Journal of Engineering Physics and Thermophysics, Vol. 75, No. 6, 2002

INFLUENCE OF THE VIBRATIONS OF A VESSEL ON HEAT EXCHANGE AT THE BOTTOM

N. V. Selivanov and A. K. Il'in

UDC 536:24

Results of experimental investigation of the influence of the vibrations of a vessel on the local heat exchange near the bottom in a wide range of variation of uniqueness conditions are given. Three regions of influence of the vibrations in which the calculated dependences for the local and average heat transfer have been obtained are revealed.

In carrying high-viscosity and solidifying fluids, one equips the transport vessels with systems for heating the fluid to decrease its viscosity. Tubular and hot-jet heating systems are used in sea tankers. The power of the heating system and the parameters of the flow diagram of carrying cargo are largely determined by the heat exchange between the fluid and the ambient medium. In sea tankers, the heat exchange is strongly affected by the forced fluid motion caused by the rolling of the vessel and leading to an intensified heat exchange between the fluid and the vessel surface and to an increase of 1.5 to 3 times in the heat loss as compared to smooth conditions [1–5]. In the absence of vibrations, an immobile layer with a stable vertical distribution of the density is formed at the bottom of the vessel and the heat is transferred from the fluid to the bottom by conduction. The thickness of the immobile layer depends on the type of technological operation (cooling, heating, or maintenance of the temperature of fluid cargo in the vessel) [6]. Vessel vibrations increase the heat exchange between the bottom and the fluid tens to hundreds of times as compared to smooth conditions because of the destruction of the immobile layer [3–5]. The results of the experiments on determining the average heat transfer at the bottom of the vessel in the case of vibrations in the process of heating of the fluid using a tubular heating system are given in [3], while the results of the experiments for the case of cooling and heating of the fluid in a tank using a hot-jet heating system are given in [4]. The results of the experiments on heat exchange at the bottom of a 1:50 model of the tank of an oil tanker with a single-layer plating with a carrying capacity of 150,000 tons in rolling are presented in [5].

The performed investigations are few in number, and the calculated dependences obtained empirically yield values of the heat-transfer coefficients differing by several times. Local heat exchange at the bottom in the case of vessel vibrations has not been studied. In all the works, the experimental data are generalized for the case where the immobile layer was completely destroyed. The influence of the relative dimension of the vessel on the heat transfer at the bottom also remained unclarified, since the relative width of the vessel (b/h) was unchanged in the above works and the Reynolds number was calculated from the vibrational speed of the bottom surface.

A theoretical solution involves considerable mathematical difficulties; therefore, the experimental method with the use of the generalized-variable theory turned out to be the most acceptable. The analysis of the differential equations of convective heat exchange in the bottom region of the vessel and the results of determining potential fluid motion at the horizontal surface of the cavity have shown that the velocity distribution is symmetric relative to the center and attains its maximum on the axis of symmetry, while at the vertical lateral surfaces the velocity is zero. Therefore, two stationary vortices occur at the bottom surface in vibrations; they are located on each side of the center of the bottom surface and have opposite directions of rotation. This must make the heat exchange at the edges of the bottom surface more intense than the heat exchange in the central part and conductive heat exchange. As the vibration intensity increases, the action of the forced motion of the fluid on the bottom layer must increase, subsequently improving the heat-exchange intensity. The transfer of heat by conduction will gradually decrease, while the transfer by convection will increase. Finally, for the critical parameters of vibrations the stability of the immobile layer will be disturbed and this will lead to its total destruction and separation. Destruction of the layer must begin at the edges of the bottom surface and move to the center. The intensity of heat exchange will be determined by just forced convection.

