DETACHED FLOW PAST A HEATED CYLINDER AT LOW MACH NUMBERS

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The flows of liquids and gases past heated bodies are under intense investigation in application to heat-exchange problems. The question of how forced convection affects heat transfer has now been studied in great detail. The effect of heat transfer on the characteristics of the hydrodynamic flows themselves has been studied primarily for supersonic flows (see [1], Vol. 3). For flows at low Mach numbers the effect of the temperature on the other parameters of the flow under conditions of forced convection is usually neglected, and the temperature field is usually characterized by the velocity and pressure fields [2]. In the case of flow past heated or cooled bodies, however, the change in the viscosity of the liquid in the boundary layer [2] can bring about restructuring of the entire flow. In this paper this particular mechanism of the effect of heat transfer on hydrodynamic flows is studied for the example of flow past a cylinder.

It is well known [3] that the character of the wake behind the cylinder is determined by the Reynolds number $Re = v_0 d/\nu_0$ (v is the velocity of the incident flow, d is the diameter of the cylinder, and ν_0 is the kinematic viscosity). For small Reynolds numbers $Re < Re_1$ ($Re_1 \sim 40$) stationary viscous flow past the cylinder is stable; for $Re_1 < Re < Re_2$ ($Re_2 \sim 150$) a regular vortex street arises behind the cylinder. It has been established empirically ([1], Vol. 2) that the dimensionless frequency of shedding of vortices (the Strouhal number) $Sh = fd/v_0$ (f is the frequency in hertz) is determined for these values of Re by the dependence

$$Sh = 0{,}212(1 - 21{,}2/Re). \tag{1}$$

For $Re_3 < Re < 10^4$ ($Re_3 \sim 300$) the shedding of vortices becomes quasiregular, and if f is taken to be the frequency corresponding to the maximum of the frequency spectrum of velocity pulsations, then

$$Sh = 0{,}212(1 - 12{,}7/Re). \tag{2}$$

In the intermediate interval $Re_2 < Re < Re_3$, because of the instability of the vortex street with respect to external perturbations (vibrational background, acoustic noise, pulsations of the velocity of the incident flow), no definite regularities in the dependence of Sh on Re have been established.

In this paper, in studying the effect of heating of the cylinder on the flow past the cylinder the main attention is devoted to restructuring of the wake, occurring at $Re = Re_{1-3}$. The experiment, whose arrangement is shown in Fig. 1, was performed in a low-turbulence wind tunnel whose working part was 30 × 30 cm and 120 cm long. The flow velocity v_0 reached 30 m/sec and the degree of turbulent pulsations was less than 0.15%. The cylinder in the flow consisted of nichrome wire of different diameters (d = 0.1, 0.3, and 0.8 mm) with length ℓ = 30 cm. The wire was strung vertically 30 cm from the converging tube of the wind tunnel. Nichrome was chosen because its resistivity is high and comparatively temperature independent. The wire was secured with copper clamps, mounted into the walls of the working part of the wind tunnel. The usual method of end plates [4] was used to prevent the boundary layer at the walls from affecting the shedding of vortices. Thin plates P (see Fig. 1), whose diameter $D_P \gg \delta$ ($D_P \simeq 10$ cm), were placed at a distance larger than the thickness of the boundary layer δ ($\delta \sim 1$ cm) at the wall; the rings screened the vortex street from turbulent pulsations occurring at the walls. The cylinder was heated with a constant current. The thermal power Q released at the cylinder was calculated by measuring the current strength and the applied voltage.

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Based on the known heat transfer, determined empirically for a circular cylinder [1], the dependence $Nu = 0.36\ Re^{1/2} + 0.057\ Re^{2/3}$ was determined by the temperature difference

$$\Delta T \simeq Q/\pi l \lambda_0 \mathrm{Nu(Re)}.$$

Here $Re = v_0 d/\nu_0$, where ν_0 is the kinematic viscosity and λ_0 is the thermal conductivity at the temperature of the flow incident on the cylinder. Strictly speaking, to find Re and Nu the viscosity and thermal conductivity of the medium must be taken at a temperature equal to the arithmetic mean value of the temperature of the cylinder and the incident flow [5]. If the dependence of λ and ν on T is approximated by a linear function, then the temperature difference Δt is given by the more accurate expression

$$\Delta T = \Delta T_0 \left(1 + \frac{1}{2}\left(\frac{1}{\lambda}\frac{d\lambda}{dT} - \frac{1}{\mathrm{Nu}}\frac{d\,\mathrm{Nu}}{d\,\mathrm{Re}}\frac{\mathrm{Re}}{\nu}\frac{d\nu}{dT}\right)\Delta T_0\right)^{-1}. \quad (3)$$

At the temperatures realized in the experiment the linear approximation of $\lambda(T)$ and $\nu(T)$ together with Eq. (3) determine ΔT to within 1%.

