HEAT-TRANSFER EQUATION IN PULSATIONAL CONDITIONS OF TRANSITIONAL FLOW REGION AT SUPERCRITICAL PRESSURES OF AROMATIC HYDROCARBONS

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Experimental heat-transfer data in transitional flow conditions of toluene when $P > P_{cr}$, $t_f < t_m$, $t_c/t_m = 0.32\text{-}1.90$ are outlined; a heat-transfer equation is proposed for the case in which thermoacoustic pressure self-oscillations are excited.

Aromatic hydrocarbons — in particular, toluene — are promising organic working media for autonomous power units in which the decomposition temperature considerably exceeds the temperature of pseudophase transition. This offers the possibility of realizing toluene in cycles at supercritical pressures (SCP) [1]. In this context, theoretical recommendations regarding the heat transfer in a broad range of parameter variation in the transitional flow region of SCP toluene at $t_f < t_m$, $t_c \geq t_m$ and in pulsational conditions are of scientific and practical interest.

Numerous experimental data confirm the increase in heat-transfer intensity in heated tubes in an oscillating fluid flow [2, 3]. In this case, the heat-transfer intensity depends on the amplitude—frequency characteristics (AFC) of the pressure fluctuations generated. In many heat exchangers operating at SCP, heat transfer occurs when the fluid flow core is heated to the pseudocritical temperature, but the wall temperature is higher. According to [4, 5], the amplitude of the thermoacoustic pressure self-oscillations (TASO) generated may increase with increase in heat flux, and amounts to tens of percent of the statistical value, while the TASO frequency is a few kHz.

Experimental data on the TASO frequency spectrum at SCP confirm that the pressure oscillations of the fluid are most often excited at the resonant eigenfrequency of the heated channel.

Detailed study is required to elucidate the conditions of TASO appearance and determine the influence of individual factors on the heat-transfer intensity at SCP. In the present work, these questions are considered for the transitional flow region of toluene with mixed convection in pulsational conditions.

The experimental apparatus consists of an open circulational loop. The heat-carrier is set in motion by a four-piston pump. A description of the apparatus, the experimental method, and the error in measuring individual quantities may be found in [6].

The apparatus is fitted with a unit for measuring the TASO AFC. The primary element of the measuring system is a watercooled DDI-21 pressure sensor, placed in the middle of the heated section by means of an adapter. The tube is heated by means of a low-voltage alternating current. The reliability of the experimental data on the heat transfer is established by calibration experiments. Heat-transfer data obtained in laminar motion of toluene and at SCP, with a wall temperature of less than 150°C and small temperature differences between the wall and the fluid are in good agreement with the results from the well-known equation [7]

$$\mathrm{Nu}_{f,d} = \mathrm{Nu}_0 (\mu_f/\mu_c)^{0,15}, \ \mathrm{Nu}_0 = 0{,}33\,\mathrm{Re}_{f,d}^{0,50}\,\mathrm{Pr}_f^{0,43}\,(d/x)^{0,40}. \quad (1)$$

The heating section of the tube is preceded by an unheated section, ensuring thermodynamic stabilization of the flow. The wall temperature is measured by chromel—copel thermocouples uniformly distributed in eight cross sections over the length of the heated section.