Astrakhan State Technical University, Astrakhan, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 75, No. 6, pp. 127–132, November–December, 2002. Original article submitted June 6, 2001; revision submitted May

1062-0125/02/7506-1400$27.00

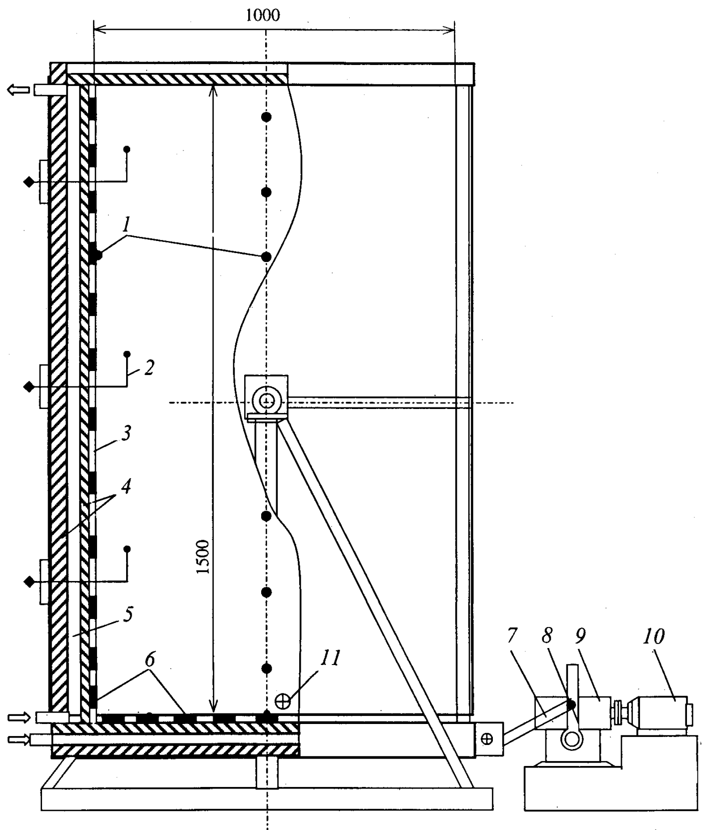


Fig. 1. Diagram of an experimental setup: 1) thermocouples; 2) thermal probe; 3) Plexiglas (acrylic-plastic) sheet; 4) casing of the setup; 5) cooling cavity; 6) heat-flux meters; 7) draft; 8) crank; 9) pressure regulator; 10) motor; 11) electric heater.

The analysis of the differential equations of convective heat exchange [1] in the bottom region yields that, at the bottom, it is described by the similarity equation

$$\mathrm{Nu}_{\mathrm{fl}x} = f\,(\mathrm{Fo}, \mathrm{Re}, \mathrm{Pr}, X, b/h, \mu_{\mathrm{fl}}/\mu_{\mathrm{w}}) \,. \tag{1}$$

The basic experiments have been conducted on a laboratory setup (Fig. 1); its transparent frontal walls allowed visual observations. The relative width of the cavity and the position of the axis of vibrations relative to the center of mass of the fluid were changed using a horizontal partition. The vibrations of the vessel were produced by a special mechanism. Their period was changed by variation of the rotational speed of a d.c. motor, and the angular amplitude was changed by changing the crank length. The local density of the heat flux was measured by heat-flux sensors (heat-flux meters), while the temperatures of the fluid and the wall were measured by copper-constantan thermocouples. Perfumery and vaseline oils were taken as the working fluids. The fluid level in the vessel was changed from 0.36 to 1.5 m.

Furthermore, we conducted experiments on a 1:10 scale model of an oil tanker with a carrying capacity of 100,000 tons (the setup is described in [2, 4]). The working fluids were transformer oil and high-viscosity petroleum product.

The basic parameters of the experiments were as follows: q_x = 20–2100 W/m^2, t_{w} = 12–60$^{\mathrm{o}}$C, t_{fl} = 20–70$^{\mathrm{o}}$C, $t_{\mathrm{w}} - t_{\mathrm{fl}}$ = 6–40$^{\mathrm{o}}$C, Θ_0 = 5–16.5 deg (0.087–0.288 rad), T = 3–15 sec, and b/h = 0.36–1.89.