The velocity pulsations were measured with a DISA 55M hot-wire anemometer (TA) with a P 11 sensor. The sensor filament was positioned vertically 2 mm from the cylinder. The signal was processed on a 2034 multichannel analyzer, manufactured by the Bruelle and Kjaer Company, directly as the measurements were performed. The average flow velocity was determined with a pitot tube, connected with a liquid micromanometer. Figure 2 shows the dependence of Sh on Re in the absence of heating. The solid lines show the dependences (1) and (2). In the range $160 < Re < 250$ the shedding of vortices was unstable, and the shedding frequency of the vortices was determined with quite coarse averaging.

Figure 3 shows the characteristic change in the spectrum of rms pulsations of the velocity S_f, when the cylinder is heated, in the region $40 < Re < 150$ for different temperatures of superheating of the cylinder $\eta = \Delta T/T_0$ (T_0 is the absolute temperature of the flow). Here vortices were shed in the absence of heating (curve 1) at the frequency $f_0 = 1240$ Hz ($v_0 = 3$ m/sec, d = 0.3 mm, Re = 60), and the width of the spectrum at 0.7 of the maximum was equal to $\Delta f = 3$ Hz or $\Delta f/f_0 = 2.4 \cdot 10^{-3}$. Curve 2 corresponds to the case when the difference of the air temperature and the temperature of the cylinder $\Delta T = 43°C$ and the shedding frequency of vortices f = 1197 Hz; curve c corresponds to $\Delta T = 111°C$ and f = 1071 Hz. For $\Delta t = 142°C$ the shedding of vortices stopped – the rms amplitude of the pulsations dropped approximately by 40 dB compared with flow past an unheated cylinder and became equal to the turbulence of the flow. Before giving a qualitative explanation of the obtained results and investigating this phenomenon in detail, we shall make two remarks.

First, heating the wire, which in the experiment reached a temperature of 350°C, changes its length by the amount $\Delta\ell$ ($\Delta\ell \sim 2$ mm) and tension P; this can affect the shedding frequency of the vortices, if it is close to the frequency of the characteristics oscillations [6]. For this reason, in the experiment measures were adopted to prevent such effects. The tension of the wire was chosen so that the characteristic frequency f_1 of the first (and most dangerous) bending mode would be an order of magnitude lower than the shedding frequency of the vortices. In addition, in the experiment a spring S (see Fig. 1) was used in order to reduce the tension by several percent, even with maximum heating of the wire. Measurements showed that doubling the tension had no effect on the vortex shedding frequency.

