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HEAT AND MASS TRANSFER IN PHASE TRANSFORMATIONS

EXPERIMENTAL INVESTIGATION OF THE DYNAMICS OF THE PHASE TRANSITION BOUNDARY IN THE MOTION OF A HEATED NON-NEWTONIAN FLUID IN A CHANNEL

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The process of growth of the boundary crystallized phase in the motion of a heated non-Newtonian fluid in a channel with a cold wall has been studied experimentally. As the fluid, polypropylene with pseudoplastic properties was used. Experimental curves of the growth of the wall crystallized phase as a function of time were obtained for different values of the initial fluid melt temperature. The experimental value of the Nusselt number at the solid-liquid interface has been computed.

Keywords: *crystallized layer, wall layer, crystallized phase, non-Newtonian fluid, nonlinear-viscous fluid, pseudoplastic.*

Introduction. The present experimental work is devoted to the study of the behavior of the interface between an immobile crystallized phase and the liquid core of a heated non-Newtonian fluid flow moving in a narrow straight channel under ambient pressure. In the presence of high values of temperature drops between the flow core and a relatively cold channel wall (whose temperature is much lower than the fluid melting temperature), there may occur a phase transition of boundary layers on that wall into a crystallized state. After the crystallization, the solid phase on the wall comes to a halt, and its height may increase with time and lead to the blockage of the flow section. This is accompanied by the presence of an intense heat flux from the mobile flow zone to the crystallized immobile phase and further to the channel wall. It is composed of the heat flux proper from the hot fluid and the heat flux originating due to dissipative heat release. Such kinds of flows are especially typical of the technological processes of processing of polymers and metals. Technologically it is of interest to elucidate the so-called flow length (or flow time), i.e., the maximum distance covered by the nonlinear-viscous fluid (time elapsed) until complete blockage of the channel and flow cessation. Scientifically it is of interest to elucidate the dynamics of the growth of the wall solid layer and the conditions of heat transfer on the mobile interface.

Schematic Diagram of Experimental Arrangement. Figure 1 shows the diagram of the experimental arrangement. A non-Newtonian fluid flows through a narrow channel 1 made of a steel slab 2. The channel was made open in order that the moving fluid could freely escape in direction 3. In this case, the drop in the applied ambient pressure has a linear character. The upper part of the channel is covered with a transparent glass, allowing one to make a video film of the flow process with the aid of a digital camera 4; it is capable of withstanding the corresponding pressure on injection of a molten flow. To measure the boundary thermal regimes, a thermocouple 5 is located on the metal wall of the channel and a thermocouple 6 is fixed on the lower boundary of the glass, with both being connected to a recorder 7. A pressure pickup 8 is connected ia a copper pipe with the channel and also with block 7. The non-Newtonian fluid is fed under pressure at point 9. With the aid of block 10 and a fiber-optic cable, the channel is illuminated to improve the quality of video filming.

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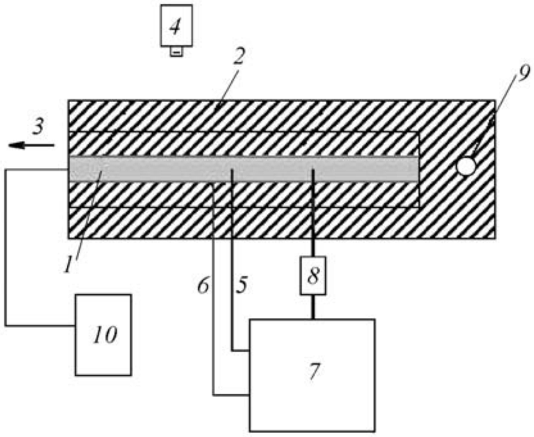

Fig. 1. Schematic diagram of experimental setup.

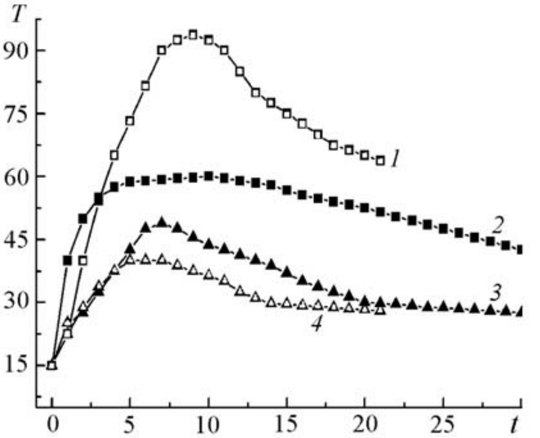

Fig. 2. Variation of temperature on the boundaries of the channel as a function of time: 1, 2, boundary of glass; 3, 4, channel wall; 1, 3, melt temperature T_m = 260°C; 2, 4, melt temperature T_m = 190°C. T, °C; t, sec.