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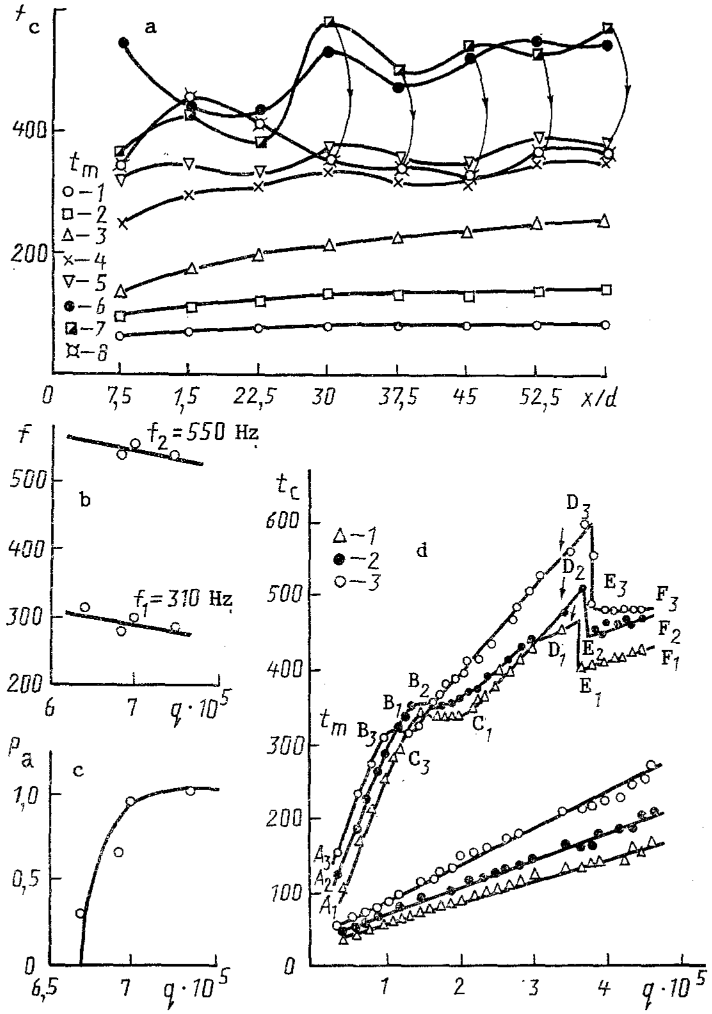

Fig. 1. Variation in wall temperature and amplitude-frequency characteristics of thermoacoustic pressure self-oscillations when ρu = 286 kg/m²·sec; t_f^{in} = 23°C; Re_{in} = 2000; a, b, c) P = 7.2 MPa, $q \cdot 10^5$, W/m²: 1) 0.866; 2) 1.487; 3) 2.453; 4) 3.010; 5) 4.393; 6) 7.127; 7) 7.390; 8) 7.451; d) P = 4.6 MPa, ρu = 286 kg/m²·sec; x/d = 17 (1), 25 (2), 43 (3); Re_{in} = 2000. The arrows indicate the direction of wall-temperature variation with excitation of pressure TASO of the heat carrier. t_c, °C; f, Hz; q, W/m²; Pa, MPa.

The creation of acoustic reflection boundaries at the input and output of the experimental tube is ensured by expansion chambers. The amplitude and frequency are measured by means of an S1-68 oscillograph and an SK4-56 spectral frequency analyzer calibrated by a G1-36A acoustic-frequency generator. The spectrograms are recorded by an N-337/1 high-speed graph plotter.

In the pressure range $0 \le P_{co} \le 2P_{co}$, the sensor characteristic is linear (P_{co} is the control pressure, corresponding to the pressure in the middle of the measurement range cited in the rating of the DDI-21 inductive sensor, P_{co} = 3.0 MPa).

The error in measuring the TASO amplitudes is 10%; that for the frequency is 5%. Experiments are conducted with upward motion of the toluene. At fixed pressure, mass velocity, and input temperature, the heat flux is increased smoothly, in small steps, up to the appearance of pressure TASO. The heat flux just below the onset of oscillation is taken as the lower boundary of the region of existence of pressure TASO. The increase in heat flux is limited by the wall temperature of 600°C (taking account of the temperature of thermal decomposition of toluene). The chosen apparatus corresponds in accuracy class to that used in investigating TASO in [8]. In the experiments, the parameter variation is as follows:

