

DYNAMICS OF THE TOMS EFFECT IN FLOW OF POLYETHYLENE  
OXIDE SOLUTIONS IN A PIPE

V. M. Kulik

UDC 532.135:532.517.4

Variation of the decrease in frictional resistance over the length of a pipe in the flow of polyethylene oxide solutions is investigated experimentally.

In pipe flow of solutions of high-molecular-weight polymers possessing the Toms effect, some authors [1, 2] note a dependence of the decrease in frictional resistance on the position of the measurement section on the pipe. In [3, 4] it was shown that the reason for this is variation of the hydrodynamic efficiency of a polymer solution in the course of flow. The experiments in [3, 4], however, were carried out on an installation containing coaxial cylinders, making it possible to investigate the dynamics of the variation of efficiency at concentrations  $>10^{-4}$ . In [4] it was shown that during the turbulent flow of a concentrated solution of high-molecular-weight polyethylene oxide, two alternative processes occur: breakup of supermolecular formations, leading to a greater decrease in frictional resistance, and destruction of macromolecules, leading to a decrease in efficiency.

In the present paper we investigate the variation of the decrease in frictional resistance for dilute polymer solutions ( $c < 10^{-4}$ ) in the flow process, i.e., at different distances from the pipe entrance. Polyethylene oxide from the Bulgarian Badimol Co., with a molecular mass  $3.5 \cdot 10^6$ , was used.

A diagram of the installation is shown in Fig. 1. The chamber is designed to operate at a pressure of 160 atm. The liquid is displaced by compressed air supplied through an electromagnetic valve 6. Platinum sensors react to the conductivity of the medium between them and the chamber housing and serve to trigger the timer (upper electrode) and to stop the timer and close the valve (lower electrode). The volume of liquid between the sensors is 642 ml and the volume of filling solution is at least 1 liter. Outflow of the liquid lying above the level of the upper electrode, with a volume  $\sim 0.25$  liters, establishes the working flow regime before the timer is turned on. Measurements were made for five pipe lengths: 0.25, 0.5, 1.0, 2.0, and 4.0 m. The small-bore pipes of stainless steel, with an inside diameter  $D = 2.0$  mm, were mounted horizontally and had no bends. The pressure in the chamber was measured with standard manometers of class 0.15, and a Ch3-35A electronic frequency meter was used as the timer, which provided highly repeatable results (the spread of the points was less than 1%).

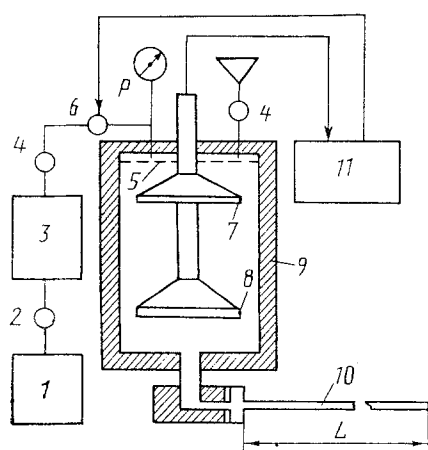


Fig. 1. Diagram of the installation: 1) compressed air tank; 2) reducer; 3) receiver; 4) valves; 5) grid; 6) electromagnetic valve; 7, 8) upper and lower electrodes; 9) chamber; 10) interchangeable working pipe; 11) timer and valve control.

A week before the measurements, the base solution with 2% concentration was prepared. The working solutions with the required concentrations were prepared by dilution a day before use. Distilled water was used to prepare all of the solutions. To make the medium sufficiently electrically conductive, immediately before a measurement 1 ml of an 0.5% NaCl solution was added to 1 liter of the solution of the investigated concentration.

The time of outflow of a measured volume of liquid through pipes of the five indicated lengths was measured in the experiments. The investigated concentrations of the solution ranged from  $10^{-6}$  to  $10^{-4}$ . For water and for each concentration we constructed a family of dependences of the average outflow velocity  $U$  on the pressure  $P$  in the chamber. For water flow we obtained good agreement between the measurement results and a calculation from the Blasius formula with a correction to allow for the kinetic energy of the stream carried off by the flow [5].