The channel is made in the form of two split slabs manufactured from 5KhNM grade steel. In the upper slab there is a special groove of depth 12 mm to place the transparent glass. The channel cavity was milled without applying subsequent finish of the surface. The channel had height H = 3 mm, width S = 10 mm, and length L = 150 mm. Such a relationship of the dimensions $H \ll S$ was selected in order to intensify the heat flux in the direction of interest for us — along the height H. To attain a uniform supply of the molten mass and the absence of the effect of "flow over an unfilled cavity," the transition between the point of injection and the channel has a special shape of an expanding generatrix. The geometry of the expansion was selected on the basis of practical experience and recommendations given in a special literature on construction of machine-tool attachments [1]. The temperature was measured with the aid of a chromel-alumel thermocouple and a DTM-15 pressure pickup. An ordinary machine oil served as a filler of the reducing pipe connected to the pressure pickup. As a source of a molten polymer we used a small vertical-type casting machine with a mobile table and with a volume of the material cylinder of 50 cm^3. The detectors of the machine made it possible to control the melt temperature and the injection pressure. As a test fluid we used polypropylene of grade Lipol. The choice was based on the following considerations: as a melt, Lipol has a good fluidity and is transparent; on crystallization it becomes cloudy, which facilitates observation of the phase transition boundary; it has a wide range of temperatures at which the fluidity is maintained, and, consequently, there is a possibility of changing the thermal regimes of an experiment in wide ranges.

The selected polypropylene belongs to a class of pseusoplastics, for which usually a power rheological model with the exponential dependence of viscosity on temperature is adopted. The Lipol has the following characteristics: fluidity of the melt 2.5–4.0 g/10 min; scatter in the values of the fluidity index no more than 10%; VICAT softening

