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NATURAL CONVECTION IN A CLOSED VOLUME FILLED WITH VARIOUS SUBSTANCES

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The books of Gebhart and Jaluria et al. [1, 2] are devoted to natural convective heat transfer. In a closed volume, convective heat transfer differs significantly from heat transfer in free space [2]. A heated light liquid rises (to the cover) and displaces a cold liquid downward (to the bottom). Two accompanying processes occur: the formation of temperature-stratified liquid layers and the circulation of the liquid in the volume. These phenomena complicate the study of natural convection.

Thorough experiments [3] on heat transfer from a horizontal cylinder to air, water, and silicon oil in an isothermal vessel with diameter 20 cm and height 120 cm show that, with the edge losses eliminated by constructive means, the data in the developed laminar-regime region are in good agreement with the known dependences (see, for example, [4]). It was shown by Incropera and Yaghoubi [5] that heat transfer is significantly affected by the presence of an upper free cold surface, which results in the increase in the integral heat-transfer coefficient up to 200%.

In this paper, we present experimental results on natural convection in a closed vessel (working volume) with water, air, and Freon-13 at densities lower than the critical values in the saturated-vapor region and in the gas region behind the critical isotherm. We describe a setup that makes it possible to study the convective heat transfer when the state parameters are close to the critical ones.

Experimental Setup. The general view of the setup is shown in Fig. 1. The working volume 1 is a high-pressure vessel of Kh18N10T steel whose outer shape is cylindrical. The height of the vessel is 20 cm, its inner square cross section is 10 × 10 cm, and it is closed by flanges from top and bottom. The water jacket 2 maintains a constant temperature at the walls. To visualize convective processes, there are two windows 3 and 4 of diameter 54 cm in the working volume. The axis of the windows is directed horizontally and passes through the center of the working volume. There is a connector for the terminals of the temperature gauges and of the heater.

A thermostatic-control system 17 allows us to control temperature roughly and exactly in the jacket. By means of a water thermostat 9, the temperature is controlled with accuracy of 0.5°C. When the thermostat is switched off, the temperature is maintained by a low-power (40–60 W) heater 15, which is also used for temperature control. The liquid was additionally mixed by a mixer 6 mounted on the cover of a thermostat 5. Temperature fluctuations in the liquid do not exceed 0.05°C and are recorded by four temperature gauges 16 placed around the working volume. The temperature is taken by a platinum resistance thermometer 20 connected to the bridge circuit 21.

To visualize heat-transfer regimes, we used the simplest version of the schlieren method. The optical scheme is composed of a light source 10, a collimator 11, a lens 13, a light knife 12, and a shield 14 or a photocamera with a long-focus lens. The light source is a helium–neon laser.

The cylindrical heater is shown schematically in Fig. 2a, and its location in the volume is illustrated in Fig. 2b. The heater was made from a copper tube 1 with diameter 6 mm and length 96 mm. A 100-cm long ceramic straw 2 with a nichrome wire 3 soldered at the ends to copper terminals was tightly inserted into the tube. At the ends, the heater was closed by Plexiglas holders, which reduces considerably the edge effects. The wire resistance was 5.31 Ω. The temperature was taken by a MT-64 semiconductor temperature-sensitive

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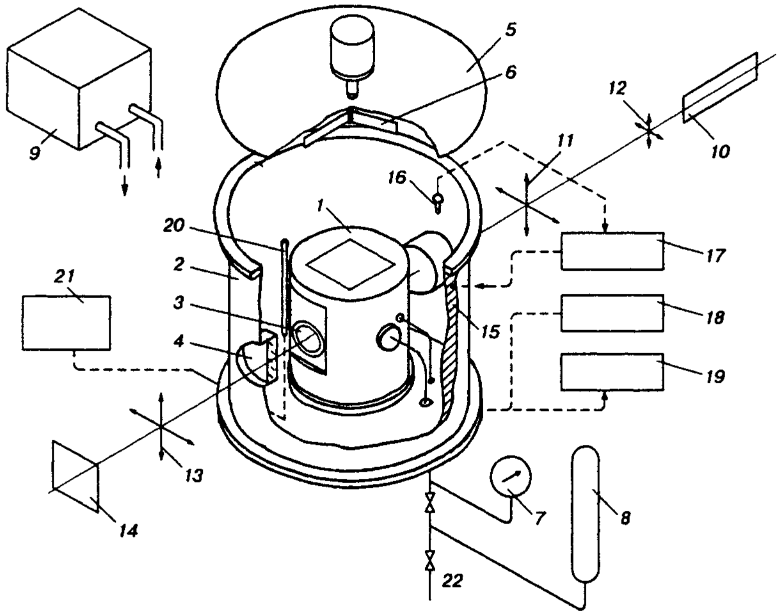