The fluid was heated and its temperature in the volume was maintained using Nichrome wire heaters 0.5 mm in diameter (to decrease their influence on fluid motion near the bottom) and using a hot-jet heating system in the experiments with the scale model. A procedure analogous to that of [2–4] was selected for experimental investigations.

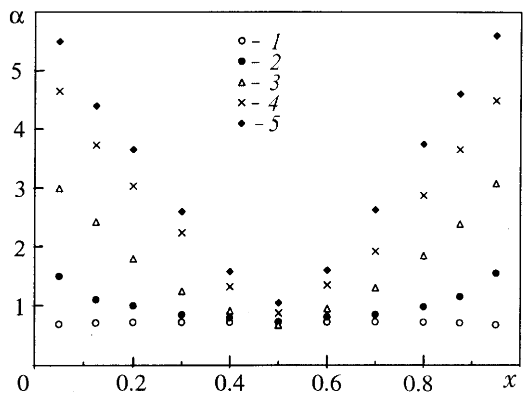


Fig. 2. Influence of vibrations on the local coefficient of heat transfer: 1) $\Theta_0 = 0^o$; 2) $\Theta_0 = 5$ and $T = 10$ sec; 3) 5 and 7; 4) 5 and 5; 5) 9 and 5.

The visual observations of fluid flow in the boundary layer and the analysis of the results obtained on the laboratory setup enabled us to reveal the following features of heat exchange in the bottom region in the case of vessel vibrations (Fig. 2). When the intensity of the vibrations is low ($Re_{fl l} \le 200$), they virtually exert no influence on the intensity of the heat exchange at the bottom; however, the heat exchange increases somewhat at its edges and decreases at the center (for $x = b$). The average heat transfer over the bottom surface remains the same as in the absence of vibrations, and heat transfer from the fluid to the bottom surface is predominantly by conduction. As the vibration intensity becomes higher, we have a further increase in the coefficient of heat transfer at the edges of the bottom, but as the center of the bottom is approached the influence of the vibrations on heat exchange becomes weaker. Here the heat transfer is no different from such in heat conduction; the region of the bottom where the heat exchange is intensified moves closer to its center, and fluid flow in the central part remains laminar and is sine in character with a frequency equal to the vibrational frequency of the vessel. These processes are time-independent and are observed immediately after the onset of vibrations. The temperature field in the fluid volume remains constant vertically but near the bottom we have the transformation of the temperature profile. Directly at the bottom surface, it acquires the shape of that in convective heat exchange. In the remaining part of the immobile layer, the temperature field remains the same as in the absence of vibrations.

The results obtained coincide with the results of a qualitative analysis of differential equations. This is also due to the presence of the transverse vibrational velocity component that has a maximum value at the edges of the bottom, is equal to zero at its center, and is in direct proportion to the frequency and amplitude of vibrations. Because of this, the fluid with a lower density penetrates into the layer with a stable velocity distribution over the height and creates regions with an unstable vertical density distributions in a certain part of it. This leads to the appearance of disturbances in the immobile layer and to a decrease in its thickness and hence the enhancement of heat exchange. In the case of vibrations in the angular zones, vortex flows develop on the surface of the immobile layer; these flows propagate over the surface to the central part of the bottom with increase in the vibration intensity. But near the bottom surface fluid flow remains laminar.

When $Re_{fl l} \ge 2000$, heat exchange is intensified over the entire surface of the bottom; the intensification becomes stronger with increase in $Re_{fl l}$. However, as compared to the heat transfer at the center of the bottom the local relative heat transfer is independent of vibration parameters. The motion of the fluid in the boundary layer remains laminar. For these cases the Richardson number changed from 25 to 0.4, which is larger than $Ri > 0.3$ for which turbulence is suppressed by buoyancy forces and the boundary layer on the plate remains stable [7].