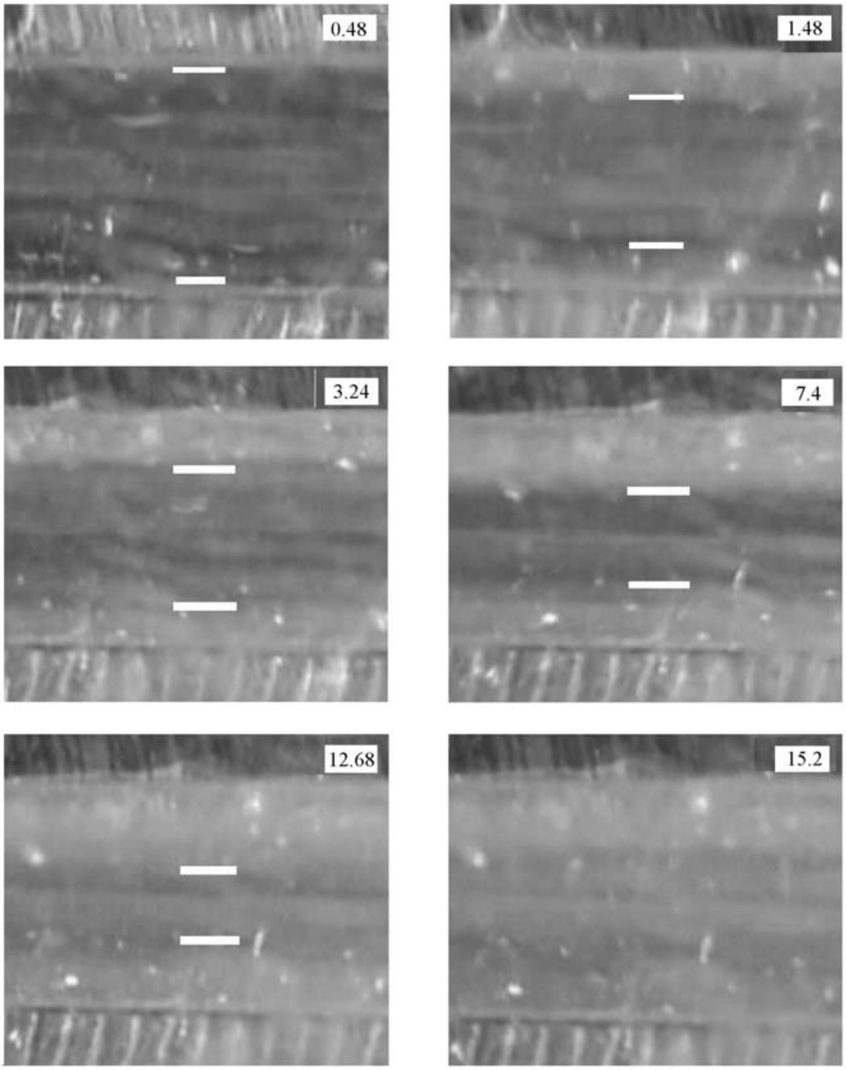

Fig. 3. Dynamics of the formation of the wall crystallized phase for T_{m} = 210$^{\mathrm{o}}$C. The figure in the right upper corner shows the time from the beginning of flow *t*, sec. Markers show the boundary of the crystallized phase.

point at 10 N no less than 153$^{\mathrm{o}}$C; temperature of deformation heat resistance 93$^{\mathrm{o}}$C; and density 500 kg/m^3. To ease visual observations of the process of flow, the melt was doped with visualizing particles such as an ordinary fine abrasive crumb. The concentration of particles in the flow did not exceed 2%. The particles were added directly into the working cylinder of the casting machine.

The general scheme of the experiment consisted in the observation of the flow and of the behavior of the interface at different initial temperatures of the polypropylene melt. The temperature varied in the range from the lower threshold at which the polymer still maintains its fluidity (160$^{\mathrm{o}}$C) and to the upper one, when destruction has already set in (260$^{\mathrm{o}}$C). The average time of flow up to the joining of the crystallization layers at the center of the channel was equal approximately to 15–20 sec. According to the analogy with the casting technologies, the flow with a concrete temperatures of the melt will be called "pressurizing."

Analysis of Results. The curves representing the change in the temperature regime during pressurizing are given in Fig. 2. A comparison of the temperature dependences shows that the temperatures attained by the metal wall of the channel exceed twice the temperatures reached at the glass boundary. Thus, the condition of heat transfer intensification in the studied direction, that is over the channel height, was established. The flow velocity measured at the beginning of flow by the displacement of the initial profile was equal to about 90 mm/sec. The pressure at the ob-

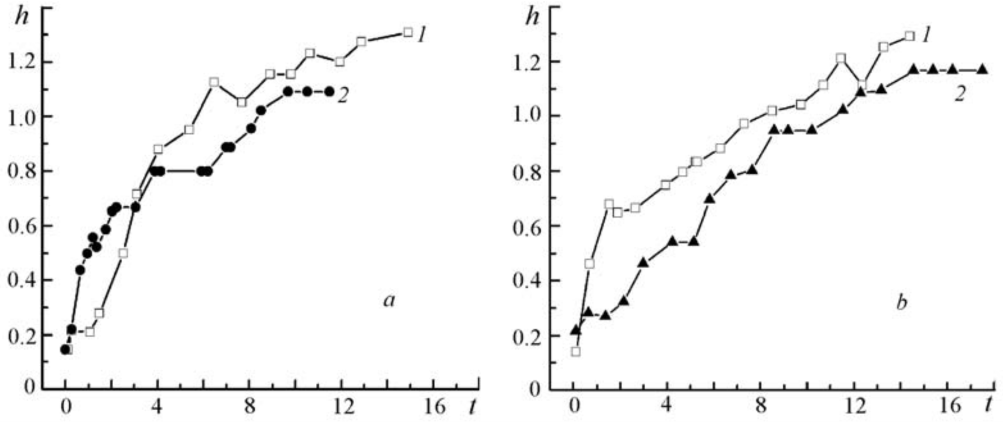

Fig. 4. Experimental curves of the growth in height of the crystallized layer *h* as a function of time *t* at different temperatures of the melt: a) 1, T_m = 190°C; 2, 210; b) 1, T_m = 240°C; 2, 260. *h*, mm; *t*, sec.