Fig. 1

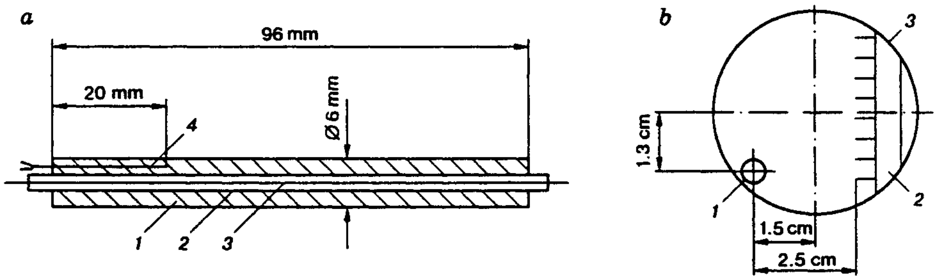

Fig. 2

microresistor 4 built in the copper body of the heater with the power $W = I^2R$. The heater was fed from a B5-47 stabilized constant-current source 18. The current I was controlled by a B7-21 ampere voltmeter. The resistance R of the temperature-sensitive microresistor was measured by a Shch-301 ohmmeter 19 and was then recalculated relative to the temperature by the formula $R(T) = R_0 \exp(-B/T)$, where R_0 and B are temperature-sensitive microresistor constants.

Experimental Technique. Experiments with water and air were performed at room temperature and atmospheric pressure, while in experiments with Freon, the state parameters were varied. The critical parameters of Freon-13 ($CClF_3$) are as follows: pressure $P_* = 3.96$ MPa, temperature $T_* = 302.02$ K, and density $\rho_* = 580$ kg/m^3.

The working volume was prevacuumed through valve 22 of a suction pump and was then filled with Freon at room temperature from a container 8. We controlled the pressure (by a manometer 7) and the temperature. The amount of the substance was determined from the equation of state [6]. The thermostat was then switched off, and the working temperature T_0 in the thermostat was reached. In reaching the working temperature in the thermostat and in smoothing the Freon temperature over the volume, convective flows ceased: the clean, uniformly illuminated field was observed on the screen. During the tests, the thermostat was switched off, and the temperature was maintained by a control heater. The temperature T_0 of the medium was recorded by a gauge mounted on the heater. The heater was then switched on, and the temperature T of the heater was recorded. At the end of the experiment, the heater was switched off, and the temperature of the medium was checked.

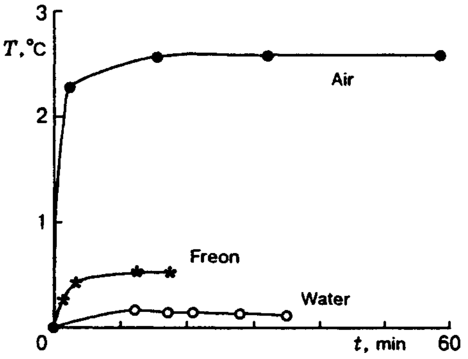

Fig. 3

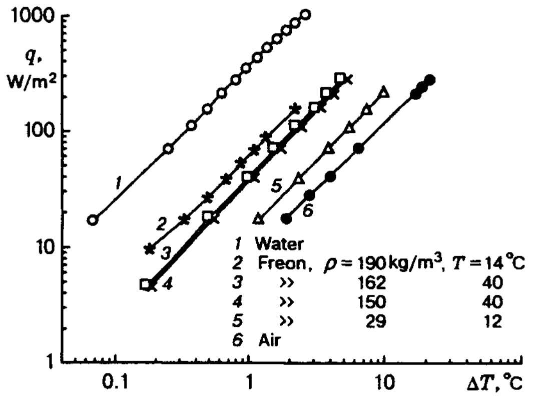

Fig. 4

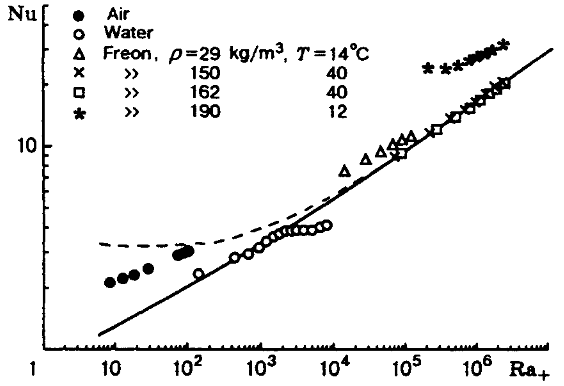

Fig. 5

TABLE 1

Medium	A	m
Water	330	1.14
Freon, ρ, kg/m^3		
190	58	1.13
162	40	1.24
150	39	1.24
29	12.6	1.21
Air	8.8	1.1

The temperature of the heater was established for 5–15 min for each value of the heat flux q. Figure 3 shows characteristic heating curves. One can see that the time needed to reach the stationary temperature consists of the heating time (of the order of 1 min), which is mainly determined by the boundary-layer formation time, and the time required to reach a stationary-temperature regime governed by the dynamics of the medium. With an increase in the heat flux, the time of reaching a stationary regime decreases.

