HEAT AND MASS TRANSFER IN A FIELD OF IR RADIATION UNDER CONDITIONS OF SWIRLING FLOW OF AN OPTICALLY ACTIVE MEDIUM

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Results are presented of investigations of the heat and mass transfer process under deep oxidation of low-concentration hydrocarbons in a volume of a gas—air optically active medium on a catalyst surface.

1. FORMULATION OF THE PROBLEM

Quests of the flow, interaction, and formation of expanding gas streams in cylindrical channels with axial swirling apparatus have been examined in sufficient detail in [1-3]. Features of the change in the temperature field of such stream along the radius and length of the cylindrical channel that are characteristic for jet flow of a gas in a near-wall layer have been investigated [3].

In connection with the development of reactor apparatus on the basis of vortex tubes [4], the need occurs to study heat and mass transfer processes for the conduction of chemical reactions on the inner catalytic surface of cylindrical channels.

In contrast to known research [5], the influence of the external binary IR radiation field on the heat and mass transfer process in a swirling stream of an optically active medium is confirmed in this paper.

Such a process is realized in practice during conduction of a heterogeneous exothermal chemical reaction on the surface of a solid catalyst in an external diffusion domain under the action of a flux of IR radiation generatable by a special source. Placement of the IR radiation source along the cylindrical channel axis and of the catalyst on the tube wall produces conditions for the motion of the swirling optically active medium between two IR radiation fields. The IR radiation from a special generator proceeds from the axial domain while from a heated catalyst from the circumference.

2. METHODOLOGY OF THE EXPERIMENT

Tests were performed at a pressure of the medium in the inlet chamber to 0.15 MPa in the vortex reaction tube of 80 mm inner diameter and up to 2.0 mm thickness of the catalyst film on its inner surface for a total 800 mm length and 350 mm long reaction zone. An axial swirling unit with two or three spiral channels at an angle of 65...78° to the tube axis are mounted in the initial section of the tube. The area of the channel through section was 0.05...0.2 of the area of the tube section.

Heat insulated KhK thermocouples of 0.3-mm electrode diameter submerged in the catalyst film were placed with a 50 mm spacing along the whole length of the tube. The thermocouples were calibrated in a thermostat with up to 0.1°C accuracy. Measurements of the temperature of the medium in the inlet chamber and at the reactor output were performed with mercury thermometers. The apparatus housing was heat-insulated with an asbestos cement coating up to 40 mm thick. The source of IR radiation was an electric lamp of KGT-200-1000-1 type according to OST 160.535.024-76.

Composition of the initial optically active medium was the following: air + 0.3 mass% propane. During the test the composition of this mixture varied long the tube length because of progress of the propane oxidation reaction.

The intensity of the IR radiation flux from the electric lamp was regulated by changing the voltage at the lamp terminals through a transformer of RNO-10 type.

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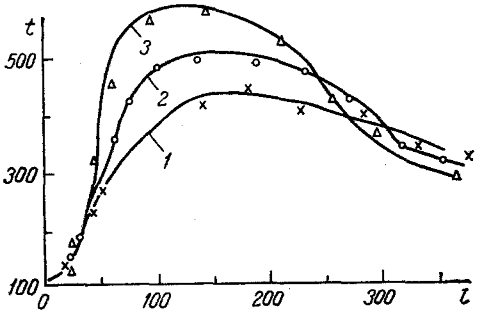

Fig. 1. Change in temperature of the catalyst surface along the length of the reaction zone for different flow modes of the medium: 1) Re = $1\cdot10^2$; 2) $1\cdot10^3$; 3) $1\cdot10^5$. t, °C; ℓ, mm.

Analysis of the optically active medium for CO_2 content was performed on a VTI-2 analyzer. Selection of samples was accomplished by a sampling apparatus in the reactor housing.

The air flow rate was measured by RS-7 rotameters and the propane flow rate by a RS-3 type rotameter.

