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SPACE-TIME STRUCTURE OF A TRAIL BEHIND A HEATED CYLINDER

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Heat transfer which arises with flow around heated bodies may have a marked effect on hydrodynamic flows. With low flow rates (characteristic velocity much less than the speed of sound) this effect is mainly caused by the dependence of liquid viscosity on temperature. A local change in viscosity, and consequently shear stresses, leads to a change in the average velocity profile. This in turn affects the stability of hydrodynamic flows and the space-time characteristics of the natural modes.

Similar processes have been studied both for a boundary layer [1, 2] and for the trail behind a heated cylinder [3, 4]. Recently a detailed study has been made of the effect of heat transfer on the time characteristics of a trail with Reynolds numbers $\mathrm{Re} \leq 10^2$. The effect of heat transfer on the spatial structure of the vortex trail is studied in this work.

A qualitative explanation of this effect of heat exchange is quite simple. With an increase in temperature T there is an increase in air kinematic viscosity $\nu = \nu(T)$: the dynamic viscosity $\mu = \mu(t)$ depends weakly on temperature and air density ρ is inversely proportional to temperature. Therefore with an increase in temperature $\nu = \mu/\rho$ increases.* If Reynolds number is determined as $\mathrm{Re} = Ud/\nu(T_c)$ (U is approach stream velocity, d is cylinder diameter, T_c is cylinder temperature), then it decreases with an increase in temperature. It is clear that temperature only increases in the boundary layer and in the trail. However, in air the Prandtl number $\mathrm{Pr} = \nu/k$ (k is thermal diffusivity) is close to one ($\mathrm{Pr} \simeq 0.75$), and the spatial distributions of average temperature and average vorticity are similar [5]. This means that where there is a shear velocity there is a temperature field caused by heat transfer. Naturally the temperature in the trail is less than that of the heated cylinder, but nonetheless the action of local heating may be marked, at least in the case of studying flow close to bifurcation parameters.

The result of the effect of cylinder heating on the vortex trail parameters may be predicted from the following physical considerations. As is well known, dimensionless shedding frequency, i.e., the Strouhal number $\mathrm{Sh} = f(d/U)$ (f is frequency, Hz) decreases with a reduction in Re. Due to the fact that with an increase in temperature there is effectively a reduction in Reynolds number the vortex shedding frequency decreases, and with sufficient heating vortex shedding may cease. In fact these effects have been observed in experiments [3, 4].

In view of the qualitative explanation given above for the dependence of the shift in frequency on cylinder temperature it should be noted that in a number of works another method is suggested for explaining this effect. In [6] there is calculation of the increment of the absolute instability for a trail which is not uniform with respect to temperature, and this means with respect to density (the density is less at the center of the trail than at the periphery). These results were used in order to explain the effect of heating on trail characteristics behind a cylinder. Calculation showed that with quite low air density behind the cylinder absolute instability disappears and this explains the suppression of vortex formation with an increase in cylinder temperature. It follows from calculations that cylinder heating should lead to an increase in the frequency of vortex formation whereas an experiment [3, 4] showed that heating leads to the opposite effect. The authors in [6] emphasize that disappearance of absolute instability also occurs for a nonviscous model. The basic effect is connected with a change in air density. The explanation which we have provided is based on the fact that a change in cylinder temperature affects viscosity which in turn causes a change in velocity profile behind the cylinder (the effect of cylinder heating on the average velocity profile was actually detected in [3]).

The effective temperature is used as a quantitative characteristic of the effect of heating in [3, 4]. By this we understand the increase in temperature of the medium ΔT_{eff} which leads to the same result as cylinder heating by the value ΔT_c. The

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*It is noted that for water there is a reverse dependence, i.e., its kinematic viscosity decreases with an increase in temperature: the reduction in dynamic viscosity is more marked than the reduction in density.