When $Re_{fl l} = 6500–7000$, the flow in the boundary layer is still laminar in character but the process of destruction of the immobile layer due to a powerful vortex formation begins at the edges of the bottom; this process gradually propagates with time to the center of the bottom. Upon completion of the transient period and when $Fo \cong Fo_{tr}$, the boundary layer loses stability and is destroyed over the entire bottom surface. Fluid flow is vortex in character, and heat transfer increases tens of times over the entire surface of the bottom, which is determined by the forced motion of the fluid. The Ri number changed from 0.35 to 0.075. These results agree with the conclusions obtained in [7] for $Ri < 0.3$. The vertical temperature field of the fluid becomes constant (except for the boundary layer

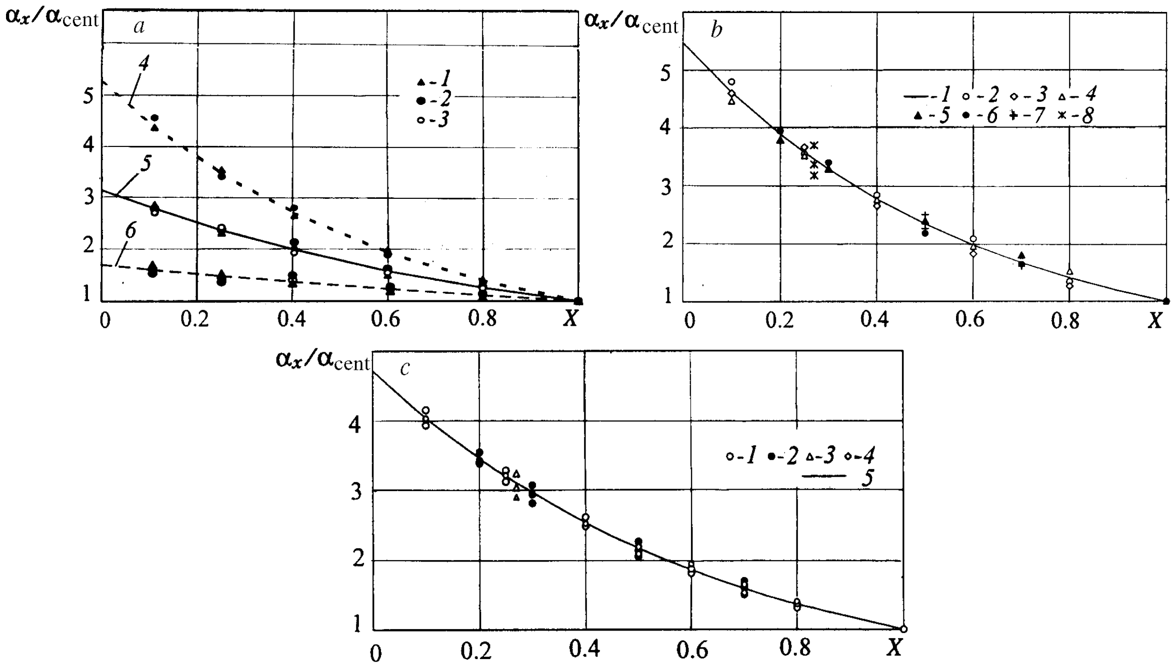


Fig. 3. Local relative heat transfer at the bottom: a) $\mathrm{Re}_{\mathrm{fl}l} < 2000$: 1) Pr = 360; 2) 270; 3) 550; 4) $\mathrm{Re}_{\mathrm{fl}l}$ = 1950; 5) 1350; 6) 620; b) $2000 \le \mathrm{Re}_{\mathrm{fl}l} \le 6500$: 1) calculation from (5); laboratory setup, oil: 2) $\mathrm{Re}_{\mathrm{fl}l}$ = 2540; 3) 4300; 4) 6250; scale model of the tank, mazut (black oil): 5) 5890; 6) 2330; 7) model, ethylene glycol [5]; 8) tanker, petroleum [5]; c) $\mathrm{Re}_{\mathrm{fl}l} > 6500$: 1) laboratory setup, oil; 2) scale model of the tank: mazut, oil; 3) tanker: petroleum [5]; 4) model: water, kerosene; 5) calculation from (8).