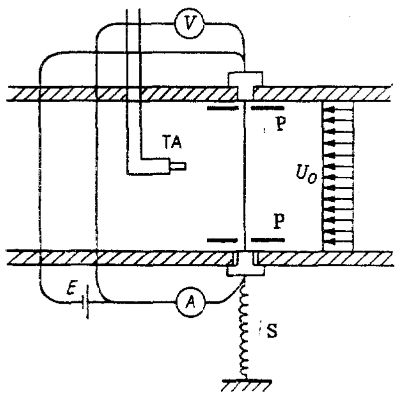


Fig. 1

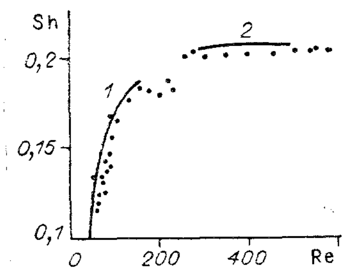


Fig. 2

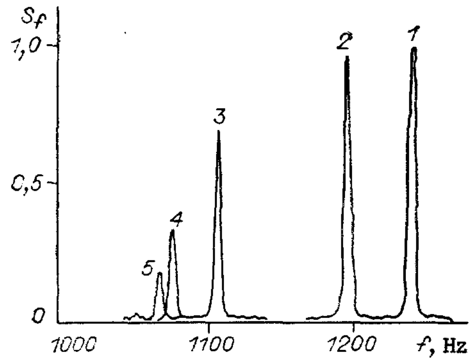


Fig. 3

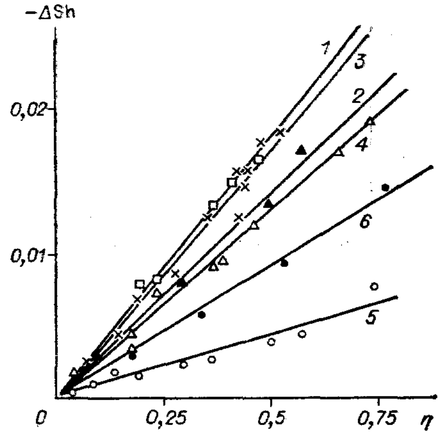


Fig. 4

Therefore, the effect of the heating-induced stretching of the wire on the vortex shedding frequency can be neglected.

The second remark concerns the estimation of the thermogravitational effects. The ratio of the inertial forces to the forces arising as a result of a change in density is characterized by Froude's number $Fr^2 = v_0^2/g\beta\Delta T\delta$ (g is the acceleration of gravity and β is the volume thermal expansion coefficient). For the conditions of our experiment $Fr^2 \sim 10^3$-10^5, i.e., the effect of gravity on the detached flow past the cylinder can be neglected. The effect of the heating of the cylinder on the flow regime in the wake was analyzed on the basis of the model of nonstationary flow of a viscous liquid past a hot body. In the process the temperature dependence of the dynamic viscosity μ, the thermal conductivity λ, and the density ρ must be taken into account. With the help of [7] it is possible to construct a system of parameters that determine this effect (here there are 12 such parameters) and to describe, based on the π theorem, the motion of the liquid with eight dimensionless parameters. Some of these parameters cannot be varied in the experiment (they depend on the type of gas; for example, the Prandtl number), while other parameters are close to zero (for example, the Mach number), so that the most important, from our viewpoint, dependences — that of Sh and Re and the relative superheating η — were studied. Figure 4 shows an example of these dependences. In the course of the experiment the diameter of the wire, the flow velocity, and the electric power dissipated in the wire were varied. The lines 1 and 2 were obtained for d = 0.1 mm and they correspond to Re = 60 and 77; the lines 3, 4, and 5 correspond to d = 0.3 mm and Re = 60, 80, and 117; and, the line 6 corresponds to d = 0.8 mm and Re = 106. As the cylinder heats up the temperature of the gas in the boundary layer and in the wake increases. In the process, μ increases, ρ decreases, and the kinematic viscosity $\nu = \mu/\rho$ increases, which is equivalent to a decrease of Re.

If the entire gas were heated up to the temperature of the cylinder, then the effect of heating would be different. We shall determine the effective superheating η_{eff}, showing by how many more times the gas must be heated in order to obtain the same frequency reduction as in the case when the cylinder is heated by ΔT. For this we shall estimate the quantity $\left(\frac{\partial\eta}{\partial\,\mathrm{Re}}\right)_e = \frac{\partial\eta}{\partial\,\mathrm{Sh}}\frac{\partial\,\mathrm{Sh}}{\partial\,\mathrm{Re}}$ from the experimental data, $\partial\eta/\partial\,\mathrm{Sh}$ from the slope of the straight lines in Fig. 4, and $\partial\,\mathrm{Sh}/\partial\,\mathrm{Re}$ from Eq. (1). On the other hand, assuming that only the kinematic viscosity depends on the temperature, the theoretical estimate for $\partial\eta/\partial\,\mathrm{Re}$ will be

$$\left(\frac{\partial\eta}{\partial\,\mathrm{Re}}\right)_T = -\frac{\nu}{\mathrm{Re}\,T_0}\left(\frac{\partial\nu}{\partial T}\right)^{-1}. \quad (4)$$

Comparing the values of $\partial\eta/\partial\,\mathrm{Re}$ obtained in the experiment and computed from Eq. (4) we obtain

$$\eta_{eff} = (\partial\eta/\partial\,\mathrm{Re})_e/(\partial\eta/\partial\,\mathrm{Re})_T$$

(η_{eff} = 0.224, 0.218, 0.228, 0.206, 0.186, and 0.150 for d = 0.1, 0.3, 0.1, 0.3, 0.8, and 0.3 and Re = 60, 60, 77, 80, 106, and 117).