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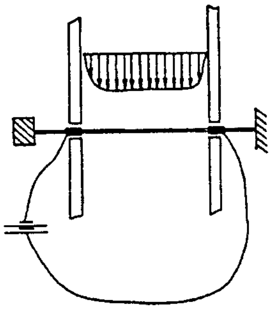

Fig. 1

effective temperature may be determined by different methods: by the reduction in vortex shedding frequency or by the suppression of vortex formation behind the cylinder. Both of these methods give approximately the same effective temperature although the results in [3, 4] are different. In [4] $\Delta T_{eff} = 0.3\Delta T_c$,* and in [3] $\Delta T_{eff} \approx 0.23\Delta T_c$. This difference was probably due to the fact that in [3] the cylinder was arranged vertically, and in [4] it was horizontal. This influenced the efficiency of convection. According to estimates provided in [4] natural convection at a heated cylinder may be ignored compared with induced convection if

$$\mathrm{Re} > (\mathrm{Gr})^{1/3}, \tag{1}$$

where $\mathrm{Gr} = (gl^3/\nu^2)\beta\Delta T_c$; g is free fall acceleration; l is vertical size; β is the temperature coefficient for volumetric expansion.

For experiments in [4] l is cylinder diameter and condition (1) is fulfilled. For experiments in [3] l is cylinder length and the reverse condition is fulfilled ($\mathrm{Re} \leq (\mathrm{Gr})^{1/3}$). This probably explains the difference in results in [3, 4]. Natural convection reinforces heat exchange of the medium and as a result of this it reduces the effective temperature.

Apart from changes in effective temperature and conditions for suppressing vortex formation in [3] a study was made of the effect of heating on the change-over from regular vortex shedding to random shedding with Re ~ 160.

It is well known [7] that with Re ~ 160 vortex shedding becomes random. As shown in [3], an increase in cylinder temperature leads to a regular vortex trail, i.e., the pulsation spectrum becomes very narrow.

We emphasize that in the work cited a study was made of the time characteristics of the vortex trail, but an idea of trail development in space may be obtained by using the results of measurements at different points. A more detailed study of the trail structure is possible if time characteristics are studied simultaneously with flow visualization. In fact a study was made of the trail behind a heated cylinder in this work.

The experiment was carried out in a wind tunnel at the Institute of Nonlinear Studies of California University (San Diego, California). The working part of the tunnel had a cross section of 61 × 61 cm. A hollow steel cylinder with diameter d = 0.08 cm was suspended in a special frame so that it did not touch the tunnel walls; holes were made in the upper and lower wall of the working section and outside the tunnel a load weighing several kilograms was fastened to the end of the cylinder (Fig. 1). With this fastening method the effect of wall vibration on vortex shedding was excluded. Cylinder heating was performed by a direct current source. As in [3] the cylinder temperature was calculated from the electric power Q discharged in the cylinder. The empirical dependence of Nusselt number Nu on Re [7] was used:

$$\mathrm{Nu} = 0{,}36\,\mathrm{Re}^{1/2} + 0{,}057\,\mathrm{Re}^{2/3}.$$

Cylinder temperature ΔT_c was determined as

$$\Delta T_c = Q/\pi l \lambda_0\,\mathrm{Nu}\,(\mathrm{Re}),$$

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*The effective film temperature $\Delta T_{eff.fi} = 0.5\Delta T_{eff}$ was determined in [4].