at the bottom of the vessel). Here it is the same as in forced convection. This phenomenon is observed in both the process of cooling and heating and at a constant temperature of the fluid in the isothermal core. The time of the transient process is 0.5 to 1.5 h and depends on the intensity of vibrations and the fluid viscosity. The dimensionless time of the transient process is related to vibration parameter and is determined from the formula

$$\mathrm{Fo}_{\mathrm{tr}}\, \mathrm{Re}_{\mathrm{fl}l} = 3.60\,. \tag{2}$$

Processing of experimental data enabled us to obtain dependences to calculate the coefficient of heat exchange in vibrations for the cases observed (Figs. 3 and 4). In processing the experimental data, the $\mathrm{Re}_{\mathrm{fl}l}$ number was calculated from the amplitude value of the velocity of relative motion of the fluid at the bottom, which enabled us to take into account the influence of the parameter b/h on heat exchange. By solution of the differential equations for the potential motion of the fluid in the cavity we obtained the dependence for the fluid velocity:

$$U_{\mathrm{fl}} = U_{\mathrm{w}}\, f(b/h) = 2\pi\Theta_0 h/T f(b/h)\,, \tag{3}$$

where $f(b/h) = 1.1713(b/h) - 0.3164(b/h)^2 - 0.037(b/h)^3$.

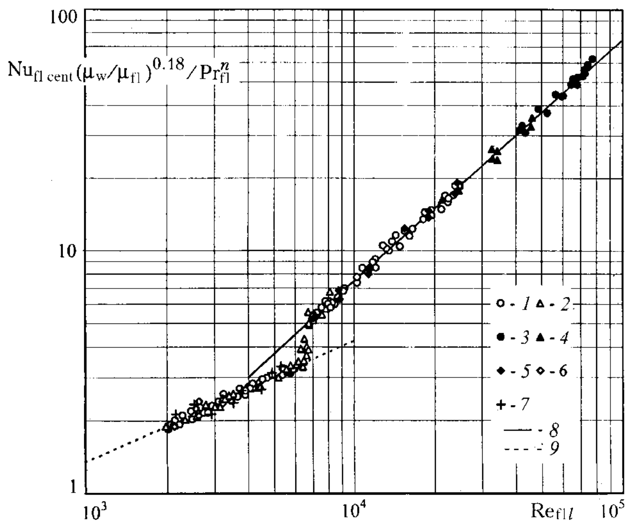
For the case where the vibration intensity is low ($\mathrm{Re}_{\mathrm{fl}l} \le 2000$) we have

$$\alpha_x/\alpha_{\mathrm{cent}} = \exp\,[8.5\cdot10^{-4}\,\mathrm{Re}_{\mathrm{fl}l}\,(1 - X)]\,, \tag{4}$$

here $\alpha_{\mathrm{cent}} = q_{\mathrm{cond}}/(t_{\mathrm{fl}} - t_{\mathrm{w}})$.

The heat-flux density q_{cond} is determined from the equations given in [6] depending on the process (heating, cooling, maintenance of the temperature of the fluid in the vessel) in the absence of vibrations.

For $2000 \le \mathrm{Re}_{\mathrm{fl}l} < 6500$ the local relative heat transfer is