The effective overheating can also be determined in a different manner. Figure 5 shows the heating of the cylinder at which vortex shedding stops versus Re (line 1). If the entire

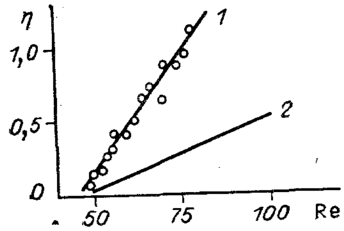


Fig. 5

gas were heated, then vortex shedding would stop at an air temperature giving rise to a decrease of Re from Re_1 (2). Knowing the slopes of the straight lines 1 and 2, we can find η_{eff}. In this case $\eta_{eff} = 0.23$, which is in good agreement with the method for determining η_{eff} based on the decrease in the vortex shedding frequency.

Why does the frequency of the vortex street change? For $Re > Re_1$ the vortex street forms from the shear flow, whose profile is formed by the flow past the cylinder. As visualization has shown (see, for example, [8]), the vortex street arises because of instability of the antisymmetric mode, which grows downstream. As Re changes the profile of the velocity behind the cylinder becomes deformed, and the repetition frequency of the vortices changes. In this connection it is interesting to compare the flow profile behind heated and unheated cylinders with different numbers. The measurements were performed with the standard DISA 56C hot-wire anemometer with a temperature compensation system. A sensor with two parallel tungsten filaments, 5 μm thick and ~3 mm long, was employed. The filaments were oriented parallel to the cylinder in the flow. One of them was a thermistor. The other, positioned 1 mm farther downstream, operated in the regime with superheating, and the velocity was measured with its help. By moving the latter sensor about in the flow we studied the profile of the average velocity v(y) (y is the transverse coordinate) at different distances from the cylinder (Fig. 6). The plots I correspond to three diameters, II correspond to six diameters, and III correspond to nine diameters; the plots *a* through c correspond to Re = 60, 80, and 100. The circles show velocity profiles for an unheated cylinder and the crosses show the profile for a cylinder heated up to temperatures such that $\eta = 0.53$, 0.46, and 0.4 (a-c, respectively). The heating results in a sharp reduction of the velocity behind the cylinder. The uncertainty associated with the fact that the heated filament is located

