primarily, however, it is due to the difficulties in obtaining reliable experimental data for this kind of unstable flow. The latter determines the efficiency of numerical methods for investigating the process at this stage.

NOTATION

r, z, axes of cylindrical coordinate system; ψ, stream function; ω, vortex; T, excessive temperature in relation to unperturbed surrounding medium; t, time; g, gravitational acceleration; β, volume expansion coefficient; ν, a, coefficient of kinematic viscosity and thermal diffusivity; ν_t, a_t, turbulence analogs of the respective coefficients; Q, power of instantaneous heat generation; L, V, and Θ, length, velocity, and temperature scales, respectively; L_t, V_t, and Θ_t, the same, but for turbulent flow; Gr and Pr, Grashof and Prandtl numbers; α_1, α_2, proportionality coefficients; Z, highest ordinate of frontal boundary of heated bulk (on the isotherm $T = 0.1T_m$); T_m, highest value of excessive temperature.

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INVESTIGATION OF HEAT TRANSFER OF FREE CONVECTION IN BOUNDED VOLUME WITH HEATING FROM ABOVE

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UDC 536.25

The convection coefficient is found against the Rayleigh number in a bounded volume with heating from above.

The effect of free convection in the case of heating from above has been studied relatively little [1]. It was established in [2-4] that free-convection streams arise in a bounded volume in the case of nonuniform heating of the upper wall. In [3], Nu as a function of Ra was found experimentally in the interval 10^2-10^5 in accordance with which Nu increases from 1 to 1.2.

The neck is the basic "thermal bridge" in vessels for cryogenic fluids with a wide neck and in cryostats. It is established in the present article that convection streams can arise in the neck due to heating from above from the surrounding medium leading to a considerable increase of the heat influx to a cryogenic fluid.

The investigations of free-convection heat transfer were carried out on models in the form of vertical cylindrical vessels or tubes in the 60-200-mm-diameter range and the 90-180-mm-height range. The stand arrangement is shown in Fig. 1. The cylindrical vessel 1 whose lower part is filled with liquid nitrogen is enclosed by a protective chamber 2. The evaporating nitrogen leaves the vessel at the top. Heat transfer between the vessel wall and the exiting cold gas results in a decrease of the heat flux along the wall [5]. In addition to forced convection in the neck, free convection can also arise which produces heat flux through the gas from the upper cap toward the liquid.

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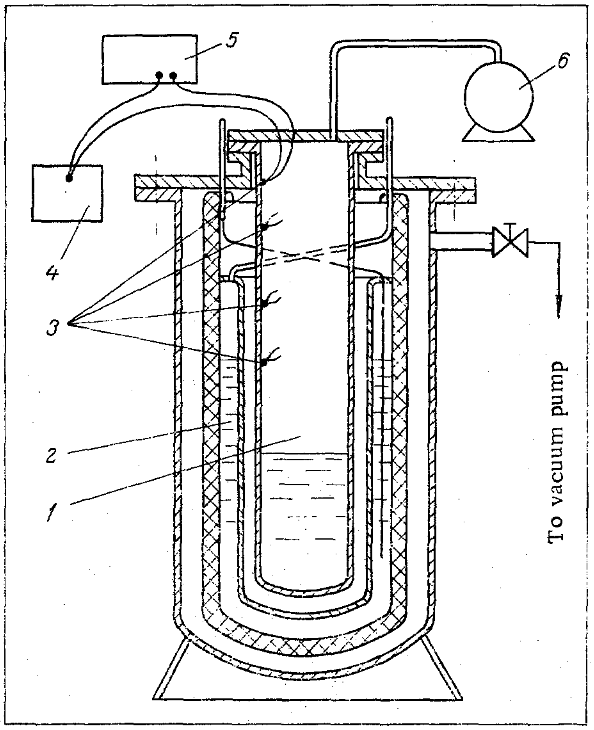

Fig. 1. Experimental setup: 1) cylindrical vessel; 2) protective chamber; 3) thermocouples; 4) zero thermostat; 5) potentiometer; 6) gas meter.

The total heat flow from the upper to the lower part of the vessel was determined by using the evaporation rate of the liquid nitrogen. The magnitude of the heat flow due to free convection was determined in three ways.

The first way consisted of evaluating the heat influx to the fluid due to the heat conduction in the cylindrical shell and also taking into account the cold of the state of the existing gas in accordance with the procedure described in [4-6]. The heat flow of free convection was found by subtracting the computed quantity from the total heat flow.

The second approach consisted of placing in the upper part of the cylindrical element a plug having a small gap made of expanded polyurethane which eliminates free convection. If either of the methods is used the forced convection is not eliminated and the heat influx along the wall of the neck is determined by taking into account the heat exchange between the departing gas and the wall. The computations using the procedure developed on the basis of theoretical and experimental investigations [5-7] have shown that this heat influx remains virtually constant if a plug is placed in the cylindrical element. Therefore, the heat flow due to free convection by using the second approach was determined by the difference of the heat influxes to the liquid without a plug and with it.

The heat flow of free convection was also determined in this manner by eliminating the forced convection. In the latter variant the cooled gas was removed through a separate tube and did not wet the wall of the cylindrical shell. The magnitude of the heat flow due to free convection changes only slightly (it increased by 5-10%), which explains why the interaction between the heat-transfer mechanisms of the forced and free convection was weak in the case under consideration.

The measurement error of the heat influx did not exceed 10%, due to the existence of existence of the protective chamber filled with liquid nitrogen, which guarded the lateral surface of the neck against heat influx from the surrounding medium.

