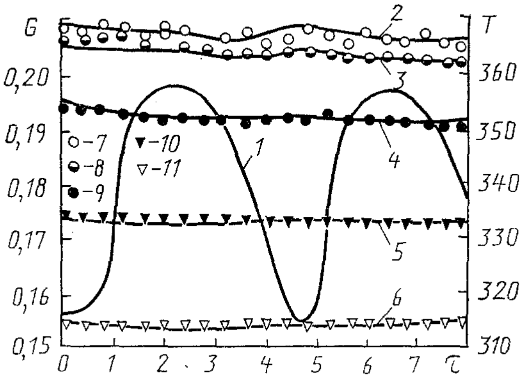

Fig. 3. Comparison of experimental and theoretical temperature fields of heat carrier for N = 2.5 kW, G_{max}/G_{min} = 1.28, and t = 4 sec; 1) G = G(τ); 2-6) calculation with r/r_h = 0.073, 0.193, 0.334, 0.479, 0.624; 7-11) experiment with r/r_h = 0.073, 0.193, 0.334, 0.479, 0.624.

ditions with periodic flow-rate variation when G_{min}/G_{max} = 0.62 and the period t = 20 sec, the heat-carrier temperature increases initially and takes on a regular character with the same period t = 20 sec in the course of one and a half periods (τ = 1.5t; Fig. 2b). The minimum of the temperature curve is shifted in phase by 0.25 of a period relative to the maximum of the curve of G = G(t), again because of thermal inertia of the tube walls, as in the first case. With decrease in flow rate G, the coefficient κ characterizing the influence of nonsteady conditions on the interchannel mixing in the spiral-tube bundle increases initially by 28% in accordance with Eqs. (2)-(4), which is also characteristic of the case of sharp reduction in flow rate; the maximum of κ corresponds to a minimum of the flow rate G_{min}. With increase in G, κ decreases, reaching a minimum at $G = G_{max}$. The minimum of κ is $\kappa = 0.87$ for the given experiment. Then κ undergoes harmonic variation in the interval 0.83-1.17 (Fig. 2b). Analogous behavior is observed for t = 13 and 68 sec (G_{max}/G_{min} = 1.685 and 1.638; Table 1).

With decrease in the period of flow-rate variation to t = 4 sec and with $G_{max}/G_{min} = 1.28$ ($G_{min}/G_{max} = 0.78$), there are no effects due to deviation in κ from one (deviation of K_N from K_{qs}), i.e., the oscillation of the flow rate has no pronounced influence on the temperature. This is evident from Fig. 3, where the experimental temperature field of the heat carrier when $Fr_M = 220$ is compared with theoretical results obtained by the method of [1, 2] when $K_N = K_{qs}$ for harmonic variation of the flow rate with t = 4 sec and $G_{max}/G_{min} = 1.28$. The agreement of the experimental and theoretical temperatures is adequate.

The influence of the period (frequency) of flow-rate variation when $Fr_M = 57$ with constant G_{max}/G_{min} is experimentally investigated with t = 12.5, 20, 50, and 70 sec. It is found that the amplitude of temperature variation over time in regular conditions increases with increase in t (±3, ±6, ±13, and ±17°, respectively), i.e., the increase in the frequency of periodic variation in heat-carrier flow rate with the same amplitude leads to smoothing of the temperature variation over time.

The results obtained indicate significant difference of the transfer properties of nonsteady flow from those of a steady turbulent flow, which must be taken into account in calculating the nonsteady temperature fields for nonsteady hydrodynamic conditions of the given type.

CONCLUSIONS

1. In calculating the nonsteady temperature fields of the heat carrier in the case of periodic variation in heat-carrier flow rate over time, the influence of the period (frequency) of harmonic oscillation of the flow rate on the amplitude of temperature variation must be taken into account.

2. At large oscillation frequency of the flow rate, the influence of nonsteady conditions of this type on the temperature field may be neglected (when $t \lesssim 4$ sec).

3. Immediately after the introduction of the perturbation in the system, for approximately four periods of flow-rate oscillation, Eqs. (2)-(4) and (7) for sharp slowing and acceleration of the heat-carrier flux may be used to calculate the relative mixing coefficient κ.

NOTATION

K, dimensionless effective turbulent-diffusion coefficient; κ, relative heat-carrier mixing coefficient; u, velocity; d_e, equivalent diameter; D_t, effective turbulent-diffusion coefficient; Fo_b, Fourier number; Fr_M, modified Froude number; G, heat-carrier flow rate; τ, time; d_h (r_h), diameter (radius) of tube bundle (housing); ρ, density; λ, thermal conductivity; c_p, specific heat; d, maximum dimension of oval spiral-tube profile; Re, Reynolds number; N, thermal loading power; t, period of flow-rate oscillation; s, spiral step of tube profile; r, radial coordinate. Indices: N, nonsteady; qs, quasi-steady; b, mean mass; 1, 2, parameters before and after the introduction of the perturbation in the heat-carrier flow rate.

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