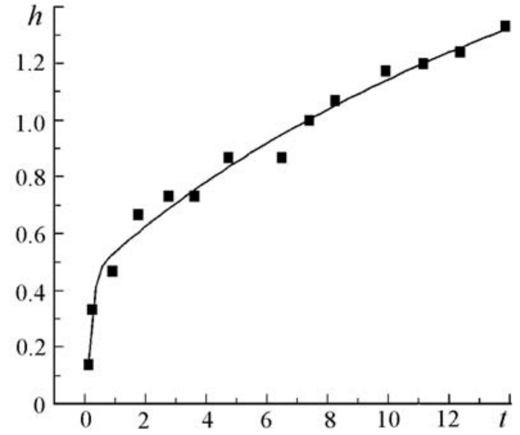

Fig. 5. Approximation curve of the growth of the wall phase. *h*, mm; *t*, sec.

servation point (at a distance of 100 mm from the channel outlet) amounted to 12 atm. An analysis of the video recordings of the flow shows that the growth of the wall crystallized layer is clearly seen visually. At a melt temperature of 160°C the formation of the crystallized layer partially occurred also on the glass surface, thus somewhat hindering the observation. At higher temperatures crystallization practically did not appear on the glass, and the observed growth of the solid phase occurred from the walls of the channel to its center. In Fig. 3 six video-recording frames for the case of a melt flow with a temperature of 210°C are presented. The markers show the position of the interface for each instant of time. The motion of the interface along the channel was synchronous, with no visible deviations along the channel length. Based on the data of video recordings, experimental dependences of the growth of the wall layer as a function of time were constructed (Figs. 4 and 5). Measurements were made by a measuring rule on the video-recording frames, with the visible height of the channel on the photographs being equal to about 45 mm. At errors of visual measurements of up to 1 mm, the error of measurement of the layer height did not exceed 3%. The dependences show that at the initial stages of flow a rather intense growth of the height of the crystallized layer is observed; thereafter the rate of the growth decreases and the growth curve becomes flatter. Such a behavior can be attributed to two circumstances:

1) the crystallized layer plays the role of thermal insulation whose height grows in time;

2) the narrowing of the flow section leads to a deformation of the flow velocity profile and to an increase in the dissipative heat release, which also can slow down the crystallization rates at the boundary.

The growth curves of flows at different temperatures of the melt have a qualitatively identical form. An analysis of the obtained experimental dependences has shown that the growth curve is well approximated by an exponential dependence of the form

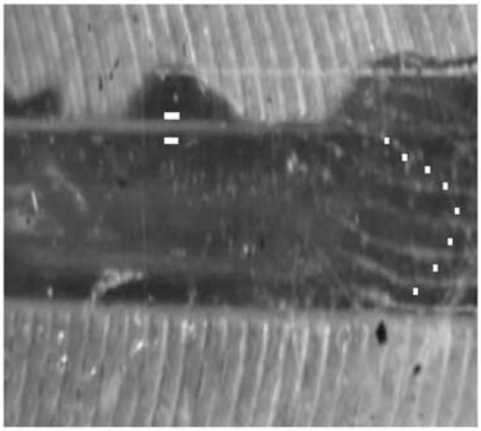

Fig. 6. Formation of the wall layer in the initial phase of flow at t = 0.04 sec. The dashed curve shows the position of the initial flow profile; the marker shows the position of the wall layer boundary.

$$h = a_0 + a_1 \exp\left(-\frac{t}{t_1}\right) + a_2 \exp\left(-\frac{t}{t_2}\right) + a_3 \exp\left(-\frac{t}{t_3}\right). \tag{1}$$

The approximation curve plotted from Eq. (1) and its correspondence to experimental data can be seen in Fig. 5. The video recordings made it possible to elucidate the characteristic features of the process of the wall solid phase formation at the initial stage of flow. An analysis of the still frames has shown that the immobile layer of thickness 0.26 mm is formed virtually instantaneously behind the initial flow profile at times less than 0.04 sec (from the start of polymer contact with the wall). This is clearly seen on the photograph in Fig. 6. This result can be used to correlate experimental and theoretical data in calculations of the stability of the crystallization boundary; according to [2], a rapid formation of large initial thickness of the wall phase degrades the conditions for maintaining stationary regimes of flow.

