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FREE LAMINAR CONVECTION OF A LIQUID IN A RIBBED SLOT

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UDC 536.25

Free convection in the vertical gaps of technical apparatus and constructions often occurs in layers having walls with complex geometry. Transverse projections on one or both walls of a liquid or gas layer may overlap part of the width of the layer. It is obvious that the presence of such projections may change the flow pattern in the gap and may lead to a change in the heat transfer from the hot to the cold wall.

We used the arrangement shown in Fig. 1 to investigate free convection in a vertical channel with projections. The walls were copper plates 1 (plate thickness 15 mm), placed in a container 2 with the working liquid (ethyl alcohol, $Pr = 16$). In all the experiments we used a channel of height $H = 342$ mm and depth $B = 56$ mm. Its width was changed using a thickness-calibrated attachment made of Plexiglas, trapped between the working surfaces of the plates. The temperature of each of the heat exchangers was maintained constant by circulating water from thermostats through the cavity situated behind the working plates. The constancy of the plate temperature along the height was monitored by means of five Nichrome–Constantan thermocouples (diameter 0.2 mm), embedded flush with the working surface.

To measure the temperature in the layer we used a Nichrome–Constantan thermocouple 0.06 mm in diameter. The thermocouple wires in PVC insulation were placed in a thin-walled capillary of stainless steel along the rear vertical end of the layer, which was shifted by means of an external coordinate reference system in a vertical direction with a reading accuracy of 0.1 mm. The junction of the thermocouple was introduced into the middle depth of the layer through the bent end of the capillary. The junction was displaced in a fixed horizontal plane by rotating the metal capillary. The coordinates of the thermocouple were found using a KM-6 cathetometer with an accuracy of 0.03 mm. The emfs of the thermocouples were measured with a R348 low-resistance potentiometer (class 0.002). The thermocouples were calibrated against a standard platinum resistance thermometer with an accuracy of up to 0.01°C in the temperature range 15–60° C.

For hydrodynamic investigations the method of stroboscopic visualization was used. Aluminum powder in the form of spheres with dimensions of 5 μm was used as the marker. Visual observations and photographs of the structure of the flow were made in reflected light through the transparent wall of the container 6. Part of the layer near the middle was illuminated from the side through a narrow 2-mm vertical glass insertion 3 in one of the plates and a transparent window 4 in the side wall of the container. The illuminating flux was

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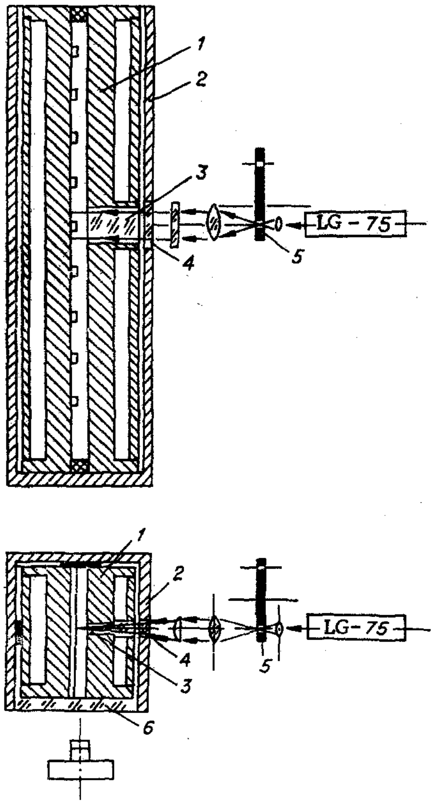

