# EFFECT OF THE THERMOPHYSICAL PROPERTIES OF A WALL ON RELEASE OF HEAT IN TURBULENT NATURAL CONVECTION. 1. EXPERIMENTAL RESEARCH

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*We have experimentally studied the exchange of heat in vertical cylinders for the turbulent natural convection of liquid nitrogen and Freon-113. We have observed the influence of thermophysical properties of a wall on the coefficient of heat release.*

The effect exerted by the thermophysical properties of a material forming a heat-releasing wall on the heat-transfer coefficient $\bar{\alpha}$ determined experimentally has been noted in experiments involving the forced turbulent flow of liquid metals through tubes [1]. The relationship between $\bar{\alpha}$ of vertical cylinders under conditions of natural convection of supercritical helium was shown to be dependence [2, 3] on the thermophysical properties and thickness of the wall.

The results of this study served to expand the experimental material and make it possible to undertake an analytical analysis of the phenomenon.

## EXPERIMENTAL METHOD AND RESULTS

Figure 1 shows the design of the specimens. We utilized cylinders 1 of M-3 copper (with a diameter of d = 11.7 mm) and 12Cr18Ni10Ti stainless steel (d = 12.06 mm) with a wall thickness of 0.35 mm. The heater was fabricated out of manganin wire 2 and positioned within the groove of a textolite insert 4 with a spacing of 1.5 mm, thus making it possible to maintain a constant heat-flux density q at the inside surface of the hollow cylinder 1. The cold junctions of the copper—constantan thermocouple (the electrode diameters were, respectively, 0.09 and 0.12 mm) were positioned within the fluid at points a-d on a single horizontal plane with the corresponding hot junctions 3 (the latter were soldered with a POS-40 flux into 0.4-mm diameter orifices drilled into the wall, subsequent to which the surface of the cylinder was carefully polished), thus allowing us to account for the possible stratification of the fluid beyond the limits of the boundary layer in the determination of the local temperature head $\vartheta(x) = (T_w(x) - T_\infty(x))$. The emf of the differential thermocouples $E(T_w, T_\infty)$ was measured by means of a compensation circuit which involved the use of a R-306 potentiometer and an M-195/1 galvanometer, exhibiting a sufficiently large time constant to ensure the integral averaging of the signal $[\bar{E}(T_w, T_\infty) = \int_{\tau_1}^{\tau_2} E(T_w, T_\infty)d\tau/(\tau_2 - \tau_1)]$. The thermocouples used in these experiments were tested to coordinate with the nominal copper—constantan thermocouple characteristic that is based on the reference saturation temperatures for liquid nitrogen and liquid oxygen (the temperatures of the liquid nitrogen and oxygen were measured by means of a silicon—germanium resistance thermometer; the hot junction of the thermocouple was kept at a temperature of T = 273.15 K in icy sludge), subsequent to which, in experiments involving liquid nitrogen, we used the indicated characteristic. The maximum absolute error in the determination of $\bar{\vartheta}$ amounted, in this case, to 0.1 K. In the high-temperature region (for studies of the natural convection of saturated Freon-113) the thermocouple was calibrated by respectively immersing the hot and cold junctions into a Dewar's flask containing deionized water whose temperature was measured with a copper resistance thermometer, and also containing icy sludge (T = 273.15 K). In order to calculate $\bar{\vartheta}$ from the direct emf measurement data for a differential thermocouple, we utilized the values of the differential thermo-emf about the boiling point of liquid Freon-113 ($t_s$ = 47.68°C for p = 0.1013 MPa, dE/dT = 41.77 μV/K), which allowed us to determine $\bar{\vartheta}$ with a maximum absolute error of 0.2 K. The averaged density of the heat flow $q_w$ to the outside surface of the cylinder was calculated by means of the formula $q_w = UI/F$, where I represents the current in the heater circuit and U is the drop in voltage over a specified segment; F is the area of the outside surface of the cylinder, corresponding to the length of this segment, with a relative error of <1%.