We determined the average decrease in frictional resistance over pipe sections of 0.25-0.5, 0.5-1, 1-2, and 2-4 m. The decrease in frictional resistance over the initial section 0-0.25 m or  $(0-125)D$  was not determined, since the regime of pipe flow is formed over that section of pipe. The efficiency was calculated from the formula  $\psi = (\Delta P_0 - \Delta P) / \Delta P_0$ , where  $\Delta P_0$  and  $\Delta P$  are the pressure differences over pipes of two successive lengths in the flow of water and polymer, respectively, taken at the same flow velocity. To obtain the decrease in frictional resistance over the section 2-4 m for flow of a  $10^{-5}$  solution at a velocity  $U = 5$  m/sec, for example, from the family of  $U(P)$  dependences for water we take the pressure difference in the chamber needed to provide a 5 m/sec flow velocity through 4 and 2 m pipes; the same thing is done for  $c = 10^{-5}$  and calculations are made from the above formula.

The results of the measurements are given in Fig. 2. It is seen that the decrease in frictional resistance varies over the length of the pipe. The efficiency of action of the solution therefore cannot be defined by one number: It is a function of time and of the intensity of interaction of the polymer with the turbulent flow. Here, as in [3, 4], we identify three regions in which the efficiency behaves differently. The first is determined by a rise in the efficiency of action of the polymer along the length of the pipe. For low velocities and high concentrations this region occupies most of the pipe length. For 3 m/sec and  $c = 10^{-4}$ , for example, the decrease in frictional resistance is observed to grow over the entire length of the pipe. The second zone is characterized by a maximal decrease in friction. This region, like the first, is not observed in all regimes. For a fixed concentration, the region of maximal efficiency shifts toward the start of the pipe with increasing flow velocity. For  $c = 2 \cdot 10^{-5}$ , for example, the maximal action of the polymer solution at 5 m/sec is manifested in the interval 1-2 m, which at 13 m/sec is manifested in the interval 0.5-1 m. Finally, a decrease in efficiency occurs in the third characteristic stage. This type of behavior of the Toms effect is typical of low concentrations and high flow velocities.

The reason for the rise in efficiency has been investigated in detail in [4, 6]. Measurements of viscosity and light scattering have shown the breakup of supermolecular formations of the globule type. In [4, 6] methods have been suggested and tried for the preliminary preparation of the solution, resulting in a considerable decrease in the viscosity of concentrated solutions and making them clearer, which enhances the integral efficiency in reducing frictional resistance by eliminating the section of rise in efficiency and prolonging the action of the maximal efficiency. The hypothesis developed in [7] for explaining the mechanism of action of the Toms effect by the formation in the solution of a supermolecular network structure is consistent with the experimental data on homogenization of the solution obtained in [4, 6], since molecules liberated from globules can go into reinforcing the network.

The maximal efficiency is an important quantity in a study of the dynamics of the Toms effect, i.e., the variation of the decrease in frictional resistance in the course of flow. In our experiments we have also determined the position of the section of maximal efficiency.

Let us compare our results with calculated values of the maximal hydrodynamic efficiency. For water flow we take the classical two-layered velocity profile, while for the flow of polymer solutions we take the Virk velocity distribution [8],

$$\begin{aligned} u^+ &= y^+, & y^+ &\leq 15, \\ u^+ &= 11,7 \ln y^+ - 17, & 15 &\leq y^+ \leq y_p^+, \end{aligned}$$