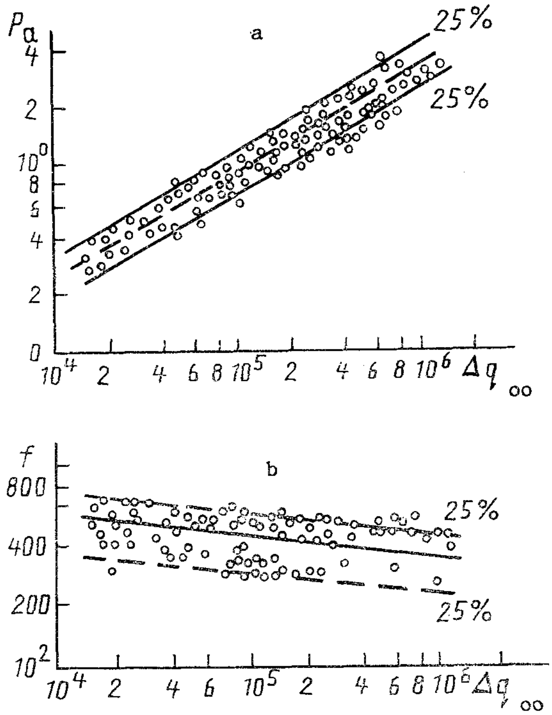

Fig. 2. Amplitude and frequency of the first harmonic of pressure TASO as a function of the heat-flux increment relative to the onset of oscillations. Δq_{oo}, W/m².

P/P_{co} = 1.12-1.80; t_c/t_m = 0.32-1.90; t_f/t_m = 0.06-0.90; $q = 2\cdot10^4$-$2\cdot10^6$ W/m²; Gr = $2\cdot10^3$-$3.5\cdot10^6$; $\rho u = (0.2\text{-}2)\cdot10^3$ kg/m²·sec.

The working channel is a seamless tube of stainless steel 1Kh18N10T with internal diameters of 1.50, 1.90, and 3.50 mm and wall thicknesses of 0.25 and 0.55 mm.

The variation in wall temperature over the heated section of the tube is shown in Fig. 1a (ℓ = 540 mm, ℓ_{heat} = 235 mm, d_{ex}/d_{in} = 4.0/3.5 mm). At $P > P_{cr}$, $t_c < t_m$, the wall temperature varies as in normal convective heat transfer (curves 1-3). When $t_c > t_m$, the monotonic variation of t_c over the length of the tube is disrupted (curves 4-7). The wall temperature becomes undulatory. This is explained by strong variation in the physical properties of the fluid in the wall layer and the influence of free convection of the heat extraction. The appearance of TASO disrupts the flow stability and influences the hydrodynamics of the flow in the boundary layer, which leads to increase in intensity of heat transfer [9].

The TASO AFC are shown in Fig. 1b and c. In the given experiments, the frequency spectrum consists of two harmonics, one being almost a multiple of the other. The frequency of the first harmonic is 310 Hz.

The amplitude of the acoustic pressure increases with increase in heat flux (Fig. 1c). At large heat fluxes, the growth rate of the pressure amplitude decreases. The onset of pressure TASO leads to reduction in wall temperature over the length of the heated section (Fig. 1a, curve 8). Further increase in the heat flux has little influence on the temperature conditions of the wall. Thus, the heat-trasfer intensity depends on the acoustic mechanism of heat transfer. It follows from the TASO spectrograms and oscillograms that resonant oscillations of the heat carrier are excited in an acoustically isolated tube (standing waves). The frequency of the first harmonic is considerably less than the resonant frequency of the longitudinal oscillations of the fluid in the channel with no heating. Some reduction in resonant frequency with increase in heat flux in the experiments is associated with decrease in the sound velocity to the output, which may be explained by increase in the mean-mass temperature of the fluid over the length of the heated tube.