In the experiments with liquid nitrogen the overheating of the wall relative to $T_\infty$ changes approximately from 0.75 to 3.0 K for the copper cylinder and from 1.2 to 3.7 K for the steel cylinder, in the range $q_w$ = 200-900 W/m$^2$. In the experiments with liquid Freon-113 $\bar{\vartheta}$ changed from 2.6 to 6.0 K for each of the cylinders at thermal loads of $q_w$ = 250-970 W/m$^2$. The maximum relative error in the determination of $\alpha = q_w/\bar{\vartheta}$ for liquid nitrogen amounted to 12% in the case of the copper specimen, while

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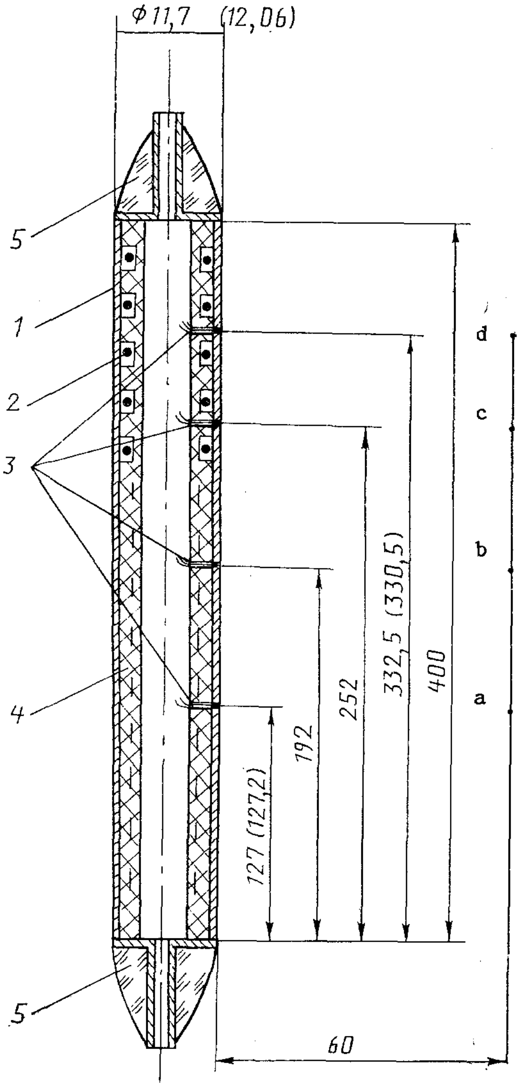


Fig. 1. Design of experimental specimens.

for the stainless steel specimen it amounted to 8%; in liquid Freon-113 it amounted to approximately 10% for each of the specimens. As the densities of the heat flows exceeded the cited values the liquids began to boil. Throughout the experiment the liquid nitrogen and Freon-113 were kept in glass cryostats with an inside diameter of 120 mm. When working with nitrogen to reduce the flow of heat to the cryostat containing the specimen, we made use of an additional (shielded) Dewar's vessel. The saturation temperature for the Freon-113 was maintained through the heat released by the specimen and monitored with a copper resistance thermometer. All communication wiring led from the specimens through an orifice in the upper fairing cone 5 (a glass-covered Kovar tube), which was then glued by means of an epoxide compound; the orifice of the lower fairing cone was sealed shut. The side surfaces of these cylinders were polished, thus making it possible to eliminate initiation of nucleate boiling centers within the limits of the above-cited $q_w$. During the course of the experiments the liquid was brought to a boil only at the conductors (above the specimen) and it exerted no influence on natural convection. The liquid level in the cryostat rose above the uppermost point of the fairing cone by no less than 0.15 m.

Figures 2 and 3 show the dimensionless coefficient $\tilde{Nu}_{x,\infty} = \tilde{\alpha}x/\lambda$ of heat transfer to liquid Freon-113 and to the liquid nitrogen as a function of $Gr_{x,\infty}{}^*$. The thermophysical properties of the liquids [4], contained in the similarity figures, were determined at a temperature $T_\infty$ equal to the liquid saturation temperature.

In order to determine this relationship we used a single-coordinate Hewlett—Packard 3390 A automatic recording potentiometer, which allowed us to evaluate the magnitude of the "noise" in the thermocouple circuit and to isolate the useful component of the signal. The characteristic recordings of oscillations in $\vartheta$ for each of the specimens are shown in Fig. 4.