The influence of the IR radiation intensity on catalyst heating and on the optically active medium moving in the form of a swirling flow during progress of the chemical reaction was verified in a series of tests.

3. RESULTS OF THE EXPERIMENTS

Certain characteristic results of the experiments are represented in the figure where temperature profiles are displayed of the catalyst surface for different rates of efflux of the optically active medium from the swirler nozzle. It is seen that as the flux velocity increases an abrupt rise in the catalyst surface temperature is observed in the entry zone. This is explained by intensification of the mass transport from the stream core to its circumference because of turbulization.

Heating of the catalyst can be quite significant in the case of a rise in concentration of the component being oxidized in the initial mixture above the critical value [6] independently of the temperature of the medium. The temperature gradient between the stream core and circumference was 400...500°C in our tests.

The later equilibrium of the temperature profile along the tube length is explained by lowering of the concentration of the initial component because of its entrance into the oxidation reaction in the entry zone.

Spinning of the optically active medium in the cylindrical channel raises the heat elimination intensity because of increasing the stream velocity relative to the channel surface, the appearance of a rotational velocity component, a rise in the turbulization level in the entrance jets, and the origination of Tayler—Goertler vortices at the catalyst surface. The experimental value of the magnitude of the Stanton criterion along the length of the reaction zone corresponded to the computed value for a plane wall for a turbulent boundary layer with correction factor m = 1.6-1.8

$$\mathrm{St} = 0{,}03\,\mathrm{Re}^{-0{,}2}\,\mathrm{Pr}^{-0{,}6}\,m. \qquad (1)$$

The jet flow velocity of the stream rather than the mean delivery velocity along the whole channel section was used in computation of the Re criterion. Taking into account the spiral jet nature of the flow of the optically active medium, the similarity equation for the heat transfer has the form

$$\mathrm{Nu}_{\mathrm{z.p}} = 0{,}023\,\mathrm{Re}_{\mathrm{z.p}}^{0{,}8}\,\varphi_{\mathrm{T}}\varphi_{\mathrm{H}}\,\mathrm{Pr}^{0{,}4}. \qquad (2)$$

The coefficients φ_T, φ_H, are functions taking into account the influence of the nonisothermy of the macrovortex motion and the growth of turbulence on the heat transfer process. The value of the coefficients φ_T and φ_H is complicated to determine since they depend on not only the geometric characteristics of the swirling unit and the technological parameters of the entrance medium but also on the wave and fluctuating changes of the temperature field originating along the length and section of the cylindrical channel.

In practical computations $\varphi_T\varphi_H = 1.03\text{-}1.08$ for a 0.105-0.160 MPa range of variation in the initial pressure level of the medium.

According to the theory of Landau and Levich [7, 8], damping of the turbulence near a solid surface is determined by the presence of a viscous sublayer. In this sublayer in a gaseous medium the convective transport of substance in the normal direction to the surface will influence the magnitude of the heat and mass transfer.

In a bilateral field IR radiation raises the temperature at the viscous sublayer of an optically active medium, resulting in diminution of its thickness and growth of the heat and mass transfer from the catalyst surface to the stream core. In the absence of a chemical reaction in the optically active medium, the temperaure of the inner wall surface of the reactor catalyst will be determined by the emissivity of the absorbing surface and the intensity of the IR radiation. The quantity of energy absorbed by the wall can be determined by computational means from the condition that the cylindrical (r, θ, z) coordinate system and the z axis coincide with the apparatus axis while the geometry of the system possesses azimuthal symmetry $(d/d\theta = 0)$. The transformed Lambert-Bear equation [9] can be written in the form

$$R'_\lambda = \frac{r_1}{r_2} R^0_\lambda \exp\{-k_\lambda n(r_2 - r_1)\}. \tag{3}$$

We determine the value of $R_\lambda{}^0$ by the Planck formula [10] by assuming that the spiral of the source is an absolutely black body

$$R^0_\lambda = \int\limits_{\lambda_1}^{\lambda_2} \frac{c_1 d\lambda}{\lambda^5 \exp\left(-\frac{c_2}{\lambda T}\right) - 1}. \tag{4}$$

The quantity of energy absorbed by the optically active medium components under stationary condition from a computation per mole of substance is determined by this expression. For an exact determination of the quantity of energy absorbed by the wall (by the catalyst) the emissivity of its surface must be taken into account.