Fig. 1

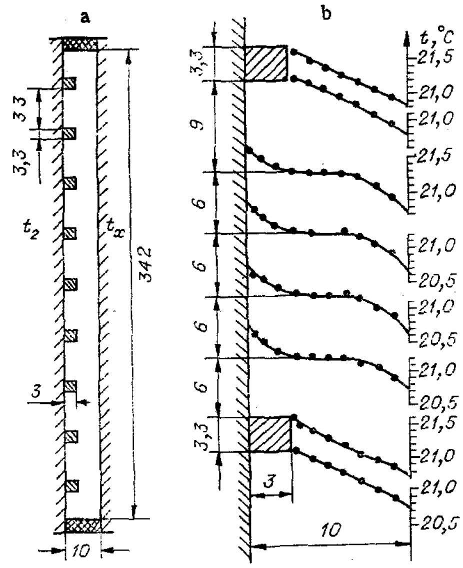

Fig. 2

formed using an LG-75 laser with the aid of a lens system, which first converted it into a parallel beam of diameter 2.5 cm and then converted it by means of a cylindrical lens into a vertical converging beam focused onto the plate opposite the window. Hence, a plane vertical part of the layer was illuminated through the window. In the plane where the light beam had the least cross section it passed through a system of openings uniformly situated along the diameter of a disk 5 rotating with constant speed, i.e., the flow with the aluminum particles was illuminated by light pulses with specified duty ratio.

Initially we considered the flow in a layer with a single projection on the heated wall. The layer of height H = 342 mm and width L = 10 mm had a transverse projection of Textolite 0.5 mm thick in the middle of the height of the whole depth of the layer. The size of the projection along the width of the layer was 2.4 mm

TABLE 1

No. of sections of measurement	Flow rate in ascending flow, mm^3/sec	Flow rate in descending flow, mm^3/sec	Ratio of flow rates K	Parameters of operation
1	14,2	15,0	0,94	
2	12,3	13,6	0,90	
3	11,8	12,2	0,97	
4	9,3	9,42	0,99	t_2=21,68°C
5	8,6	8,9	0,97	t_x=20,75°C
6	11,4	10,0	1,14	Ra=$7,2\times10^4$
7	12,9	11,3	1,14	
8	15,2	14,0	1,08	
9	15,2	14,5	1,05	
10	14,9	14,4	1,03	
Middle of projection	0,63	0,71	0,89	t_2=25,44°C t_x=20,30°C
Middle between projections	1,12	1,34	0,83	Ra=$4,5\times10^4$
Middle of projection	0,385	0,78	0,49	t_2=21,48°C t_x=20,58°C
Middle between projections	0,965	1,07	0,9	Ra=$1,7\times10^4$

and 5 mm. The qualitative picture of the flow is the same for all values of the projections: Vortex structures formed in the upper and lower parts of the slot are superimposed on the general circulation motion existing in the channel. Analysis of the rates of flow of liquid at unit depth of the layer in the ascending and descending flows carried out for a projection width of 5 mm showed that in the section of the projection in the flow rate is 2.5 times less than at a distance of 5 mm from it. Hence, a large part of the liquid participates in the vortex motions above and below the projection and a smaller part participates in the general circulation motion. The experimental values of the maximum vertical component of the velocity at a small distance from the projection is 25% less than the theoretical value of the velocity maximum [1], calculated for a relative height of the layer $h = H/L$ equal to half the overall height of the channel.

We then considered the flows in a layer when there were several transverse ribs situated on one of the walls of the layer at equal distances from one another in height. The projections were in the form of rectangular ribs laid horizontally over the whole depth of the layer. The working material of the projections was Duralamin. The first group of projections considered have the dimensions shown in Fig. 2. Figure 3 shows the flow pattern in the region of one of the middle projections, which is qualitatively similar to that observed in the case of a single projection: the presence of a general-circulation flow in the layer with superimposed eddy structures formed between the projections. The temperature distribution between the projections in the middle section with respect to the depth for this mode is shown in Fig. 2. The experimental dimensionless heat-transfer coefficient was found from the measured temperature gradient near the wall. In the middle section between the projections the Nusselt number $Nu = 1.6$, and for the same Rayleigh number Ra in a channel without projections, Nu – whose experimental value is identical with the theoretical one determined by the differential equation for the temperature [1] on the wall – is 2. The presence of transverse ribs on the surface leads to a slowing down of the flow, a reduction in the amount of liquid participating in the general circulation motion, and to a reduction in the heat transfer. The partial closing of the flow between the ribs facilitates a local increase in the longitudinal temperature gradient in these parts. Figure 3 shows profiles of the vertical component of the velocity u in a series of horizontal sections near a projection, the upper experimental profile relating to the middle section between two projections. The theoretical velocity profile, shown above the experimental ones, was calculated for the whole height of the layer and has a maximum value 25% greater than the experimental value. We calculated the flow rate of the liquid in the ascending and descending flows through the sections shown in Fig. 3. The dimensions of the section over the depth of the layer were taken to be 1 mm. The results of the calculations are shown in Table 1.