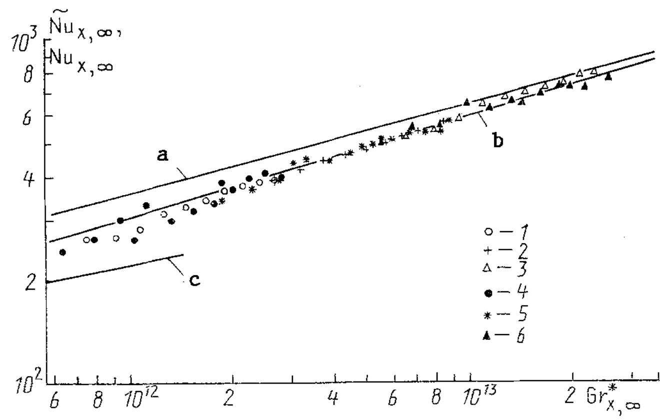


Fig. 2. Release of heat from vertical cylinders fabricated of M-3 copper and 12Cr18Ni10Ti in the transition and turbulent regimes of natural liquid Freon-113 convection ($t_\infty \approx 47.68°C$): 1) x = 0.192 m; 2) 0.252; 3) 0.3325 (M-3 copper); 4) 0.192; 5) 0.252; 6) 0.3305 (12Cr18Ni10Ti); a, b) correlation (1) and theoretical (2) relationships for the turbulent regimes; c) theoretical relationship (3) for the laminar regime.

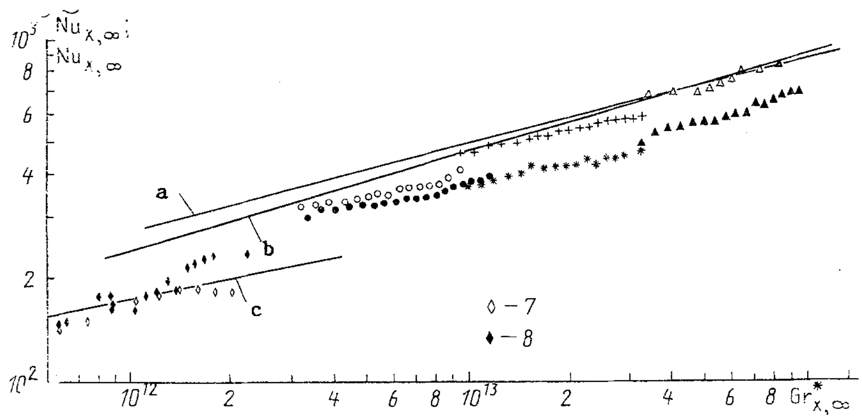


Fig. 3. Release of heat from vertical cylinders fabricated of M-3 copper and 12Cr18Ni10Ti steel in the laminar, transitional, and turbulent regimes of natural liquid-nitrogen convection ($T_\infty \approx$ 77.35 K): 7) x = 0.127 m (M-3 copper); 8) 0.127 m (12Cr18Ni10Ti steel). The remaining notation is the same as in Fig. 2.

## DISCUSSION OF RESULTS

As we can see from Fig. 2, the local values of $\tilde{Nu}_{x,\infty}$ for the copper cylinder in liquid Freon-113 virtually do not differ from the corresponding quantities for a stainless-steel cylinder over the entire investigated range of changes in $Gr_{x,\infty}{}^*$. The divergence of the experimental data does not exceed the experimental error. The known [5] correlation equation $Nu_{x,\infty} = CRd_{x,\infty}{}^{1/3}(Pr_w/Pr_\infty)^{1/4}$ ($Pr_w/Pr_\infty \to 1$, since $\bar{\vartheta}$ is not large; C = 0.135), expressed in terms of $Gr_{x,\infty}{}^*$, assumes the form

$$Nu_{x,\infty} = 0,2227\,(Gr^*_{x,\infty}\,Pr_\infty)^{1/4} \tag{1}$$

and is in good agreement with the results from [6].

We see some lack of coordination in Fig. 2 between relationship (1) and the experimental data, particularly in the region $Gr_{x,\infty}{}^* = 10^{12}\text{-}10^{13}$ for $Rd_{x,\infty} = 2.5\cdot10^{10}\text{-}10^{11}$, determined from the measured values of $\bar{\vartheta}$. For the vertical cylinders this region is usually assumed to be transitional, between the laminar flow regime to the turbulent [5, 6] (at Pr numbers close to the Pr number for liquid Freon-113, and under these conditions equal to 6.7).