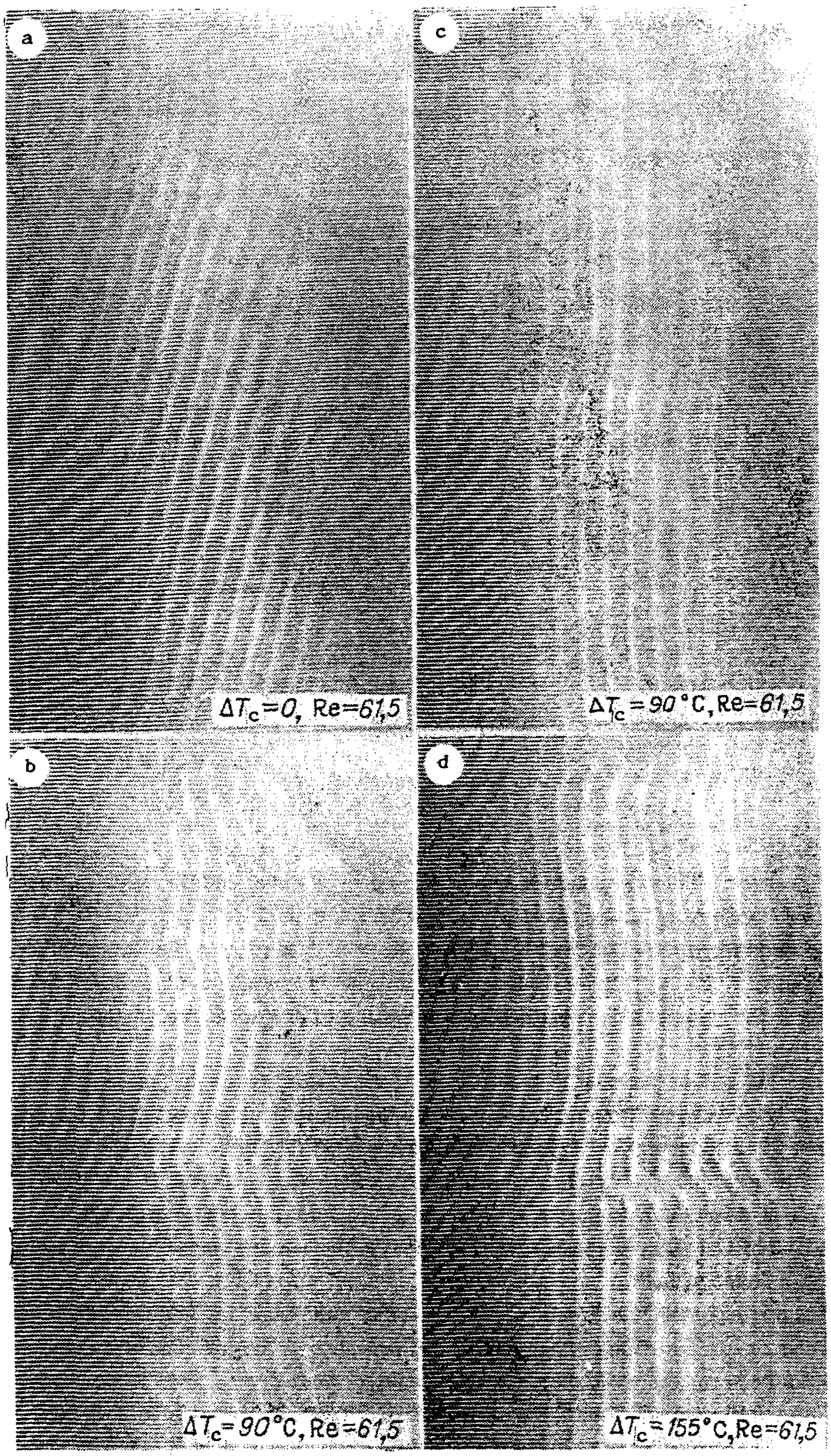

Fig. 2

where λ_0 is thermal conductivity of air at the approach stream temperature. In order to visualize the vortex trail a smoke visualization technique developed in [8, 9] was used. A thin wire which was moistened with liquid was stretched in parallel behind the cylinder. In order to obtain smoke the wire was heated by a pulsed electric current. Smoke distribution in the vortex trail was illuminated by a flash lamp. An instantaneous record was made by means of a CCD-camera into a recorder and then