For dynamic conditions the total quantity of absorbed energy is detemined as a function of the concentration of the optical active substances in the working medium and the velocity of stream motion of the medium. The catalyst temperature is determined by the thermal effect of the reaction and the absorbable energy from the IR light source. Assuming that all the heat of the oxidation reaction is accumulated on the catalyst surface its temperature can be computed from the equation

$$T = T_0 + \Delta T_1 + \Delta T_2 + \Delta T_3, \tag{5}$$

where $\Delta T_3 = Q/(\alpha F)$.

For an adiabatic process [11]

$$\Delta T_1 = \frac{Q_1}{ac_p\rho} W(T). \tag{6}$$

The rise in catalyst surface temperature because of IR light absorption is

$$\Delta T_2 = \frac{Q_2}{c_{\text{к}} G}. \tag{7}$$

The results of experiment on the change in temperature of catalyst heating during delivery of an optically active medium containing up to 0.3 mass % hydrocarbon components in a field of IR radiation in the form of a high-speed swirling flow indicate the possibility of conducting a deep oxidation process without heating the whole mass of gas to achieve a 100% degree of transformation of the hydrocarbon components into CO_2 and H_2O. The dependence of the heating temperature on the flow rate of the swirling initial gas jets is shown. The proposed computational dependences in the temperature yield not more than 15% relative error in the investigated range of variation of the Reynolds criterion and the hydrocarbon concentration.

NOTATION

R'_λ, density of IR radiation reaching the wall, W/cm^2; r_1, r_2, radii of the IR radiation source and the channel, m; R_λ^0. total IR radiation density within the wavelengths $\lambda_1 < \lambda < \lambda_2$; n, concentration of the hydrocarbon component, mole/liter; k, absorption coefficient of the medium; c_1 and c_2, constant dependent on the wavelength measurement units; T_0, initial temperature of the medium; ΔT_1, temperature rise for an adiabatic chemical reaction process; W(T), reaction rate; a, thermal diffusivity; ρ, density; Q_1, quantity of reaction heat; c_p, specific heat of the medium; Q_2, quantity of heat absorbed by the catalyst; c_k, specific heat of the catalyst; Q, quantity of heat transmitted by convection from the wall to the stream; α, heat elimination coefficient; F, heat transfer surface; G, mass; and ℓ, length of the reaction zone.

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EFFECTS OF THE KINETICS OF FUSION OF THE SURFACE LAYER OF METAL BY A CONCENTRATED ENERGY FLUX

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A study is made of the fusion of a thin layer of metal by a powerful heat flux and the subsequent crystallization of the melt as a result of heat removal into the body of the material, with allowance for the kinematics of the process.

Increasingly wide practical use is being made of concentrated energy fluxes to alter the surface properties of metals [1]. The fusion of a thin layer of metal makes it possible to obtain different microstructures — including amorphous microstructures — directly on the surface of massive specimens. The fusion problem is usually solved in a Stefan formulation [1-3], where the temperature at the phase boundary is equal to the equilibrium melting point. However, this approach is valid only in the case where the amount of superheating which occurs at the phase boundary is negligible, i.e., when the heat flux is sufficiently small [4, 5]. This precludes consideration of the physics of the process, since a small but finite amount of superheating must occur [6, 7] for fusion to take place. Allowance for the kinetics of crystallization of the thin fused layer of metal is necessary to determine the regimes by which the surface of a massive specimen is transformed to the amorphous state [8]. In order to study the initial stage of fusion, determine the superheating at the phase boundary, and establish the effect of this superheating on surface temperature, the depth of fusion, and the

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