In the region of the projection the profile is symmetrical, and the ratio of the flow rates in these flows $K = 0.98$. At a relative distance of 1 (the distance from the projection to the cross section considered referred to the height of the projection), $K = 1.14$. The disagreement in the flow rates in the ascending and descending flows indicates that the flow has a three-dimensional structure. The three-dimensional nature of the eddy flows behind projections for forced motion has been known for a long time [2-4], but for free convection three-dimensional eddy formations have not been observed.

To investigate the flow at lower values of Ra we used a layer geometrically similar to the preceding one: In a layer of width $L = 5$ mm projections of height 1.6 mm and thickness 1.5 mm were fixed to the heated

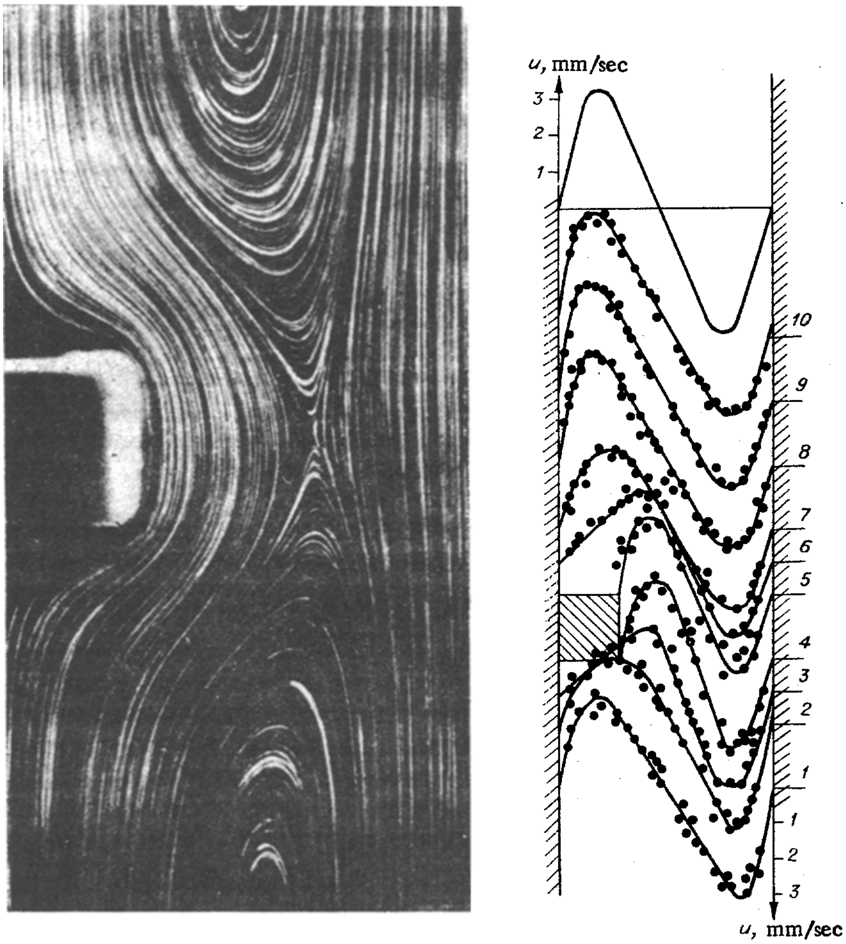

Fig. 3

TABLE 2

Section of measurement	Flow rate in ascending flow, mm³/sec	Flow rate in descending flow, mm³/sec	Ratio of flow rates K,	Parameters of operation
Lower projection	1,1	1,57	0,7	t_2=21,41°C
Halfway between projections	1,09	1,98	0,55	t_x=20,23°C
Upper projection	1,29	1,84	0,7	Ra=10^4
Lower projection	0,75	1,14	0,65	t_2=20,99°C
Halfway between projections	0,88	1,26	0,7	t_x=20,21°C
Upper projection	0,74	1,16	0,63	Ra=6,6×10^3
Lower projection	0,543	1,41	0,38	t_2=20,67°C
Halfway between projections	0,81	1,47	0,55	t_x=20,20°C
Upper projection	0,6	1,31	0,46	Ra=3,9×10^3