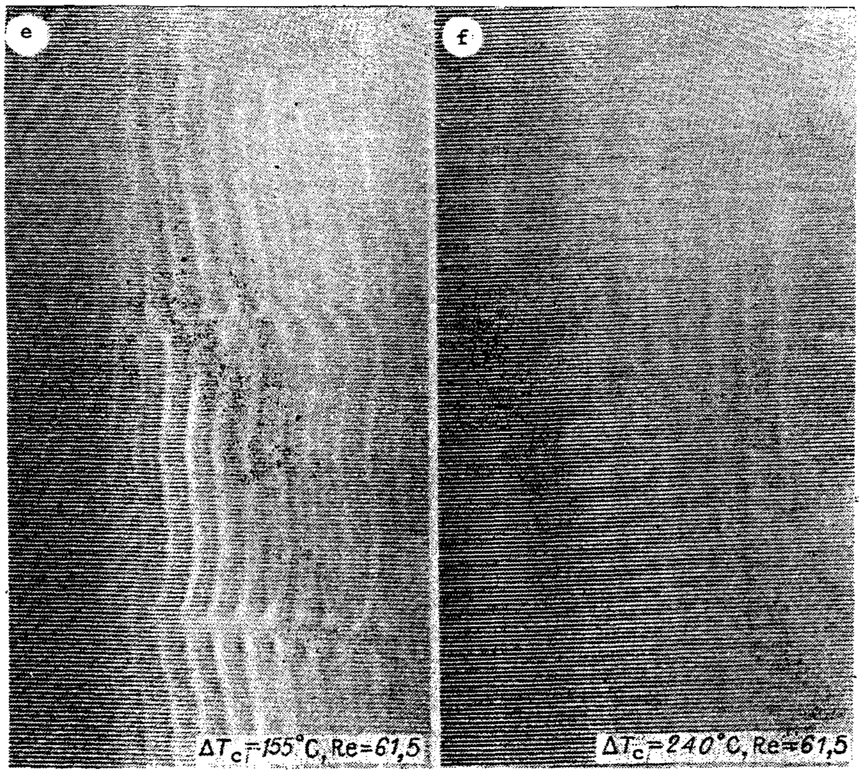

Fig. 2 (continued)

transferred to a video recorder. Velocity pulsation was measured by a direct current hot-wire anemometer TS1 and time characteristics of the signal were recorded by means of an SD380Z analyzer.

As visualization showed, in the absence of heating with Re = 61.5 vortices in the Karman trail behind the cylinder are arched with curvature counter to the flow; in the central part vortex lines are parallel to the cylinder, but at the tunnel walls they are inclined with respect to the cylinder axis. Visualization of a small area of a vortex trail in the region near the wall is shown in Fig. 2a.

As can be seen, the trail is periodic with respect to space. Time spectra for pulsations recorded by the hot-wire anemometer at a distance of 60d (5 cm) from the cylinder are quite narrow which points to time periodicity of the vortex trail.

Concerning the approach stream with cylinder heating there is a reduction in vortex shedding frequency. The effective temperature is about 30% less than for experiments described in [3]. The reduction in effective temperature is probably connected with the effect of natural convection. With the same temperature differences as in [3] the Grashoff number in this experiment is greater by a factor of eight (the transverse dimensions of the working part of the wind tunnels and correspondingly cylinder length differ by a factor of two).

Heating changes markedly the spatial structure of the vortex trail. Lines become wavy (Fig. 2b). Visually the vortex trail picture resembles the zig-zag instability of rolls in thermal convection. The instantaneous records were different instants of time (Fig. 2c). As can be seen, the wave amplitude and length of these zig-zag disturbances is not constant with time. A typical detail of this vortex trail regime behind a heated cylinder is the fact that at any instant of time the central position of a vortex line is parallel to the cylinder. This structure arises instead of a set of arched vortices with $\Delta T_c > 70°C$.

The time spectrum of pulsations B(f) corresponding to vortices in Fig. 2b, c is shown in Fig. 3b. The increase in the width of the spectrum compared with the spectrum in Fig. 3a is connected with excitation of wave movements in the vortex trail.

With a higher temperature (Fig. 2d, e) not only zig-zag vortices were observed, but defects also arose in the vortex trail. The time spectra of pulsations (Fig. 3c) were quite broad.