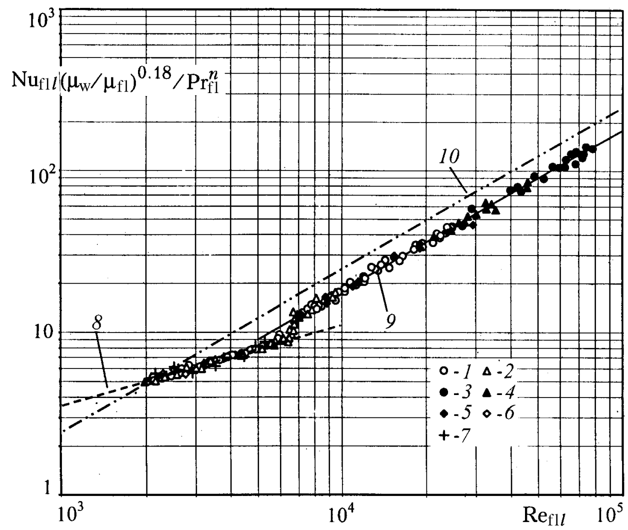


Fig. 4. Heat transfer at the center of the bottom (generalization of experimental data): 1) laboratory setup, oil; scale model of the tank: 2) mazut; 3) oil; model: 4) water; 5) kerosene; 6) ethylene glycol [5]; 7) tanker, petroleum [5]; 8) $Nu_{fl\,cent} = 7.5 \cdot 10^{-4} \cdot Re_{fl\,l}\ Pr_{fl}^{0.5}(\mu_{fl}/\mu_{cent})^{0.18}$; 9) $Nu_{fl\,cent} = 0.0424\ Re_{fl}^{0.5} \times Pr_{fl}^{1/3}(\mu_{fl}/\mu_w)^{0.18}$ ($Re_{fl\,l} \le 6500$ $n = 1/3$ and $Re_{fl\,l} \ge 6500$ $n = 0.5$).

Fig. 5. Average heat transfer at the vessel bottom: 1–7) notation is the same as in Fig. 4; 8) $\overline{Nu}_{fl\,l} = 0.112\ Re_{fl\,l}\ Pr_{fl}^{1/3}(\mu_{fl}/\mu_w)^{0.18}$; 9) $\overline{Nu}_{fl\,l} = 1.8 \cdot 10^{-3}\ Re_{fl\,l} \times Pr_{fl}^{0.5}(\mu_{fl}/\mu_w)^{0.18}$; 10) $\overline{Nu}_{fl\,l} = 2.4 \cdot 10^{-3}\ Re_{fl\,l}\ Pr_{fl}^{0.5}\ (Pr_{fl}/Pr_w)^{0.25}$ [4] ($Re_{fl\,l} \le 6500$ $n = 1/3$ and $Re_{fl\,l} > 6500$ $n = 0.5$).

$$\alpha_x/\alpha_{cent} = Nu_{fl\,x}/Nu_{fl\,cent} = 5.47 \exp(-1.7X)\,, \tag{5}$$

the $Nu_{fl\,cent}$ number is generalized by the dependence (Fig. 4)

$$Nu_{fl\,cent} = 0.0424\ Re_{fl\,l}^{0.5}\ Pr_{fl}^{1/3}\ (\mu_{fl}/\mu_w)^{0.18}\,. \tag{6}$$

The equation for the local heat exchange with account for (5) and (6) has the form

$$Nu_{fl\,x} = 0.232\ Re_{fl\,l}^{0.5}\ Pr_{fl}^{1/3} \exp(-1.7X)\ (\mu_{fl}/\mu_w)^{0.18}\,. \tag{7}$$

For $Re_{fl\,l} > 6500$ the time of the transient process is no longer than 1.5 h; therefore, we can disregard the transient process for full-scale objects, and the local relative heat transfer is calculated from the equation

$$\alpha_x/\alpha_{cent} = Nu_{fl\,x}/Nu_{fl\,cent} = 4.71 \exp(-1.55X)\,. \tag{8}$$

The data on the heat exchange at the center of the bottom (Fig. 4) are generalized by the dependence

$$Nu_{fl\,cent} = 7.5 \cdot 10^{-4}\ Re_{fl\,l}/Pr_{fl}^{0.5}\ (\mu_{fl}/\mu_w)^{0.18}\,. \tag{9}$$

The final dependence for the local exchange at the bottom is

$$Nu_{fl\,x} = 3.53 \cdot 10^{-3}\ Re_{fl\,l}/Pr_{fl}^{0.5} \exp(-1.55X)\ (\mu_{fl}/\mu_w)^{0.18}\,. \tag{10}$$

Relation (10) holds for $Re_{fl\,l} = 6.7 \cdot 10^3 – 8 \cdot 10^4$ and $Pr_{fl} = 9–4000$.