The possibility of improving the heat transfer in the region of pseudophase transition of the liquid is confirmed by the graph of $t_c = f(q)$ plotted for certain tube cross sections

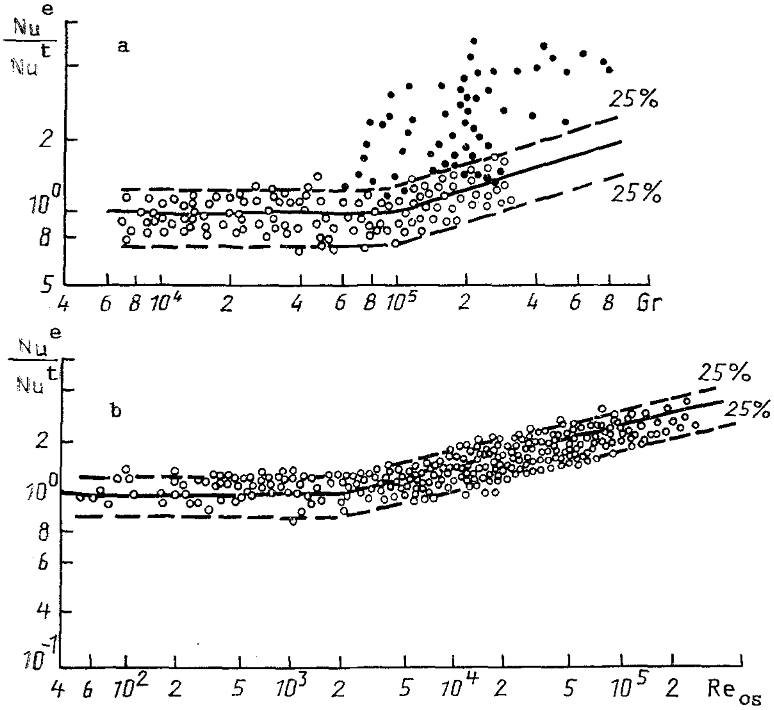

Fig. 3. Heat transfer at SCP and pulsational conditions in the transitional region of induced toluene pressure.

far from the input (Fig. 1d); on this curve, there are two successive regions where the heat transfer is increased. In the initial section (section AB), the wall temperature increases monotonically, as in normal conditions of convective heat transfer. As the wall temperature approaches t_m (t_m = 332°C) for the liquid (the region of strong variation in physical properties of the material), section BC is formed on the curve of $t_c = f(q)$; it is similar in external form to the plateau appearing in bubble boiling. On this section, the wall temperature does not much change, and heat transfer increases. The formation of a point of inflection corresponds to the condition that the thermophysical properties of the material in the wall layer of liquid pass through extremal values; in particular, when $t_c = t_m$, the isobaric specific heat in the wall layer of liquid passes through a maximum.

Further increase in the heat flux leads to the formation of section CD, where $t_c > t_m$ and the isobaric specific heat of the liquid in the boundary layer passes through a maximum and then decreases, which is evidently the reason for some reduction in heat-transfer intensity in this section. The wall temperature increases from C to D. With TASO excitation in section DE, the wall temperature decreases sharply. With increase in heat flux in the tube, a broad frequency spectrum is excited. The first harmonic is 370 Hz.

The amplitude of pressure TASO in the experiment increase nonlinearly with increase in heat flux. Its maximum value is no greater than 0.32 MPa. Further increase in heat flux leads to weak increase in wall temperature on section EF. This is associated with the influence of pressure TASO on the heat-transfer intensity. The improved conditions appearing when $t_f < t_m \leq t_c$ may conventionally be divided into two sections on the graph of $t_c = f(q)$: 1) BCD, where the initial improvement in heat transfer occurs; 2) DEF, the section of secondary improvement in heat transfer due to TASO. As shown in [10], data on the heat transfer in the region of secondary improvement are not generalized using the known dimensionless equations because of the failure to take account of the acoustic heat-transfer mechanism in pulsational conditions, which leads to additional intensification of the heat transfer. The variation in acoustic-pressure amplitude and frequency of the first pressure harmonic on the increment in heat flux $\Delta q_{oo} = q - q_{oo}$ relative to the onset of oscillational conditions is shown in Fig. 2, from which it is evident that the amplitude increases and the frequency decreases with increase in heat flux.