The most unexpected result was that with a temperature of $\Delta T_c > 230°C$ vortices became strictly parallel to the cylinder (Fig. 2f), but the width of the pulsation spectrum was sharply reduced (Fig. 3d). In a certain sense cylinder heating led to vortex trail lamination. It is noted that with the measurements of time characteristics for a trail behind a heated cylinder the hot-wire

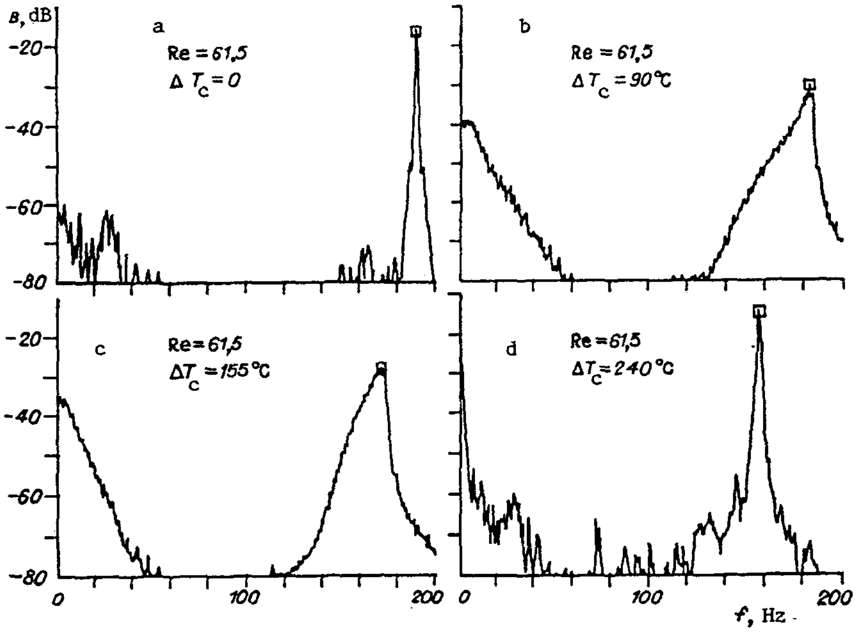

Fig. 3

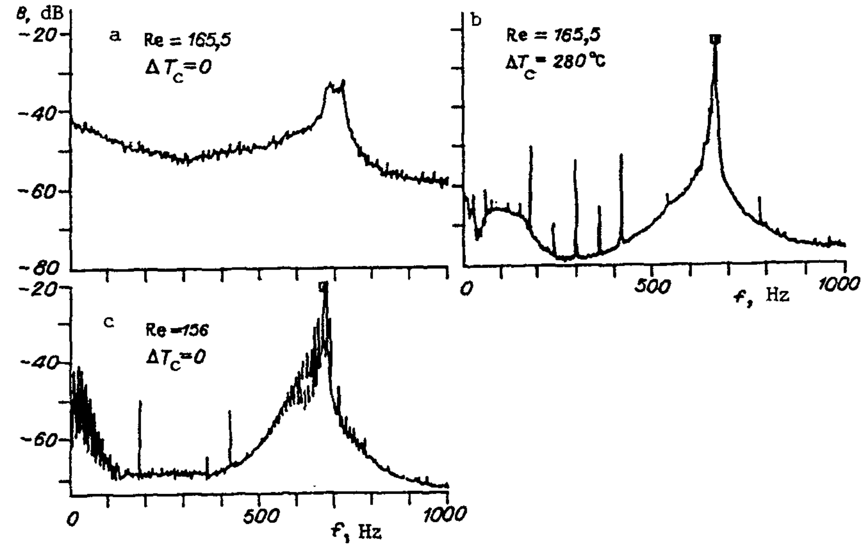

Fig. 4

anemometer records a 'mixture' of temperature pulsations and velocity pulsations. Therefore use of a hot-wire anemometer for these measurements requires substantiation. There are two circumstances due to which this explanation is possible. First the experiment was performed with velocities much less than sound velocity and in this case there is no propagating additional entropy mode in the medium. Second, as already noted Pr $\approx$ 1 for air and not only are the average temperature profiles and vorticity, but also pulsations of these values are similar. Therefore, even without separating the vortex and temperature fields it is possible to obtain qualitatively correct conclusions about the evolution of hydrodynamic pulsation spectra with an increase in cylinder temperature.