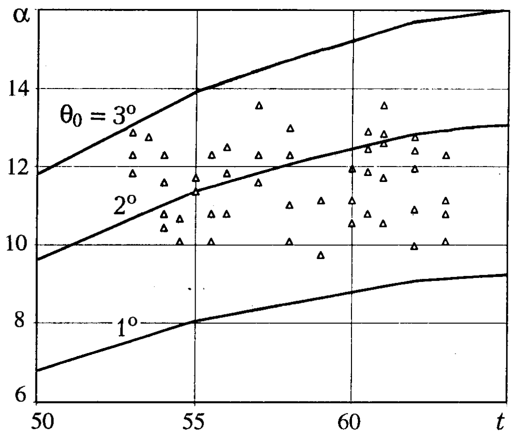


Fig. 6. Comparison of the calculated values of the heat-transfer coefficient and the experimental data for different Θ_0 (curves, calculation from (12), points, experimental data [5]).

In formulas (5)–(10), we take the final temperature in the core as the governing temperature and the compartment width as the governing dimension (the distance between the longitudinal frames in ships with a single-layer bottom). Equations (5)–(10) generalize the experimental data of [5]. The dependences to calculate the average Nusselt number for the bottom in the case of vibrations are obtained by integrating Eqs. (4)–(10) over its surface. As a result we obtain

$$\overline{\mathrm{Nu}}_{\mathrm{fl}l} = \mathrm{Nu}_{\mathrm{cond}} \frac{\exp\,[8.5\cdot 10^{-4}\,\mathrm{Re}_{\mathrm{fl}l}] - 1}{8.5\cdot 10^{-4}\,\mathrm{Re}_{\mathrm{fl}l}} \quad \text{for} \quad \mathrm{Re}_{\mathrm{fl}l} \le 2000\,, \tag{11}$$

$$\overline{\mathrm{Nu}}_{\mathrm{fl}l} = 0.112\,\mathrm{Re}_{\mathrm{fl}l}^{0.5}\,\mathrm{Pr}_{\mathrm{fl}}^{1/3} (\mu_{\mathrm{fl}}/\mu_{\mathrm{w}})^{0.18} \quad \text{for} \quad 2000 < \mathrm{Re}_{\mathrm{fl}l} \le 6500\,, \tag{12}$$

$$\overline{\mathrm{Nu}}_{\mathrm{fl}l} = 1.8\cdot 10^{-3}\,\mathrm{Re}_{\mathrm{fl}l}\,\mathrm{Pr}_{\mathrm{fl}}^{0.5} (\mu_{\mathrm{fl}}/\mu_{\mathrm{w}})^{0.18} \quad \text{for} \quad \mathrm{Re}_{\mathrm{fl}l} > 6500\,. \tag{13}$$

Dependences (12) and (13) satisfactorily agree with the results of our experiments and the data of [5]. Figure 5 compares the results obtained and those calculated according to [4]. Since in [4] the experimental data on heat exchange were obtained in the region of the bottom (X = 0.2–0.65), the values of $\overline{\mathrm{Nu}}_{\mathrm{fl}l}$ in this case are 33% higher than those obtained according to (13). Figure 6 compares dependence (12) and the results obtained in [5]. The experiments were conducted in a tanker with a single-layer bottom of carrying capacity 33,000 tons; the angular amplitude of rolling of the tanker was mainly 2 deg (at certain instants, it attained 3 to 4 deg and decreased to 1 deg), the period of rolling was $T \cong 10$ sec, and the $\mathrm{Re}_{\mathrm{fl}l}$ number was no larger than 6400 at an oil temperature of 63°C; therefore, the heat-transfer coefficients were calculated from dependence (12). The calculated values satisfactorily agree with the values measured under natural conditions.