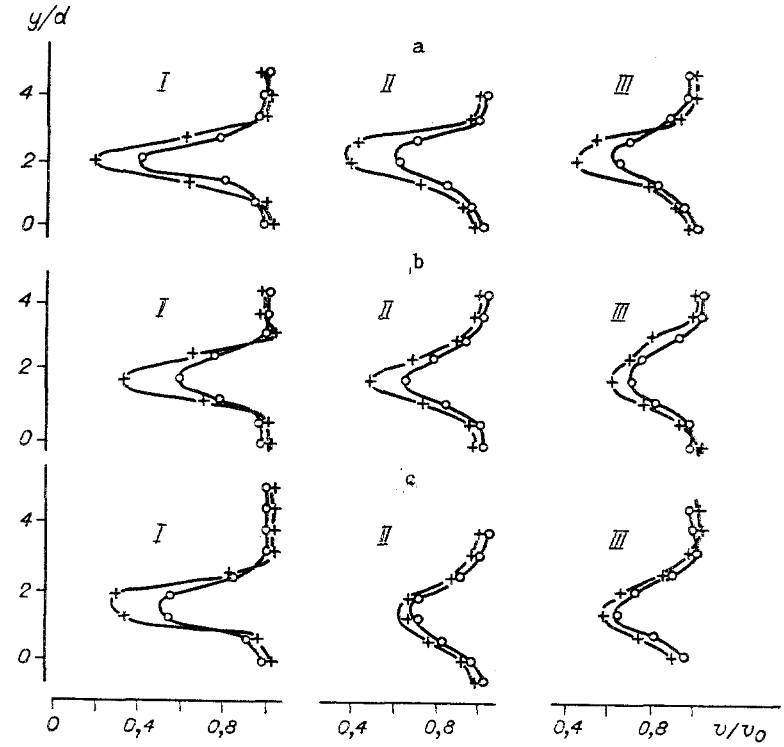
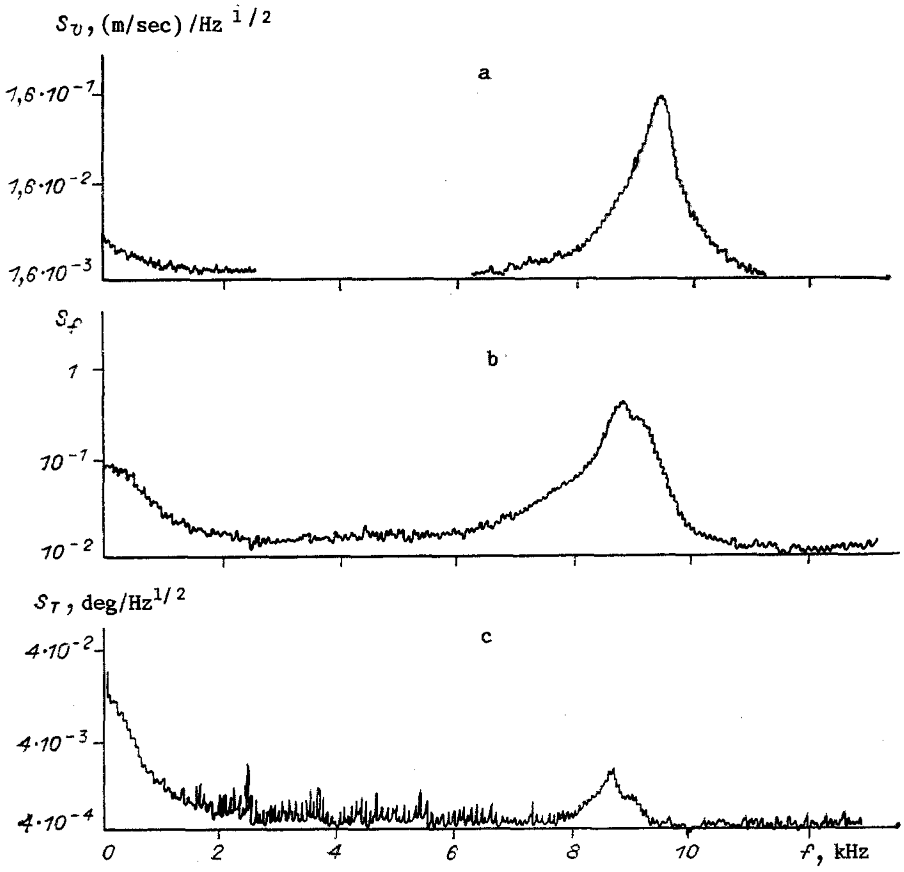
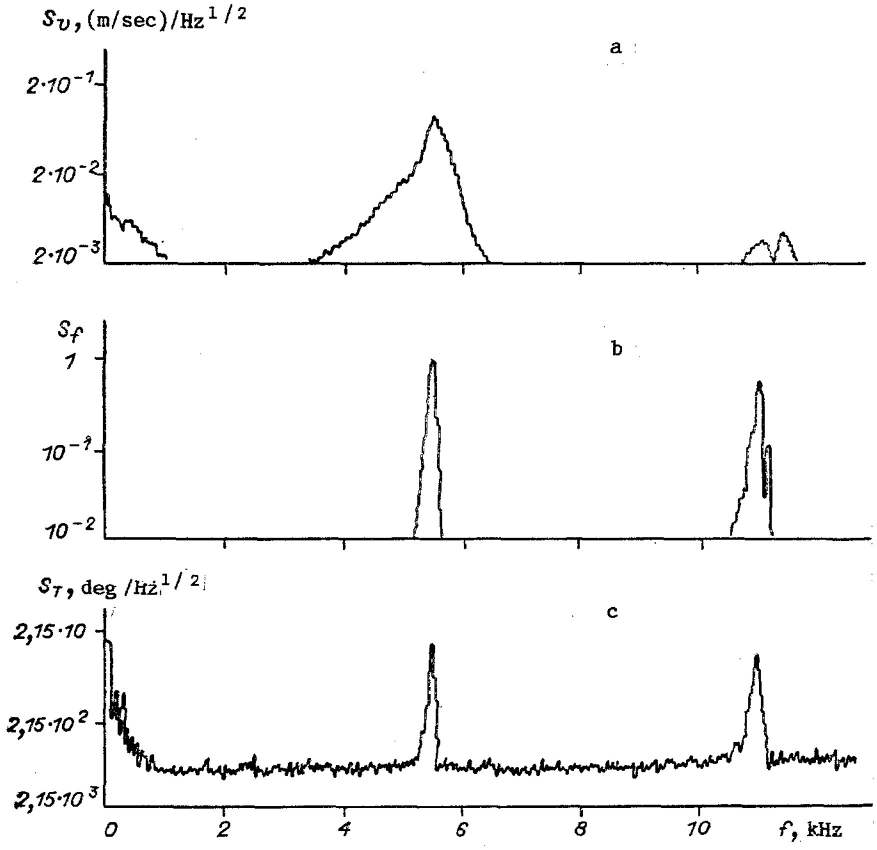