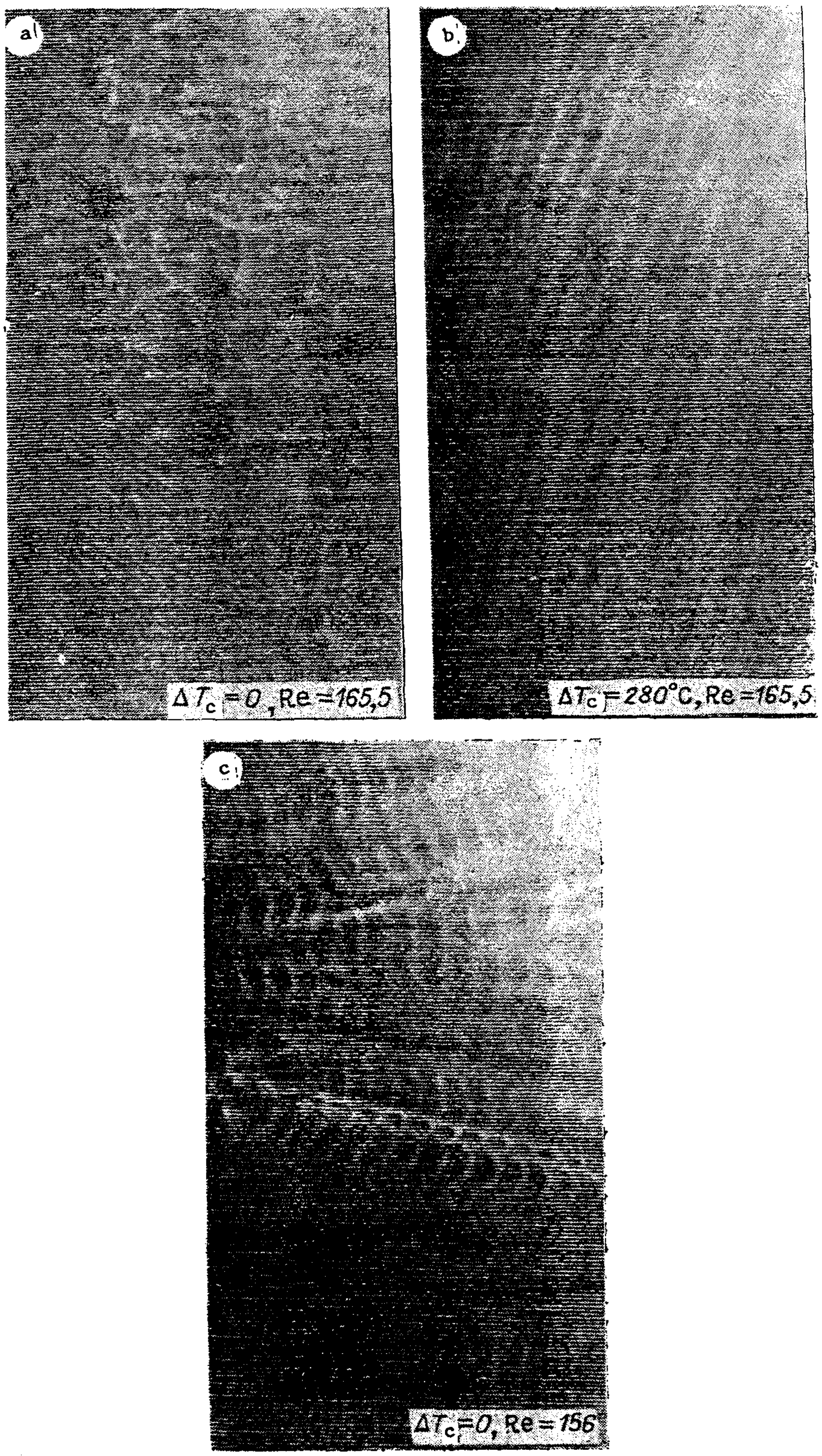

Fig. 5

With Re ~ 160 the vortex trail becomes unstable. The pulsation spectrum is continuous (Fig. 4a), but the trail behind the cylinder is spatially disordered vortices (Fig. 5a). Cylinder heating leads to regularization of vortices in the vortex trail which

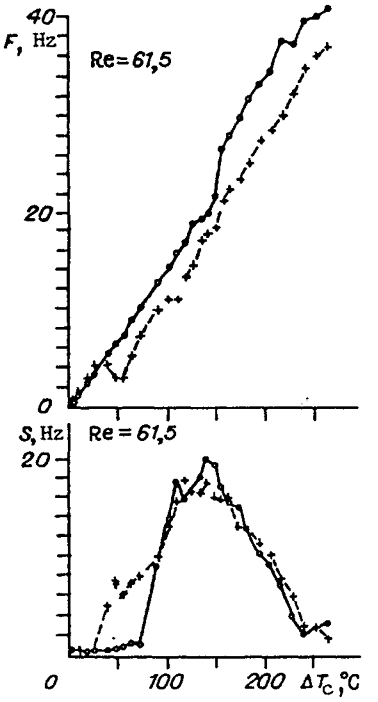

Fig. 6

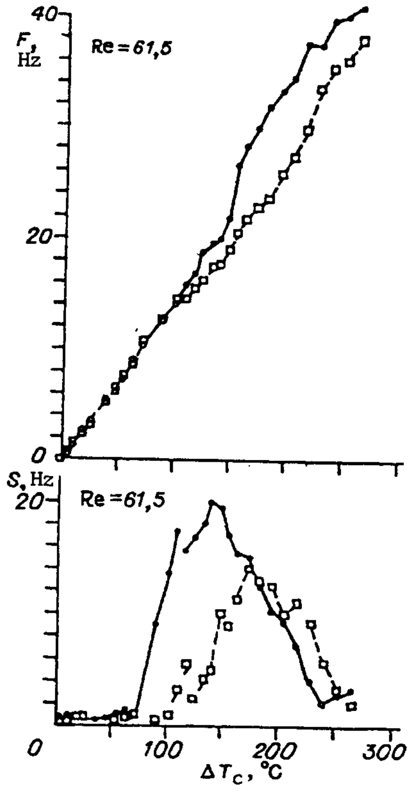

Fig. 7

becomes periodic with respect to space (Fig. 5b, $\Delta T_c = 280°C$). The time spectrum of pulsations in the trail is very narrow (Fig. 4b).

This change in vortex trail structure is not explained by the reduction Re. If the flow rate is reduced so that the vortex shedding frequency is approximately equal to the vortex shedding frequency with a heated cylinder, then the space-time structure will be entirely different. In the time spectrum (Fig. 4c) it is possible to separate the characteristic frequency, but in the instantaneous record it is possible to separate the characteristic scale of transverse modulation. Comparison of regimes presented in Figs. 4 and 5 indicates that vortices shed with a heated cylinder and the whole vortex trail are more stable than in the absence of heating.

Here is the most important question: what is the nature of zig-zag instability and defects which arise in a vortex trail in a certain temperature range for the cylinder? In principle two reasons are possible for generating these structures.

1. Instability of a vortex with a heated core. This instability should not be present if the liquid is uniform with respect to temperature.

2. Convection instability in the vicinity of a heated cylinder arranged vertically. From this instability could arise for the initial disturbances which are then transformed into zig-zag vortices or defects. The trail only gives a spatial resolution of disturbances produced at the heated cylinder.