The theoretical relationship [7]

$$Nu_x = 0,0804\,Pr^{1/3}\,[Gr^*_x/(1 + 0,444\,Pr^{2/3})]^{2/7} \tag{2}$$

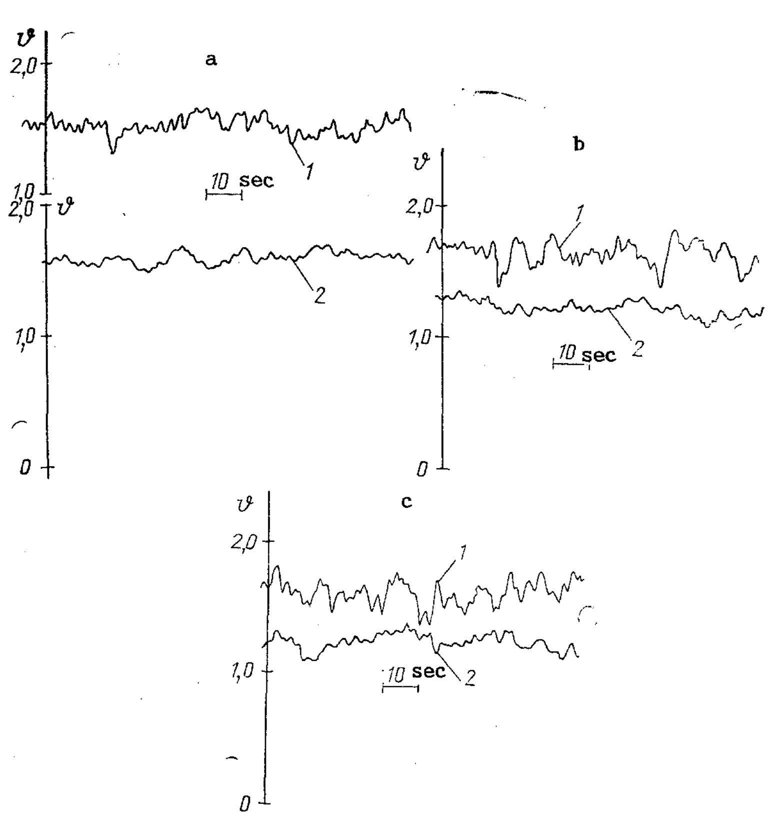


Fig. 4. Oscillations of the temperature head $\vartheta$ in the turbulent natural convection of liquid nitrogen about steel (1) and copper (2) cylinders: a) x = 0.192 m, 1) $q_w$ = 364.0 W/m$^2$, 2) 376.0; b) x = 0.252 m, 1) $q_w$ = 364.0 W/m$^2$, 2) 376.0; c) 1) x = 0.3305 m, $q_w$ = 364.0 W/m$^2$, 2) x = 0.3325 m, $q_w$ = 376.0 W/m$^2$. $\vartheta$, K.

has been obtained for the boundary condition $q_w$ = const at the surface of the vertical plate from an integral analysis of the equations of the turbulent boundary layer under the assumptions made in [8] (for the case $T_w$ = const). At the decisive temperature $T_\infty$ Eq. (2) is in good agreement with the experimental data (see Fig. 2).

The experimental results shown in Fig. 3 show the difference between the local heat transfer of the copper and steel cylinders in the turbulent region of liquid-nitrogen flow. In the laminar zone the transfer of heat from the cylinders does not differ, one from the other, nor from the theoretical relationship [9]:

$$\mathrm{Nu}_x = 0{,}6163\,[\mathrm{Pr}^2/(0{,}8 + \mathrm{Pr})]^{1/5}\,\mathrm{Gr}_x^{*\,1/5}, \tag{3}$$

which should be regarded as confirmation of the correct execution of the experiment under these conditions (natural convection of liquid nitrogen).