As a result of he investigations performed, we have revealed the following regions of influence of vibrations on heat exchange depending on the $\mathrm{Re}_{\mathrm{fl}l}$:

(1) in the first region ($200 \le \mathrm{Re}_{\mathrm{fl}l} \le 2000$), the heat transfer increases at the edges of the bottom surface and remains constant in the central part; the local relative heat transfer depends on the Reynolds number;

(2) in the second region ($2000 < \mathrm{Re}_{\mathrm{fl}l} \le 6500$), the heat transfer increases over the entire surface of the bottom and is determined by laminar convection;

(3) in the third region $\mathrm{Re}_{\mathrm{fl}l} > 6500$, the immobile layer is destroyed over the entire surface and fluid flow is vortex, as a result of which the heat transfer increases tens to hundreds of times as compared to the heat transfer in

the absence of vibrations, and the fluid temperature in the vessel is virtually constant throughout the volume, in both heating and cooling.

For these regions we have obtained the dependences for calculating the local and average coefficients of heat exchange between the fluid and the bottom of the vessel in the case of vibrations. These dependences can be applied to thermal calculations in tankers in rolling.

NOTATION

x and y, longitudinal and vertical coordinates, m; l, linear dimension, m; Θ_0, angular amplitude of vessel vibrations, rad (deg); T, period of vibrations, sec; h, half the fluid level in the vessel, m; $b = L/2$, half-width of the vessel, m; L, width of the vessel, m; λ, thermal conductivity, W/(m^2·K); μ and ν, dynamic and kinematic viscosities, Pa·sec and m^2/sec; a, thermal diffusivity, m^2/sec; ρ, density, kg/m^3; β, temperature coefficient of volumetric expansion, K^{-1}; $X = x/b$, dimensionless coordinate; τ, time, sec; t, temperature, ^{o}C; U, amplitude value of the velocity, m/sec; α, heat-transfer coefficient, W/(m^2·K); q, heat-flux density, W/m^2; Fo = $a\tau/l^2$, Fourier number; Nu = $\alpha l/\lambda$, Nusselt number; Re = $U_{fl} l/\nu$, Reynolds number; Pr = ν/a, Prandtl number; Ri = $-(g/\beta)(d\rho/dy)/(dU/\partial y)_w$, Richardson number. Subscripts: cent, center of the bottom; x, local; fl, fluid; w, wall; cond, heat conduction; tr; transient period; l, governing dimension.

REFERENCES

1. N. V. Selivanov, *Heat Transfer in Oscillations near the Vertical Surface of a Vessel.* Pt. 1. *Principles of the Theory* [in Russian], Preprint of the Department of Power Engineering of Povolzh'e at Saratov Scientific Center of the Russian Academy of Sciences, Saratov (2000).
2. N. V. Selivanov, in: *Proc. IV Minsk Int. Forum "Heat and Mass Transfer–MIF-2000"* [in Russian], Vol. 1, 22–26 May 2000, Minsk (2000), pp. 460–463.
3. A. Z. Shcherbakov, V. A. Belonogov, and N. V. Selivanov, *Sudostroenie*, No. 4, 10–11 (1985).
4. A. Z. Shcherbakov, N. V. Selivanov, A. V. Plokhov, et al., *Transp. Khranen. Nefti Nefteprod.*, No. 2, 26–28 (1978).
5. J. Suhara, H. Kato, and T. Kurihara, *Rep. Res. Inst. Appl. Mech.*, **24**, No. 76, 1–30 (1976).
6. A. Z. Shcherbakov, *Transportation and Storage of High-Viscosity Oil and Oil Products with Heating* [in Russian], Moscow (1981).
7. V. U. Bondarchuk and A. D. Chornyi, in: *Proc. IV Minsk Int. Forum "Heat and Mass Transfer–MIF-2000"* [in Russian], Vol. 1, 22–26 May 2000, Minsk (2000), pp. 174–182.