heat flux; T, temperature; α, coefficient of heat transfer to the channel wall; λ, coefficient of thermal conductivity of the liquid; ρ, density; C, heat capacity; d_h, hydraulic diameter of the channel; S, pitch of the spiral fins; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; Pr_t, turbulent Prandtl number; ε, coefficient of turbulent transfer of momentum; ν, kinematic viscosity; μ, dynamic viscosity; R_m, radial coordinate of the surface where $\tau = 0$; r_s, radius of curvature of the spiral trajectory; G, mass flow rate of the liquid; β, angle of inclination of the spiral trajectory of an element of liquid to the z axis at the radius r. Indices: 1, 2, conditions at the inner (convex) and outer (concave) walls of the channel, respectively.

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INFLUENCE OF SOLID DEPOSITS ON THE INCEPTION OF SELF-EXCITED THERMOACOUSTIC OSCILLATIONS IN HEAT TRANSFER TO TURBULENT FLUID FLOW IN TUBES

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UDC 66.096.5.536.24:532.517.4

It is established experimentally that solid carbon deposits formed in heat transfer to kerosene in small-bore tubes induce self-excited thermoacoustic oscillations.

Perspectives have changed considerably in recent years in regard to the nature of solid deposits formed in heat transfer to a fluid. It was previously thought that they merely created an additional heat resistance and caused the temperature of the heat-transfer surface to rise accordingly. It has now been established that the physicochemical and hydrodynamic processes occurring in solid deposits can exert an appreciable influence on the various heat-transfer characteristics and can, depending on their nature and the regime parameters, degrade or improve heat transfer, alter the flow resistance, intensify self-excited thermoacoustic oscillations (STAO), decrease the velocity of sound propagation along the fluid flow, etc. [1-4].

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 49, No. 4, pp. 571-573, October, 1985. Original article submitted August 15, 1984.

0022-0841/85/4904-1155$09.50

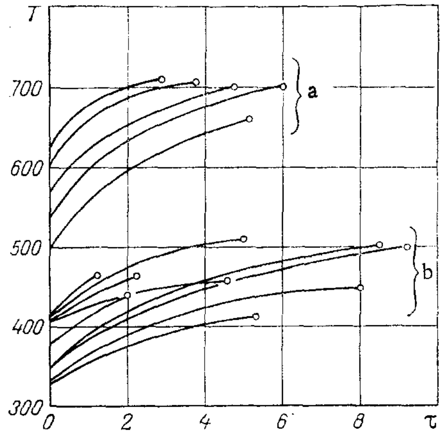

Fig. 1. Wall temperature T (°C) vs. time τ (min) in heat transfer to kerosene with the accompanying formation of solid deposits. a) In the annular ducts; b) in the tubes.

In the present note we discuss experimental results which show that solid deposits can initiate STAO, and this is absolutely inadmissible for many heat-transfer devices (e.g., in a system for the cooling of high-power electron tubes).

The experiments were carried out in kerosene (a petroleum fraction with boiling point in the interval 203-267°C) under supercritical pressure conditions ($P/P_{cr} \sim 2$) in turbulent flow (Re > 13,000). The heat-transfer device comprised a closed circulation loop of nonrusting tubes. The fuel element (FE) was heated by passing an electric current through it. Standard chrome steel 12Kh18N10T tubes with an outside diameter of 3 mm, an inside diameter of 2 mm, and a heated length of 60 mm were used for the FE assembly. The experiments were carried out in two different working sections: one with the fluid flowing inside the tube and one with the fluid flowing along the annular duct formed by the outer surface of the FE and a tubular plastic shield with an inside diameter of 4.5 mm. The construction of this type of working section is described in [5]. The experiments in a working section with an annular duct and a transparent outer wall made it possible to observe the process of the formation of solid deposits during the experiments.

All the experiments were carried out at a pressure of 40 atm, a fluid flow velocity of 10 m/sec, and a fluid temperature of 30-50°C. The wall temperature of the FE was measured with two thermocouples mounted at a distance of 15 mm from the ends of the heated zone. The thermocouple readings were recorded on the tape of a KSPP automatic potentiometer.

In the experiments with fluid flow through the interior of the FE, the wall temperature of the latter was measured on the outer surface, and in the outer-flow experiments it was measured on the inner surface. The temperature of the heat-transfer surface was calculated with allowance for the temperature drop across the wall thickness. Each experiment was performed with a fresh FE.

Figure 1 shows the experimental data in the form of curves characterizing the increase in the wall temperature of the FE during heat transfer to kerosene as a result of the formation of solid carbon deposits. The circle-points indicate the times of inception of STAO, which were determined according to the onset of a sharp noise ("whistle") and a drop in the wall temperature.

In the annular duct (upper group of curves) STAO occurred with a rise in the wall temperature to 660-710°C and in the case of fluid flow inside the FE they occurred when the wall temperature attained 410-510°C. The difference in the temperature at which STAO set in is caused by the different perimeters of the heated zone. Fedorov has determined previously [5] that the wall temperature corresponding to the inception of STAO increases with a decrease in the perimeter. Heating took place over 0.4 of the perimeter in the annular duct and over the entire perimeter in the inner-flow experiments.

The scatter of the data in each group of experiments is probably attributable to the fact that carbon deposits are formed nonuniformly on the cooled surface, affecting the wall temperature accordingly.

In our opinion, the reported results are of practical and scientific interest. Their practical significance does not require any elucidation; they demonstrate the potential danger of solid deposits for heat-transfer devices in which STAO are inadmissible. The above-described experiments are of scientific importance in that they expand our knowledge of the nature of solid deposits and the role that they can play in heat transfer to a fluid.

The inception of STAO in the above-described experiments cannot be initiated by an increase in the wall temperature of the FE, because the fluid is not in contact with the wall of the FE, but with the outer layer of solid deposits, whose temperature remains practically constant (and might even be lowered). What, then, is responsible for the inception of STAO? We propose to answer this question with the use of our concepts of the STAO mechanism based on the investigation of heat transfer in a transparent annular duct by means of high-speed motion pictures [6].

The inception of STAO in heat transfer to a turbulent fluid flow in tubes under supercritical pressure conditions is associated with the pseudoboiling regime that sets in at large temperature gradients between the tube wall and the fluid, in which case the core of the flow represents a "cold liquid" and the wall layer represents a "hot gas." Turbulent vortices of the hot-gas wall layer enter the cold core of the flow under the action of surface tension induced by the large difference in the densities, and they take the shape of spheres (or something close thereto), which are called pseudobubbles [7].

These pseudobubbles are rapidly cooled and compressed (collapse) in the cold core of the flow. Such a process is known to be accompanied by the emission of pressure pulses, which propagate along the fluid flow with the sound velocity. When these pressure pulses are reflected from any kind of acoustic obstacles, standing pressure waves are generated, which are called thermoacoustic oscillations. The causes of the inception of STAO in connection with the formation of solid deposits can be hypothesized on the basis of the foregoing conceptualization of the oscillation mechanism:

1) Solid deposits not only create additional heat resistance, but also increase the roughness of the cooled surface, which imparts turbulence to the wall layer of the fluid flow, and this is known to facilitate the inception of STAO [1].

2) The fluid is heated much higher in the pores of the carbon deposits than in the wall layer and, upon entering the cold flow core, intensifies the pseudoboiling process and thus promotes the inception of STAO.

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