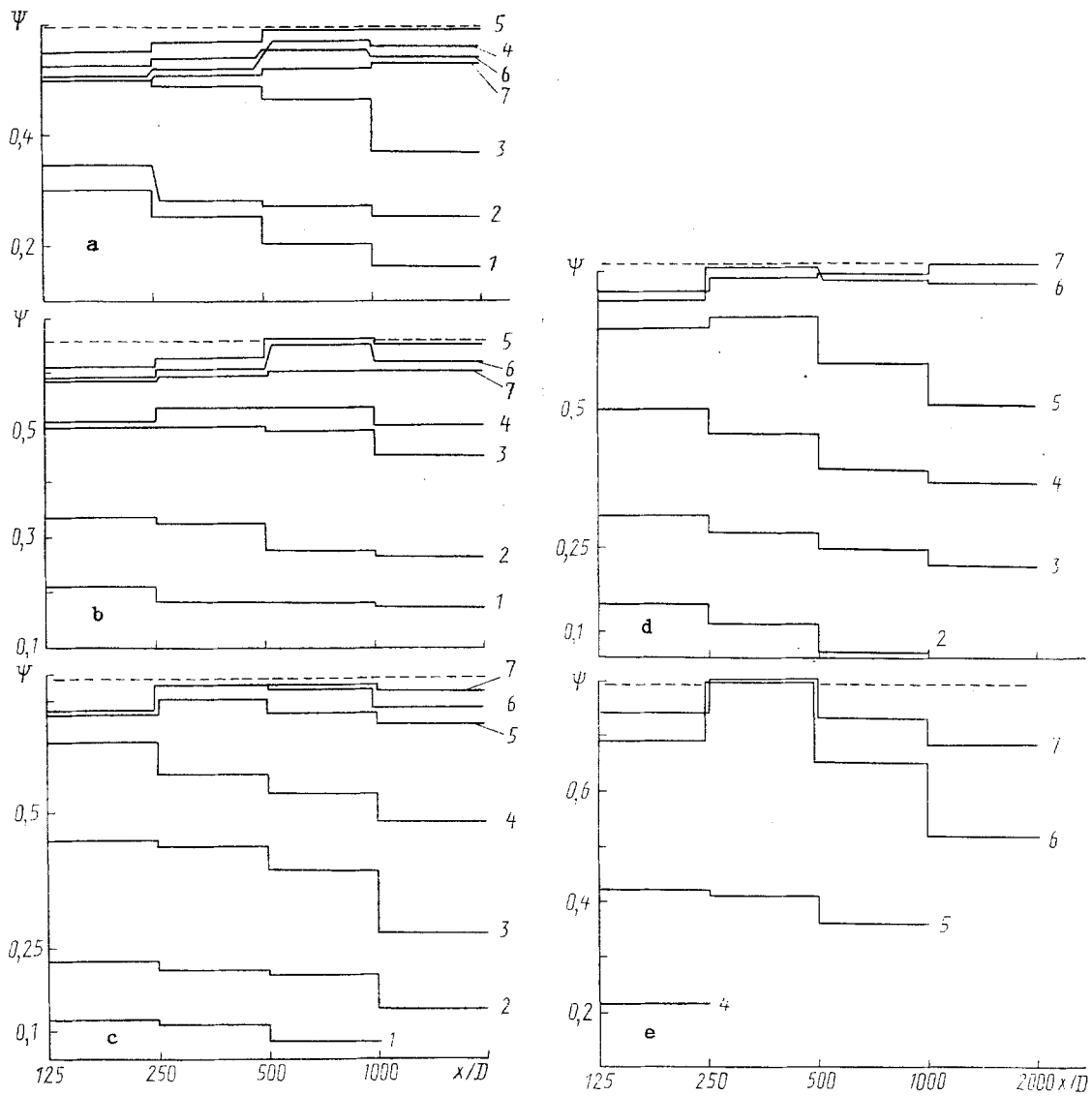


Fig. 2. Variation of the decrease  $\psi$  in frictional resistance along the length of a pipe [a)  $U = 3$  m/sec,  $\tau_0 = 45$  Pa; b) 5 m/sec, 105 Pa; c) 13 m/sec, 575 Pa; d) 20 m/sec, 1200 Pa; e) 40 m/sec, 4000 Pa] in flow of a solution with the following concentration c: 1)  $10^{-6}$ ; 2)  $2 \cdot 10^{-6}$ ; 3)  $5 \cdot 10^{-6}$ ; 4)  $10^{-5}$ ; 5)  $2 \cdot 10^{-5}$ ; 6)  $5 \cdot 10^{-5}$ ; 7)  $10^{-4}$ .

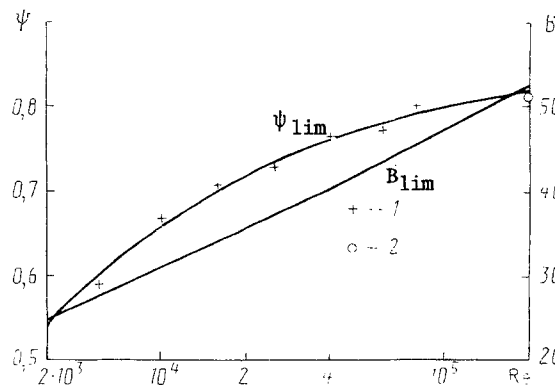


Fig. 3. Limiting decrease  $\psi_{lim}$  in frictional resistance and limiting shift  $B_{lim}$  as functions of Reynolds number: curves) calculation; 1) experimental values; 2) data of [10].