Fig. 6



S_v, (m/sec)/Hz$^{1/2}$
a
$1,6\cdot10^{-1}$
$1,6\cdot10^{-2}$
$1,6\cdot10^{-3}$
S_f
b
1
10^{-1}
10^{-2}
S_T, deg/Hz$^{1/2}$
c
$4\cdot10^{-2}$
$4\cdot10^{-3}$
$4\cdot10^{-4}$
0
2
4
6
8
10
f, kHz

Fig. 7



S_v, (m/sec)/Hz$^{1/2}$
a
$2\cdot10^{-1}$
$2\cdot10^{-2}$
$2\cdot10^{-3}$
S_f
b
1
10^{-1}
10^{-2}
S_T, deg /Hz$^{1/2}$
c
$2,15\cdot10$
$2,15\cdot10^{2}$
$2,15\cdot10^{3}$
0
2
4
6
8
10
f, kHz

Fig. 8

somewhat lower downstream than the thermistor (at the location where the temperature of the flow is lower) merely weakens the observed effect.

Comparing the profiles in Fig. 6 we can see that the heating (analogous to a reduction of Re) results in a decrease of the velocity in the wake behind the cylinder.

Now that it has been determined that the heating affects the characteristics of nonstationary flows in the same manner as a reduction of Re, there arises the question of the possibility of controlling the restructuring of the pulsation spectra at Re ~ $Re_{2,3}$. The realization of such control is shown in Figs. 7 and 8. The spectra of the rms velocity pulsations behind a heated cylinder (Figs. 7a and 8a) were obtained with Re = 170 and 260. In the first case vortex shedding is irregular and the width of the spectrum $\Delta f/f_0 = 0.11$; in the second case the vortex shedding is quasiregular and $\Delta f/f_0 = 0.06$. Heating of the cylinder results in significant restructuring of the pulsation spectra. Thus, at Re = 170 heating of the cylinder up to $\eta = 0.64$ stabilizes vortex shedding (Fig. 7b) and at Re = 260 ($\eta = 0.54$) vortex shedding becomes unstable (Fig. 8b). We note that in the measurements thermal compensation was not used, so that the spectra in Figs. 7b and 8b, obtained with superheating of the filament of the hot-wire anemometer by $\Delta T_{sh} \simeq 300°C$, are, strictly speaking, a "mixture" of velocity and temperature pulsations. Additional measurements showed, however, that the signal owing to temperature pulsations is negligibly small. To prove this we obtained pulsation spectra with the hot-wire anemometer operating in the thermistor regime ($\Delta T_{sh} \simeq 0.02°C$). The spectra of temperature pulsations in the vortex street are shown in Figs. 7c and 8c. At Re = 170 their rms amplitude $\Delta T_V \sim 1°C$. In order to compare the signal owing to temperature pulsations with the signal caused by velocity pulsations, ΔT_V must be of the order of 10°C (this condition is not satisfied in the experiment, so that the spectra in Figs. 7b and 8b correspond to velocity pulsations).

Thus, it has been observed experimentally that vortex shedding can be effectively controlled by heating the cylinder in the gas flow. This is determined primarily by the temperature dependence of the viscosity; in addition, although the thermal effect is concentrated in the boundary layer of the cylinder, the entire wake is restructured.

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