The technique of visual observation of the natural convection was used in the experiments, and this included a source of light directed at the boundary layer about the cylinder through a narrow unsilvered slot to the wall of the Dewar's vessels, as well as a movable collector lens and a linear distance scale (x), positioned at the inside surface of the cryostat. Owing to the different refractive indices for the light in the liquid at various temperatures, it became possible with great accuracy (along the x coordinate) to determine the boundary of laminar-flow stability as a function of $q_w$ and to trace the development of the turbulent boundary layer (the movement of the turbulent "moles" of liquid is easily distinguished). The boundary of the purely laminar flow region for the liquid nitrogen (Pr = 2.4), established as a result of the observations, was determined to have a value of $\mathrm{Cr}_{x,\infty}^* = 1.4 \cdot 10^{12}$ ($\mathrm{Ra}_{x,\infty}^* = 3.36 \cdot 10^{12}$), which is in agreement with the data on the averaged heat transfer (Fig. 3). This value does not contradict the results from [10], in accordance with which the region of transmission from laminar to turbulent flow (about the vertical plane of the plate at $q_w$ = const) is defined by the range $3 \cdot 10^{11} < \mathrm{Ra}_x^* < 10^{12}$ for air (Pr = 0.7) and $5 \cdot 10^{12} < \mathrm{Ra}_x^* < 1.5 \cdot 10^{13}$ for water (Pr = 6-7). With the development of turbulence in the boundary layer of the liquid nitrogen the divergence in the values of $\tilde{\mathrm{Nu}}_{x,\infty}$

for the copper and steel cylinders (Fig. 3) becomes increasingly pronounced, and their ratio reaches 1.2-1.4. In this case, the experimental points for the copper cylinder deviate slightly from the theoretical relationship (2), while the points for the steel cylinder fall systematically below that curve.

Recordings of instantaneous readings for the differential thermocouples are shown in Fig. 4 (with the scale $\vartheta$, K) for three fixed values of x and with given values for $q_w$ in the copper and steel cylinders under the conditions of natural liquid-nitrogen convection. At the point x = 0.192 m ($Gr_{x,\infty}^* \approx 5 \cdot 10^{12}$), close to the critical, pulsations in the temperature head $\hat{\vartheta} = (\vartheta - \bar{\vartheta})$ in the wall of the steel cylinder exceed the corresponding quantity for the copper cylinder; however, the averaged value of ($\bar{\vartheta}$) (Fig. 4a) is virtually identical for both cylinders ($q_w$ for the copper cylinder in this case is somewhat greater than for the steel cylinder). Consequently, the $\bar{\alpha}$ of the steel cylinder is lower than the $\bar{\alpha}$ of the copper cylinder, which coincides with the data obtained in the measurement of the compensation circuit. Analysis of the Fourier oscillations in $\vartheta$ in the wall of the steel cylinder, accomplished with a programmable Hewlett—Packard potentiometer, demonstrates the high level of their periodicity. This is in agreement with the familiar data from [11-13] regarding the rigorously periodic processes (including the temperature pulsations) in the transitional region of natural-convective flow, where, as demonstrated in [13], "filtration" of all frequencies with the exception of some fixed frequency occurs. The most probable period ($\tau_0$) in the pulsations of $\vartheta$ for x = 0.192 m changed in the experiments with liquid nitrogen within the limit 1.7-3.0 sec as a function of $q_w$.

Pulsations in $\vartheta$ in the wall of the steel cylinder in the region of developed flow turbulents (x = 0.252 and 0.3305 m; $Gr_{x,\infty}^* > 5 \cdot 10^{12}$) for liquid nitrogen, an example of which is shown in Fig. 4b, c, both in terms of the absolute value, and in terms of intensity ($\hat{\vartheta}/\bar{\vartheta}$), exceed the identical quantities for the copper cylinder (given identical x and $q_w$). As can be seen from Fig. 4b, c, at the indicated $q_w$ the measured quantity for the steel cylinder is greater than in the case of the copper cylinder; this determines the difference in the values of $\bar{\alpha}$. The same result is given by measurements of the compensation circuit (see Fig. 3). The spectrum for pulsations in $\vartheta$ in the zone of developed turbulent flow is somewhat broadened in comparison to the zone that is close to the transitional (Fig. 4a); the oscillations become more asymmetrical, retaining, however, their statistical periodicity. Fourier analysis shows that the numerical value of $\tau_0$ (the first harmonic) in the region of developed turbulence differs only slightly from this quantity in the transition region (for a given $q_w$). Apparently, this makes it possible to associate the phenomena of "filtration" in the transition region and the turbulent ejection of large vortices during motion [10] in the zone of developed turbulence in the flow near the wall. By using the internal time scale $\nu/U_*^2$, we find that we can describe the data on the values of $\tau_0$ over the entire studied range of x and $q_w$, derived under conditions of natural liquid-nitrogen convection about the steel cylinder, with a high degree of accuracy, with the following dimensionless equation: $\tau_0^+ = \tau_0 U_*^2/\nu = 325$. Here, for the calculation of $U_*$ we used the results from [14]; the local coefficient of heat transfer was determined in accordance with Eq. (2); the thermophysical properties of the liquid were referred to $T_\infty$.