$$u^+ = 2,5 \ln y^+ + B, \quad y_p^+ \leq y^+ \leq R^+.$$

Attainment of the maximal efficiency is determined by the condition  $y_p^+ = R^+$ , i.e., by the extension of the limiting Virk profile to the pipe axis. The condition of equality of the average flow-rate velocities of water and a polymer solution is expressed by the equation

$$\int_0^R u(1 - y/R) d(y/R) = \int_0^R u_0(1 - y/R) d(y/R).$$

Using  $\tau = \tau_0(1 - \psi)$ ,  $y^+ = y_0^+(1 - \psi)^{1/2}$ , and  $R^+ = R_0^+(1 - \psi)^{1/2}$ , we integrate in quadratures and solve the resulting transcendental equation on a computer.

The results of the calculation are given in Fig. 3 (also see the dashed lines in Fig. 2). Besides the limiting decrease in frictional resistance, in Fig. 3 we show the maximal possible shift  $B_{lim}$ , determined from the equation  $R^+ = 6.346 \exp(B_{lim}/9.2)$ . The results obtained have the same degree of universality as does the velocity distribution used, so they are represented as a function of the Reynolds number. In the calculations we took the viscosity of the solution to equal the viscosity of the solvent. Since  $\mu = \mu_0(1 + [\eta]c)$ , that assumption is valid for  $[\eta]c \lesssim 0.05$ . For the branch of polyethylene oxide used, that condition is satisfied for all of the investigated concentrations.

As seen from the figures, the experimental data obtained agree well with the calculation. The behavior of the limiting decrease in frictional resistance (Fig. 3) can be described by the formula

$$\psi_{pr} = 0,554 \operatorname{arctg}(0,024 \sqrt{Re}).$$

In this work the shear stress was in the range 45-4500 Pa, far higher than the threshold stress above which the Toms effect is manifested. The pipe sizes and the capabilities of the installation did not enable us to determine the maximal efficiency for all solution concentrations and stream velocities. For 3 m/sec, for example, the pipe was not long enough to determine the maximal decrease in frictional resistance for a  $10^{-4}$  solution. For  $10^{-6}$  and  $2 \cdot 10^{-6}$  solutions we could not determine the maximal efficiency for any velocity, since it occurred in the initial section of the pipe.

The increase in the interaction intensity associated with flow velocity leads to a shift toward the front of the pipe of the section in which the maximal efficiency is displayed, while an increase in the concentration of the solution leads to the opposite effect (a shift toward the end of the pipe). Because of these properties, it is fairly difficult to determine the influence of concentration on the maximal decrease in frictional resistance. We can state that with an increase in velocity from 3 to 40 m/sec, the concentration at which the maximal decrease is reached increases from  $2 \cdot 10^{-5}$  (Fig. 2a) to  $5 \cdot 10^{-5}$ - $10^{-4}$  (Fig. 2c-e).

The dependence of hydrodynamic efficiency on the concentration of the solution is often given in the literature. For a correct understanding of the results, one must allow for the variation of the hydrodynamic efficiency of solutions in the course of their flow, i.e., for the strong dependence of the results on the measurement method and on the position of the measurement section along the pipe. For small-diameter pipes one usually records the time of outflow of a certain volume of liquid with variation of the pressure. This method determines the integrated decrease in friction over the entire length of the pipe. For large-diameter pipes it is possible to measure the pressure drops in different sections. One can thus measure the local frictional decrease at different distances from the pipe entrance. Fairly long pipes with  $L/D > 10^3$  are required to determine this dependence, however. Experiments are usually carried out on shorter pipes, and the investigated volume of solution must be run through many times. Such a method of measuring the dynamics of the Toms effect does not seem sufficiently correct, however. First, during filling, the kinetic energy of the stream is dissipated by small-scale vortices, leading to additional destruction of the solution. Second, in an interval between runs, supermolecular structures form in the solution because of the partial reversibility of the initial section of growth of the hydrodynamic efficiency of the solution [4, 6]. This is confirmed by [9], in which it was shown that the result of several runs is not equivalent to that of one run through a pipe that is longer by a factor equal to the number of runs.