In order to determine which of the possibilities is realized in an experiment detailed measurements were made for the shift in frequency and width of the pulsation spectrum with different conditions for trail formation and different positions of the hot-wire anemometer.

Results obtained with placing of the hot-wire anemometer at a distance of 3.5 cm from the cylinder in the central region of the working part of the tunnel (solid lines) at the walls (broken lines) are shown in Fig. 6. It can be seen that the shift in frequency F is only the same at low temperatures. With an increase in temperature both the shift in frequency and the width of pulsation spectrum S are different. The interval $70°C < \Delta T_c < 230°C$, where the pulsation spectrum is broad (Fig. 6), corresponds to a trail consisting of zig-zag vortices or of vortices with defects. Comparison of the width of spectra presented in Fig. 6 shows that close to the wall the pulsation spectrum becomes broad at low temperatures. This indicates that turbulence near the wall (velocity pulsation) may be transformed into spatial irregularities of the vortex trail.

Apart from studying the susceptibility of the trail to velocity disturbances a study was also made of the effect of temperature pulsations. The following method was used in order to introduce disturbances in the vortex trail behind the cylinder. A thin layer of paint was applied to the cylinder surface. This layer does not affect vortex dynamics although in view of the fact that the thermal conductivity of paint is much less than that of the steel heat exchange conditions were different at painted and unpainted surfaces of the cylinder. Due to this it is possible to introduce temperature disturbances in the vortex trail. Painting of the cylinder was carried out at intervals with a spacing of ~7 cm which is close to the interval of zig-zag disturbances in vortices.

Comparison of the shift in frequency F and width of the pulsation spectrum S for painted (broken lines) and unpainted (solid lines) cylinders is presented in Fig. 7. The hot-wire anemometer was placed in the central part of the working section of the tunnel. As can be seen, introduction of temperature disturbances has almost no effect on the shift in frequency due to heating, although the width of the pulsation spectrum changes markedly. It is most important that introduction of temperature disturbances leads to a marked reduction in the width of the pulsation spectrum with low heating and to expansion of the spectrum with high cylinder temperatures. This effect is a consequence of the fact that the initial temperature space-periodic disturbances regularize the development of waves and defects in the rail behind the cylinder.

Thus, the vortex trail behind a heated cylinder is sensitive to both initial velocity disturbances and to temperature disturbances. It is particularly important that zig-zag vortices and defects exist in a certain range of heated cylinder temperature. With low and high temperatures these spectra are absent. This indicates that the first of the mechanisms mentioned above is realized, i.e., instability of vortices with a high core temperature. If the second mechanism was realized, i.e., convection instability in the vicinity of the vertical cylinder, then with an increase in its temperature (Gr, i.e., nonequilibrium parameter, increases) there would be an increase in wave amplitude and the number of defects in the vortex trail. This would lead to an increase in the width of the pulsation spectrum. Opposite effects are observed in an experiment. With a high cylinder temperature the vortex trail becomes more regular.

In view of the fact that with a low cylinder temperature flow is less stable, but with a high temperature is more stable than in a medium of uniform temperature, it is possible to make an analogy with flow of stratified liquid in a channel. It is evident that introduction of stratification affects flow stability. For shear flow in which the point of inflection coincides with the minimum vorticity, introduction of a little stratification leads to flow destabilization [10, 11]. If the stratification is quite strong, then for this class of flow it leads to flow stabilization (according to the Miles criterion flow with stratification is stable if the Richardson number is greater than 0.25). A similar effect is also observed here: with a low temperature, and consequently a low difference in densities, there is excitation of zig-zag waves in the background of the vortex trail, and with high temperatures there is flow stabilization.

In conclusion it is noted that the mechanism suggested for instability and stabilization of a vortex trail behind a heated cylinder and the analogies discussed in connection with this may now be considered as hypotheses. In order to confirm or refute them in our view not only additional experiments, but also theoretical calculations of the stability for vortices with a heated core, are necessary.

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