If there is no expanding plastic plug one must take into account the heat flow due to radiation toward the fluid from the cap, which had aluminum foil glued around it to diminish this effect. The corresponding correction was determined by calculations [8] and was between 1-25% of the total heat flow.

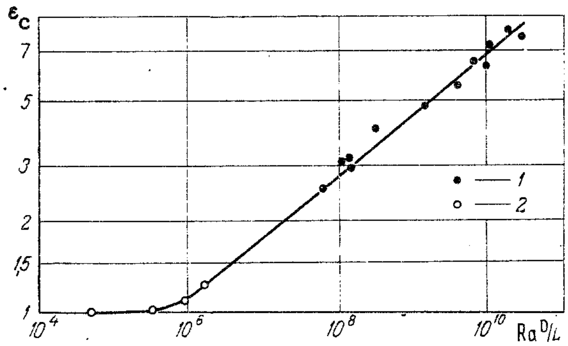

Fig. 2. The convection coefficient plotted against the product of the Rayleigh number and the ratio D/L: 1) results of the authors; 2) results of [2].

The coefficient ε_c was determined from the experimental data; it characterizes the heat-transfer intensity under natural convection in a bounded volume and represents the ratio of the equivalent gas thermal conductivity (which takes into account the heat transfer by heat conduction as well as free convection) to the heat conduction of gas at rest.

The values of ε_c plotted against the product of the Rayleigh number and the ratio D/L are shown in Fig. 2. The height L at which a change in the wall (and gas) temperatures takes place has been adopted as the determining geometrical dimension in the Rayleigh criterion. The difference between the "warm" and the "cold" ends of the neck at the height L was taken as the characteristic difference. The results were obtained at an almost constant value of Pr = 0.74-0.77. The experimental data for the value (Ra D/L) range from 10^7 to 10^{11}. The experiments have demonstrated that the heat exchange due to natural convection in a closed volume in the case of heating from above can be made sufficiently large although it is considerably lower than for heating from below.

In [3] in the experiments with heating from above within a closed volume and for which the ratio D/L was about 10, the values obtained for ε_c were from 1.0 to 1.25 in the region Ra D/L = 10^4-10^6.

By using these values one can find ε_c as a function of RaD/L in the range 10^4-10^{11} (Fig. 2). This relation is similar to the one for the heat transfer of free convection in bounded volume in the case of heating from below or from the side [9] though with 4-6 times smaller values of ε_c. This dependence can be approximated by the formula $\varepsilon_c = 0.067\ (RaD/L)^{0.2}$ which describes the experimental results within the interval RaD/L = 10^7-10^{11} and can be extended as an approximation to the region RaD/L = 10^6-10^7, as one can see from Fig. 2.

In the case of heating from above free convection can only arise if there are perturbing inhomogeneities in the temperature field. Such perturbations should in our case give rise to walls of the cylindrical element. To reveal the perturbations a number of experiments were carried out. Temperature measurements on several horizontal planes have shown that there are no noticeable temperature gradients in the gas or between the gas and the wall in the same plane. Temperature changes did not exceed 1°, which was within the measurement error.

The experiments with cylindrical elements made of steel Kh18N10T and of glass-reinforced plastic (the ratio of their thermal-conductivity coefficients is 30) yielded the values of ε_c; the latter points to the fact that the relation is of a general character (Fig. 2).

We were also able to show experimentally the existence of perturbations of the temperature field coming from the walls (the "wall" effect) by placing hollow plastic-foam cylinders into the investigated cylindrical element with minimal clearance. A relatively thin layer of plastic foam of 10 mm on the wall of a cylindrical element of diameter 175 mm resulted in the heat flux due to free convection decreasing by 30%. If in this element the inner diameter of the cylindrical insertion made of plastic foam is reduced to 80 and 50 mm, then free convection is virtually eliminated whereas in cylindrical elements of 50 to 70 mm the value of ε_c amounts to 2-4.

Thus, the experiments have confirmed that free convection in a bounded volume heated from above is due to perturbations of the temperature field in the gas arriving from the walls of the volume. If perturbations are eliminated the free convection decays. In the case of perturbations of the temperature field due to the side walls, as occurs in practice, and, in particular, in the necks of vessels containing liquid nitrogen, the free-convective heat transfer of free convection can be evaluated by using the curve shown in Fig. 2.

NOTATION

ε_c, free convection coefficient; D, neck diameter; L, height of the neck; Ra, Rayleigh number; Nu, Nusselt number; Pr, Prandtl number.

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NUMERICAL INVESTIGATION OF LIGHT-ABSORBENT CONVECTION IN HORIZONTAL TUBE

I. STEADY CONVECTION STATES IN THE FIELD OF CONTINUOUS LASER RADIATION

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The dependence of the rate of steady photoabsorptive convection in liquids, gases, and plasmas on the intensity of a horizontal laser beams is studied. A good agreement with the results of dimensional analysis is obtained.

1. Introduction

The propagation of laser radiation in an absorbing medium results in the latter being heated. The arising temperature gradients lead to the development of the convective motions in liquids or gases; the study of the latter was the subject of a considerable number of articles both experimental and theoretical character [1-6].

Since the Navier—Stokes equations governing the convection are nonlinear, analytical methods yield only some general laws, and a detailed study of convective motion is only feasible by employing numerical methods.

In [7-9] numerical simulation was carried out of photoabsorptive convection in a chamber which is uniformly irradiated orthogonally to the lengthwise axis of the chamber. In the present article numerical investigation is carried out on convective motion in liquid, gases, or plasma which arises in a long horizontal vessel of rectangular cross section exposed to a laser beam of small diameter traveling along its axis. The problem had previously been considered by us using the dimension theory [6]. It predicted the existence of three states of

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