plate with a step of 16 mm in height between them. The qualitative picture of the flow was the same as before, but the disagreement in the flow rates in the ascending and descending flows increased. The ratios of the flow rates in these flows are shown in the second part of Table 1. The effect of a reduction in the step between the projections on the flow was checked in a layer of width 5 mm, where ribs with a transverse cross section of 1×1 mm were arranged with a step of 3.5 mm in height, i.e., the relative distance between them was reduced by a factor of 3 compared with the previous case. The flow preserved the vortex structure between the projections on a background of general-circulation flow. The characteristics of these flows in this layer and their ratio in the region of two neighboring projections are shown in Table 2.

The three-dimensional flow pattern between the projections when there is a smaller step between them is more pronounced: The velocity profiles in the flows are not the same in all the sections, and the ratio of the flow rates K in the majority of the sections is less than 0.7. The tabulated data also confirm that a reduction in Ra is accompanied by an increase in the three-dimensional nature of the flow.

Hence, the presence of transverse ribbing on one of the walls of a vertical convection layer of liquid causes the appearance of three-dimensional flow. The presence of this phenomenon in the flow eliminates the possibility of calculating the flow parameters using methods applicable to plane-parallel flows and requires a special study.

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DRAINING LIQUID-FILM SOLITONS

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One-dimensional solitary waves (solitons) which can move on the surface of a thin layer of a viscous liquid, draining in a vertical plane, are investigated. The first (experimental) description of such waves was given in [1]; later, quantitative measurements of their characteristics were carried out [2, 3] and attempts were made to explain them theoretically. In [4–6] the nature of these waves are discussed and some of their properties are pointed out. In [7] the view is put forward that a stationary solution is the limiting solution of a quasiharmonic type as the wave number is reduced. In this paper we carry out a qualitative analysis of the evolution of a nonstationary soliton and on the basis of the analysis we explain its shape. The fundamental characteristics of a stationary soliton (the amplitude and velocity) are calculated and the results obtained are compared with experimental data.

1. The equation for the waves in a vertically draining film of viscous liquid for low Reynolds numbers is well known and can be obtained by different methods. Assuming long weakly nonlinear waves, the equation takes the form

$$\varphi_t + 3\varphi_x + \varphi\varphi_x + \mathrm{Re}\,\varphi_{xx} + \mathrm{W}\varphi_{xxxx} = 0, \tag{1.1}$$

where $\varphi = 6(h - \langle h\rangle)/\langle h\rangle$; h is the local thickness of the film, $\langle h\rangle$ is the thickness of the film averaged over the length, t is dimensionless time, x is the dimensionless vertical coordinate (downwards) (the scale for measuring the length is $\langle h\rangle$, the scale for measuring time is $3\nu g^{-1}\langle h\rangle^{-1}$, ν is the viscosity, and g is the acceleration due to gravity), $\mathrm{Re} = 2g\langle h\rangle^3/5\nu^2$ is Reynolds number, and $\mathrm{W} = \sigma/\rho g\langle h\rangle^2$ is Weber's number (σ is the surface tension and ρ is the density of the liquid).

Together with the Burgers and Korteweg–de Vries equations, Eq. (1.1) belongs to the number of so-called nonlinear evolution equations. The treatment of the quantities φ and $\varphi^2/2$ as the momentum density and energy density is common to these equations (this treatment is related to the Galilean invariance of the nonlinear evolution equations). By confining ourselves henceforth to considering only solitary waves (solitons) for which $\varphi \to 0$ as $x \to \pm\infty$, in which case there are integrals of the form $\int\limits_{-\infty}^{\infty} \varphi^2(x, t)\,dx$, $\int\limits_{-\infty}^{\infty} \varphi_x^2(x, t)\,dx$,

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