The heat flux is $q = W/S$ (S is the cylindrical surface of the heater). In experiments, the heat flux did not exceed 300 W/m^2, except for experiments with water where q was up to 1600 W/m^2. A further increase in the heat flux gave rise to an intense motion in the wake. Visually, we observed the appearance of circular fluxes because of the limited volume.

Measurement Results and Discussion. Experimental data on convective heat transfer from a horizontal cylinder to air, water, and Freon-13 at various densities are presented in Fig. 4.

As might be expected, the largest heat-transfer coefficient $\alpha = q/(T - T_0)$ was for water, the least was for air, and, for Freon, this coefficient increased with increasing density. All dependences $q = f(\Delta T)$, where $\Delta T = T - T_0$, are of the form $q = A\Delta T^m$. The values of A and m are presented in Table 1.

To construct dimensionless complexes Nu and Ra, one should know the density and the heat-conduction λ, viscosity ν, isobaric heat-capacity C_p, and volume-expansion β coefficients. The values of the density and volume-expansion coefficients were determined from the equation of state with virial coefficients [6] for Freon-13. The temperature and pressure are known from experiment, and C_p was taken from [7]. The experimental results were processed in the form $\mathrm{Nu} = f(\mathrm{Ra}_+)$, where $\mathrm{Nu} = \alpha d/\lambda$, $\mathrm{Ra}_+ = \mathrm{Ra}/[1 + (0.559/\mathrm{Pr})^{9/16}]^{16/9}$, $\mathrm{Pr} = \nu/a$, $\mathrm{Ra} = g\beta\Delta T d/(\nu a)$, and a is the thermal diffusivity.

Figure 5 shows heat-transfer data (the solid curve is the criterium dependence $\mathrm{Nu} = 0.36 + 0.518\mathrm{Ra}_{+}^{0.25}$ [4], and the dashed curve refers to $\mathrm{Nu}_{+} = \mathrm{Nu} + 2\mathrm{Ln}(1 + 2/\mathrm{Nu})$ which takes into account the curvature of the cylindrical heater [8].

One can see that the data obtained for water are within the known criterial dependence [4], while the data for air are somewhat above the solid curve. This is due to disregard of losses at the cylinder ends. The heat transfer increases in the axial direction as the Ra value decreases owing to the increase in the thickness of the temperature boundary layer. On the other hand, the points are below the dashed curve which represents the Langmuir approximation [8]. Consequently, there are heat losses upon heat removal from the short cylinder, but they are significant only when $\mathrm{Ra} < 10$.

The processed data for Freon in the Nu and Ra coordinates fall well on a straight line only for $\rho = 162$ and 150 kg/m^3 for $T = 40°\mathrm{C}$, i.e., in the region above the critical isotherm where Freon is the gas.

When the heat fluxes are 30–70 W/m^2 and the wake is not completely laminar, the wake deviates from the vertical, which is caused by the nonsymmetric position of the heat source in the bounded volume and also by the nonuniform circulation of the substance. However, the above fact has no effect on the heat transfer.

A completely another pattern is observed for heat transfer on the saturation curve. Even for $\rho =$ 29 kg/m^3, the heat-transfer coefficient Nu is larger than the theoretical value and larger by a factor of 1.5 for $\rho = 190$ kg/m^3 This increase is impossible to explain neither by losses nor by the enhanced compressibility or heat capacity separately.

In our opinion, the cause is the state of the substance in the vapor region, between the saturation curve and the critical isotherm. In this region, the substance is of a dispersed heterogeneous character: along with microbubbles (the reduced-density region), there are microbubbles or clusters of several water molecules (elevated-density region). The quantitative ratio between them depends on the degree of approaching the saturation curve or the isotherm [9]. Consequently, the heat-transfer mechanism in this region is more complicated and involves the dynamics of cluster disintegration and coalescence.

Thus, we have demonstrated the capabilities of the setup which makes it possible to study processes with the parameters of the medium varied over a wide range. We performed a number of convective heat-transfer experiments in the region of regular variation of the substance parameters.

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