Using the results of measurements of the boundary temperatures, we can determine the experimental value of the Nu number at the interface. We define the Nusselt number as the ratio of the heat flux through the interface to the difference of the characteristic temperatures of the problem — the average temperature of the flow core and of the temperature at the interface. The temperature at the boundary of the crystallized phase is taken equal to the temperature of crystallization of a non-Newtonian fluid T_{cr}, which agrees quite well with the physical essence of the flow. The equation of the balance of heat fluxes at the crystallization boundary has the form [3, 4]

$$\lambda_1 \left.\frac{\partial T_1}{\partial y}\right|_{y=H-h} - \lambda_2 \left.\frac{\partial T_2}{\partial y}\right|_{y=H-h} = \rho\omega \frac{dh}{dt}, \tag{2}$$

where $\frac{dh}{dt}$ is the velocity of boundary displacement. If in the definition of the Nusselt number the heat flux at the interface is considered as a sum of the flux from the flow core (the second term on the left) and the flux from crystallization at the interface (expression on the right), then as the numerator in the formula for the Nusselt number we can use the value of the derivative of T_1 obtained from Eq. (2). This derivative can be obtained from experimental data. Assuming the fact that the distribution of temperature in the immobile zone obeys the Laplace equation, we obtain an expression for Nu from experimental data:

$$\text{Nu} = \frac{1}{\tilde{h}} \frac{T_{\text{cr}} - T_{\text{w}}}{\overline{T} - T_{\text{cr}}}. \tag{3}$$

The results of calculation for two flows with melt temperatures of 260 and 190°C are presented in Fig. 7.

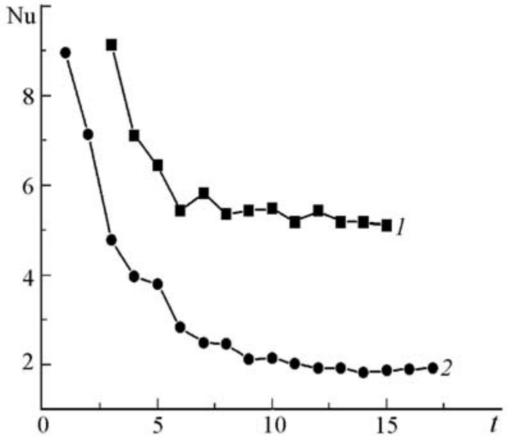

Fig. 7. Change in the Nu number at the interface as a function of time t for different temperatures of the melt: 1) T_m = 240°C; 2) 60.

The curves plotted by Eq. (3) with the use of the experimental values for the dimensionless height of the immobile layer $\tilde{h}$ and temperature T_w show that the heat transfer coefficient decreases as the crystallized phase grows, and at the final stage of flow it attains a stationary level. For higher temperatures of the melt the Nu number is smaller, which is evident from the very form of Eq. (3). There exists a correlation between stabilization of the change in the Nusselt number with time and the decrease in the rate of growth of the crystallized phase: the stabilization of heat transfer through the interface means that the influence of the process of crystallization, which is the main destabilizing factor, gradually decreases, precisely what is expressed as the retardation of the rate of growth.

Conclusions. Visualization of a flow of a non-Newtonian fluid melt made it possible to find out the basic characteristic features of the process of growth of the wall crystallized phase and the influence exerted on this process by the initial temperature of the melt. It has been established that the growth of the immobile crystallized phase is satisfactorily approximated by an exponent, i.e., the growth has an exponential character. The initial thin crystallized layer is formed rather rapidly with time in less than 0.04 sec immediately behind the initial front of the flow. The curve of the change in the local coefficient of heat transfer as a function of time is obtained; as the crystallized phase grows, the value of the peak of Nu decreases.

NOTATION

a_0, a_1, a_2, a_3, approximation coefficients; H, channel height, m; $\tilde{h}$, dimensionless height of crystallized phase; h, height of crystallized layer, m; L, channel length, m; Nu, Nusselt number; S, channel width, m; T_1, temperature in the immobile zone; T_2, temperature in the mobile zone; $\overline{T}$, average temperature of the flow core, K; T_m, temperature of the melt, K; T_w, temperature of the channel wall, K; T_{cr}, crystallization temperature of the polymer, K; t, time, sec; t_1, t_2, t_3, approximation coefficients; y, coordinate over the channel height, m; λ_1, λ_2, heat conduction coefficients in the immobile and mobile zones; ρ, density, kg/m^3; ω, latent heat of melting. Subscripts: cr, crystallization; m, melt; w, wall.

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