On the basis of the spectrograms obtained, it may be noted that the first harmonic (eigenfrequency of the liquid column in the channel) of pressure TASO is most often generated in the channel; higher harmonics, beginning with the second, are damped. As a rule,

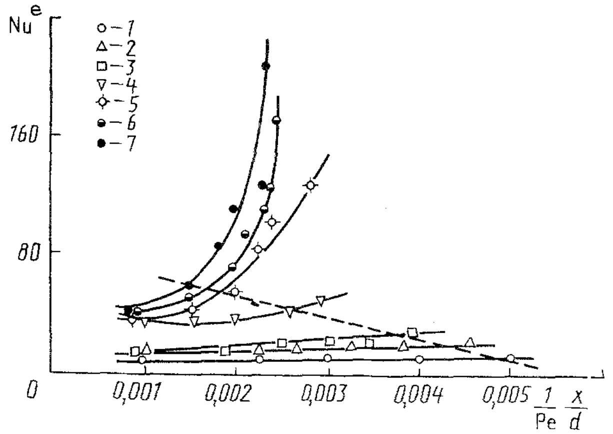

Fig. 4. Curves of $Nu^e = f(x/dPe)$ in pulsational flow conditions; P = 4.5 MPa; ρu = 480 $kg/m^2 \cdot sec$; t_f^{in} = 25°C; $q \cdot 10^5$, W/m^2: 1) 0.638; 2) 2.916; 3) 3.783; 4) 5.740; 5) 7.315; 6) 7.700; 7) 9.088.

their amplitudes decrease with increase in the number of the harmonic. Thus, with self-excitation of a standing pressure wave in the tube, the amplitude and frequency of the first harmonic may serve as a measure of the heat-transfer intensity.

The influence of free convection on the heat transfer is shown in Fig. 3a. When $Gr \leq 8 \cdot 10^4$, the influency of free convection on the heat-transfer intensity may be disregarded, and the heat transfer may be calculated from the equation for viscous flow conditions [10]

$$Nu_{f,d}^{t} = 0{,}047\, Re_{f,d}^{0,70}\, Pr_f^{0,43}\, (\mu_f/\mu_c)^{-0,20}\,. \tag{2}$$

Experimental data on the heat transfer in the transitional region with upward motion and a temperature difference t = 100-300°C, $Gr \geq 8 \cdot 10^4$ before the onset of pulsational conditions are described by the equation for viscous—gravitational flow conditions

$$Nu_{f,d}^{p} = 0{,}00162\, Re_{f,d}^{0,70}\, Pr_f^{0,43}\, Gr_{f,d}^{0,30}\, (x/d)^{-0,15}. \tag{3}$$

Experimental data obtained in pulsational flow conditions deviate greatly from the theoretical results (filled points in Fig. 3a). The description of heat transfer in conditions of TASO generation (pulsational conditions) requires special consideration. In the excitation of oscillations in the heat-carrier flux, the oscillatory Reynolds number is introduced: $Re_{os} = v_{os} d_{in}/\nu_f$; $v_{os} = A\omega = 2\pi Af$. After transformation

$$Re_{os} = 2\pi A \rho_f f d_{in}/\mu_f = 2\pi P_a f d_{in}/\mu_f. \tag{4}$$

The product $A\rho_f$ has the dimensions of pressure. Having measured the amplitude of the acoustic pressure, Eq. (4) may be used to calculate the heat-transfer intensity in pulsational conditions.

The experimental data are analyzed by means of the dependence $Nu^e/Nu^t = f(Re)$; the equation for calculating the heat transfer in pulsational flow conditions is (Fig. 3b)

$$Nu_{f,d}^{pu} = 0{,}00136\, Re_{f,d}^{0,70}\, Pr_f^{0,43}\, Gr_{f,d}^{0,30}\, (Re_{os} \cdot 10^{-3})^{925}\, (x/d)^{-0,15}. \tag{5}$$

To calculate the quantities in the expression for the oscillatory Reynolds number, the following empirical equations are obtained for toluene, within the limits of parameter variation in the present work

$$P_a = 0{,}524 \cdot 10^{-5} \Delta q_{oo} Re_{me,\ f,d}^{0,25}\, Gr_{me,f,d}^{0,20}\,, \tag{6}$$

$$f = 6{,}1 \Delta q_{os}^{-0,15}\, Re_{me,f,d}^{0,50}\, Gr_{me,f,d}^{0,14}\,. \tag{7}$$