Recordings of pulsations in $\vartheta$ for the turbulent natural convection of liquid Freon-113 demonstrated their limited absolute magnitude and intensity, as a consequence of which harmonic analysis proved to be impossible. The values of $\bar{\vartheta}$, determined on the basis of the recordings made for the copper and steel cylinders, virtually do not differ from one another (given corresponding $q_w$), which is in agreement with the measurement results for the compensation circuit (Fig. 2).

The value of the dimensionless time scale for the temperature of pulsations $\tau_0^+$ in the wall, obtained in the processing of the data for experiments with liquid nitrogen, does not contradict the numerous experimental results from various authors regarding the average dimensionless period of turbulent scattering in the near-wall zone of the forced convective flow, falling within the range $\tau_0^+ = 70\text{-}500$. The value of $\tau_0^+ = 223$, independent of the Reynolds number, is a result of the analysis of the semiempirical model of surface renewal, associated with turbulent scatter (in the absence of heat exchange) [15]. For purposes of generalizing the experimental data on the frequency ($f_0$) of pulsations in temperature in the turbulent boundary layer in the case of natural convection of air and water about a vertical plate, the characteristic frequency scale $f_T = (g\beta q_w/\lambda)^{1/2}$ was used in [10]. Here, the normalized frequency $f_0^+ = f_0/f_T$ proved to be equal to 0.03 in the range $Ra_x^+ = 10^{13}\text{-}10^{17}$. Results from calculations of $\tau_0$ according to the equation $\tau_0^+ = 325$ for the conditions of our experiments with liquid nitrogen correspond to those obtained in accordance with the relationship $f_0^+ = 0.03$, results with a maximum deviation $|\tau_0 - 1/f_0|f_0$ less than 7%. Utilization of relationship (1) for the calculation of $\langle\alpha\rangle$ in the turbulent flow region leads to a reduction in the deviation down to 5%.

The relationship found in this study between the experimentally determined coefficient of heat transfer $\bar{\alpha}$ and the thermophysical properties of the material forming the heat-transfer wall in the case of turbulent natural liquid-nitrogen convection (not noted in the turbulent liquid Freon-113 flow region), as well as the data in the literature regarding analogous phenomena in the study of the transfer of heat in forced near-wall turbulent flows indicate the need to set up not only a reliable physical model of such effects, but also to develop a rather precise method by means of which to calculate the influence which the thermophysical properties of the wall exert on the quantity $\bar{\alpha}$.

## NOTATION

$\tilde{\alpha}$, experimentally determined coefficient of heat transfer; $\langle\alpha\rangle$, coefficient of heat transfer determined from theoretical equations; q, density of heat flow to the inside surface f the wall; $q_w$, time-averaged density of the heat flow to the surface exchanging heat with the liquid; $T_\infty$, temperature of the liquid beyond the limits of the boundary layer; $T_w$ and $\bar{T}_w$, instantaneous and time-averaged local wall temperature; $E(T_w, T_\infty)$ and $\bar{E}(T_w, T_\infty)$, instantaneous and time-averaged value of the thermo-emf of the differential thermocouple; $\vartheta = (T_w - T_\infty)$, $\vartheta = (\bar{T}_w - T_\infty)$; $\hat{\vartheta} = (\vartheta - \bar{\vartheta})$; x, a coordinate reckoned from the beginning of the heated cylinder segments in the direction of the averaged flow; $\tau_0$, time scale for pulsations in $\vartheta$; $\tau_0^+ = \tau_0 U_*^2/\nu$; $U_*$, shearing velocity at the wall; $\nu$, $\lambda$, and $\beta$, coefficients of kinematic viscosity, thermal conductivity, and volumetric liquid expansion; $f_T = (g\beta q_w/\lambda)^{1/2}$, characteristic frequency scale; $f_0^+ = f_0/f_T$, normalized frequency of temperature pulsations; $Gr_x^* = g\beta q_w x^4/(\nu^2\lambda)$; $Ra_x^* = Gr_x^* Pr$; $Nu_x = \langle\alpha\rangle x/\lambda$; $\tilde{N}u_x = \alpha x/\lambda$.

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