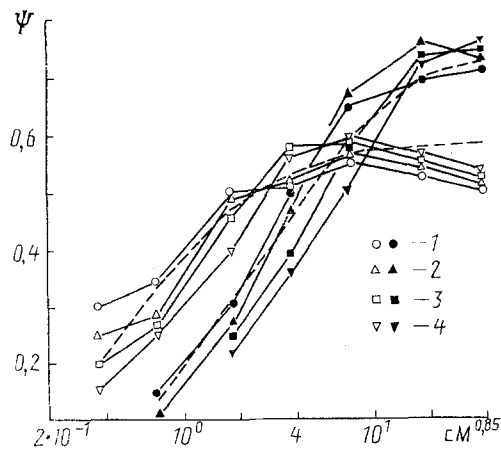


Fig. 4. Decrease in frictional resistance  $\psi$  as a function of the parameter  $cM^{0.85}$ ; data obtained in the following measurement sections: 1) (125-250)D; 2) (250-500)D; 3) (500-1000)D; 4) (1000-2000)D; light points:  $Re = 6 \cdot 10^3$ ; dark points:  $Re = 4 \cdot 10^4$ .

It is quite obvious that the decrease in frictional resistance determined by the first method, i.e., over the entire pipe length  $\psi_{\text{meas}} = \frac{1}{L} \int_0^L \psi(L) dL$ , will be less than the maximal decrease, and the actual dependences of the hydrodynamic efficiency of a solution on the properties of the polymers and the parameters of the turbulent flow will be related in a fairly complicated way.

The dependence of the hydrodynamic efficiency on the concentration of the solution determined by the second method is shown in Fig. 4. The curves are separated significantly, depending on the distance of the measurement section from the pipe entrance. That separation is especially pronounced at low concentrations. At 3 m/sec (Fig. 2a), for example, the measured hydrodynamic efficiency of a solution with a concentration  $c = 10^{-6}$  in the section (125-250)D is twice that in the section  $(10^3-2 \cdot 10^3)$ D (30 and 15%, respectively). This shows once again that the capacity of dilute solutions to reduce frictional resistance is affected very strongly by the method of preparation of the solution [11] and the past history of flow up to the measurement section. The importance of knowing the true ability of polymer solutions to reduce friction is due to the fact that an economical advantage can be obtained from their use only for solutions with concentrations in the section of growth in the dependence of  $\psi$  on  $c$  [12]. That dependence measured in one part of the pipe, however, does not allow for the dynamics of the Toms effect and considerably underestimates the actual capabilities of polymer solutions.

The approximating function  $\psi = a_2 \arctan(a_1 cM^{0.85})$ , as suggested in [12, 13], is shown by dashed curves in Fig. 4. Although this formula does not reflect the dynamics of the Toms effect, it can be used with some degree of precision because of its simplicity and clarity. As seen from Fig. 4, the coefficients  $a_1$  and  $a_2$  are functions of the Reynolds number; for example,  $a_1 = 1.7$  and  $a_2 = 0.38$  for  $Re = 6 \cdot 10^3$ , while  $a_1 = 0.4$  and  $a_2 = 0.48$  for  $Re = 4 \cdot 10^4$ . The coefficient  $a_2$  determines the maximal efficiency and can be calculated from the formula  $a_2 = (2/\pi)\psi_{\text{lim}} = 0.35 \arctan(0.024\sqrt{Re})$ . The coefficient  $a_1$  determines the steepness of the growth of  $\psi$  as a function of  $cM^{0.85}$  and depends on the properties of the polymer and the conditions under which the solution was prepared. It is possible, incidentally, that the coefficient  $a_1$  also depends on the flow parameters, such as the shear stress, which in the given example ranged from 45 to 1200 Pa for water flow. No influence of shear stress on the limiting decrease in resistance, and hence on  $a_2$ , is detected even for very large shear stress,  $\tau \approx \tau_0(1 - \psi) = 800$  Pa (see Fig. 2e).

In conclusion, it must be noted that the dynamics of the Toms effect must be taken into account in establishing the laws of influence of various parameters (temperature, molecular weight, conditions of preparation, etc.). This may introduce significant corrections into existing functions.