The boundary of onset of pulsational conditions with respect to the heat flux and wall temperature is determined by the empirical relations

$$q_{oo} = 3950P^{0,40}\rho u^{0,50}(L_{heat}/d_{in})^{0,25}, \quad (8)$$

$$t_{c,me}^{oo} = [120(q_{oo}/\rho u i_m)^{0,88} + 1]\, t_m. \quad (9)$$

These equations enable the limit of appearance of high-frequency thermoacoustic instability of toluene to be determined from the known process parameters and geometric dimensions of the tube.

It was noted above that, in the transitional flow region, a strong influence of free convection on the heat transfer is observed. However, in [11], the influence of free convection on heat transfer was considered prior to the onset of pulsational flow conditions, disregarding some additional factors. Therefore, it is necessary to refine the critical tube length X_{cr} at which the shift from viscous to viscous—gravitational conditions of convective heat transfer occurs and the critical Reynolds number corresponding to this tube length in the region of high-frequency thermoacoustic instability.

The influence of free convection on the heat-transfer intensity always begins from the output region of the tube and is shifted to the initial section with increase in heat flux (Fig. 4). A point of inflection occurs here on the curve of $Nu^t = (1/Pe)(x/d)$. In such experiments, ordinary convective heat transfer corresponding to viscous flow conditions is seen in the initial section of the tube, whereas viscous—gravitational conditions of convective heat transfer are present in the final part of the tube (curves 4-7 corresponding to the generation of pressure TASO).

Analysis of experimental heat-transfer data in pulsational conditions yields the equations

$$X_{cr}^{pu} = 0{,}310^{-6}(\mathrm{Re}/\mathrm{Gr})_{f,d}^{1,30}\,\mathrm{Gr}_{in,f,d}^{1,15}, \quad (10)$$

$$\mathrm{Re}_{in,f,d}^{pu} = 0{,}003\,\mathrm{Re}_{in,f,d}^{1,20}(\mathrm{Gr}_{f,d}\,\mathrm{Pr}_f\cdot 10^{-3})^{0,33}\,\mathrm{Re}_{os}^{0,25}. \quad (11)$$

Using Eqs. (5)-(11), the heat transfer in pulsational conditions may be calculated when $P > P_{cr}$, $t_f < t_m \le t_c$; $\Delta t = 150\text{-}300°C$; $Re = (0.2\text{-}1)\cdot 10^4$.

NOTATION

t_c, wall temperature; t_m, temperature of the fluid corresponding to the maximum specific heat at constant pressure; t_f, mean-mass temperture of the fluid; P, static pressure; P_{cr}, critical pressure; ℓ, length of tube; ℓ_{heat}, heated length of tube; d_{in}, internal diameter; d_{ex}, external diameter; x, distance from input to heated section; i_m, enthalpy of medium corresponding to a maximum of isobaric specific heat at the pseudophase-transition temperature; f, frequency of first harmonic; P_a, acoustic pressure; A, amplitude of liquid-particle displacement in standing wave; μ_f, kinematic viscosity; ν_f, dynamic viscosity; ρ_f, density; v_{os}, oscillatory velocity; ω, angular frequency; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; Gr, Grashof number; Pe, Peclet number; Re_{os}, oscillatory Reynolds number; X_{cr}, critical tube length in pulsational conditions; Re_{cr}, critical Reynolds number in pulsational conditions; q, specific heat flux; q_{oo}, limiting heat flux at onset of oscillation; $\Delta q_{oo} = q - q_{oo}$, increment in heat flux; ρu, mass velocity. Indices: pu, pulsational conditions; f, fluid; oo, onset of oscillation; e, experimental; t, theoretical; in, input; out, ouput; me, mean value calculated from values in tube cross sections at points of thermocouple attachment.

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