#### NOTATION

D, pipe diameter, m; L, pipe length, m; P, pressure, Pa;  $\Delta P_0$ , pressure drop in water flow, Pa;  $\Delta P$ , pressure drop in flow of the polymer solution, Pa;  $\psi$ , decrease in frictional resistance; U, average flow-rate velocity, m/sec; R, pipe radius, m; c, concentration of the solution,  $10^3$  kg/m<sup>3</sup>;  $R^+ = Rv^*/\nu$ , dimensionless radius; y, distance from the wall, m;

$y^+ = yv^*/\nu$ , dimensionless distance;  $u$ , local velocity, m/sec;  $u^+ = u/v^*$ , dimensionless local velocity;  $x$ , distance from pipe entrance, m;  $B$ , shift of the logarithmic part of the velocity profile;  $\tau$ , tangential friction, Pa;  $[\eta]$ , characteristic viscosity of the solution;  $M$ , molecular mass of the polymer;  $Re$ , Reynolds number;  $\mu$ , viscosity of the solution, Pa·sec.

#### LITERATURE CITED

1. E. M. Greshilov, V. S. Belokon', and B. V. Lipatov, in: Mechanics of Turbulent Flows [in Russian], Moscow (1980), pp. 358-363.
2. V. N. Kalashnikov, "Parametric laws of decrease in turbulent resistance by small polymer admixtures," Preprint No. 420, Inst. Prob. Mekh., Akad. Nauk SSSR, Moscow (1989).
3. V. M. Kulik and B. N. Semenov, *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk*, No. 3, 62-67 (1986).
4. B. N. Semenov, A. I. Amirov, V. M. Kulik, and O. N. Marennikova, in: Boundary and Free Turbulent Flows [in Russian], Collection of Scientific Papers, Novosibirsk (1988), pp. 20-52.
5. V. M. Kulik and A. I. Amirov, *Inzh.-fiz. Zh.*, 59, No. 4, 690-691 (1990).
6. B. N. Semenov, A. I. Amirov, V. M. Kulik, and O. N. Marennikova, *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk*, No. 2, 71-76 (1990).
7. V. N. Kalashnikov and M. G. Tsiklauri, *Inzh.-fiz. Zh.*, 58, No. 1, 49-55 (1990).
8. P. S. Virk, *AIChE J.*, 21, No. 4, 625-656 (1975).
9. D. H. Fisher and F. Rodrigue, *J. Appl. Polym. Sci.*, 15, No. 12, 2875-2985 (1971).
10. B. P. Mironov and V. I. Shishov, in: Third International Conference on Drag Reduction, Cambridge (1984), pp. C4/1-C4/8.
11. S. I. Bakhtiyarov, "On the Toms effect for extremely small polymer admixtures," *Izv. Vyssh. Uchebn. Zaved., Neft' Gaz*, No. 4, 52-55 (1987).
12. B. N. Semenov, *Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk*, No. 4, 90-98 (1991).
13. L. I. Sedov, N. G. Vasetskaya, and V. A. Ioselevich, in: Turbulent Flows [in Russian], Moscow (1974), pp. 205-220.

#### FEATURES OF THE DEVELOPMENT OF CONVECTIVE PROCESSES

##### UNDER NEARLY WEIGHTLESS CONDITIONS

A. M. Vetoshkin, A. V. Korol'kov, V. S. Kuptsova,  
and V. V. Savichev

UDC 536.25

Measurements of microaccelerations on board an orbital station are analyzed from the standpoint of the influence (of the state determined by them) on the development of convective processes of a gravitational nature. Two regimes of development of convection are identified, depending on the nature of the variation of the acceleration vector: In one of them the intensity of convective motion is the determining factor, and in the other convection is suppressed and heat conduction (diffusion) is the main transport mechanism.

Features of the development of convective processes (in comparison with analogous processes occurring under terrestrial conditions) in various on-board systems and devices, as well as in technological experiments carried out on board a spacecraft, are the consequence of the special state existing on board a spacecraft, defined as a nearly weightless state. A characteristic of that state is the continuous time variation of the local acceleration vector in magnitude and direction. The variety of laws of time variation of the acceleration vector determines the variety of features in the development of convective processes of a gravitational nature. Systematic investigations of the behavior of a fluid

---

Moscow Wood Technology Institute. Translated from *Inzhenerno-fizicheskii Zhurnal*, Vol. 62, No. 2, pp. 235-242, February, 1992. Original article submitted April 19, 1991.