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EFFECT OF A MAGNETIC FIELD AND THE TEMPERATURE OF A HEATED HOLLOW MAGNETIZABLE CYLINDER ON MASS AND HEAT TRANSFER DURING COOLING OF THE CYLINDER IN A MAGNETIC FLUID

V. V. Gogosov,[1] M. Yu. Klimenko,[2]
and A. Ya. Simonovskii[2]

Experiments on the cooling of a hollow magnetizable cylinder in a magnetic fluid are described. The effects of the magnitude and direction of the magnetic field and of the initial temperature of the heated cylinder on the rate at which various points on the outer and inner surfaces are cooled and on the boiling regime for the magnetic fluid inside and outside the cylinder are studied.

Introduction. Experiments on the cooling of a hollow magnetizable cylinder in a magnetic fluid are described. The effects of the magnitude and direction of the magnetic field and of the initial temperature of the heated cylinder on the rate at which various points on the outer and inner surfaces are cooled and on the boiling regime for the magnetic fluid inside and outside the cylinder are studied.

The concepts of "cylinder poles" and "lateral cylinder surface" are introduced. "Cylinder poles" are the points on the generatrices of the outer surface of the cylinder for which the angle θ between the radius vector and the direction of the applied magnetic field $\mathbf{H}_0$ far from the cylinder equal zero or 180°. The "lateral generatrices" of the cylinder are its generators for which the angle θ = ±90°, while the "lateral surfaces" of the cylinder are the regions on the outer surface which lie in the neighborhoods of its "lateral generatrices."

It is found that initially, without a magnetic field, the inner surface of a hollow cylinder heated to a temperature of 800°C is cooled substantially more rapidly than the outer surface. This is because of explosive boiling of the magnetic fluid that enters the cylinder cavity as it is immersed in the fluid and the formation of a powerful vapor-liquid flow in the inner hollow which emerges from the upper opening of the hollow. New unheated fluid which replaces the escaping flow through the lower opening of the hollow cools the inner wall of the cylinder, boiling as it comes into contact with the wall: new bubbles are formed and push the foam outward, etc. The inner wall of the cylinder is more rapidly cooled than the outer wall because it is continually washed by new, unheated fluid entering the hollow from the bottom end of the cylinder. The outer surface is cooled sequentially through film, transition, and nucleate boiling, whose character can be evaluated from the structure of the precipitate of stratified magnetic fluid on the cylinder surface. Without a magnetic field, the boiling process and the rate of cooling are independent of the angle θ at all points on the inner and outer surfaces.

In a magnetic field, the rate at which a hollow cylinder is cooled in a magnetic fluid is not only different at the inner and outer surfaces, but also depends strongly on the angle θ as the outer surface is cooled. As the magnetic field is increased, this dependence becomes stronger. The initial temperature T_0 of the heated cylinder, at which cooling begins, has a controlling effect on the time dependence of the cooling rate in a magnetic field.

When T_0 exceeds the Curie temperature T_C of the cylinder material, the cylinder is in a paramagnetic state in the magnetic field and will distort a uniform applied magnetic field $\mathbf{H}_0$ slightly. Cooling of the cylinder at the initial time also takes

[1] Institute of Mechanics, M. V. Lomonosov Moscow State University, 117192 Moscow, Russia.
[2] Stavropol Agricultural Academy, 355014 Stavropol, Russia.

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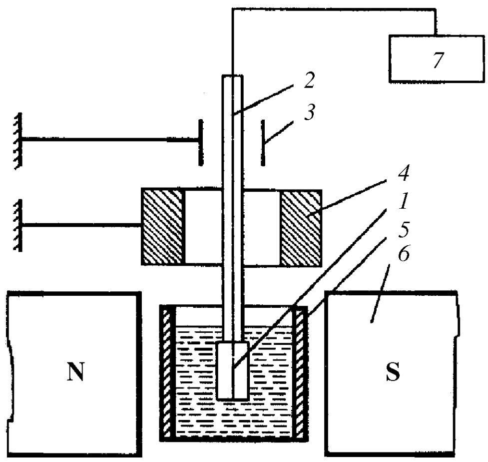

Fig. 1. A sketch of the experimental apparatus. Explanations are given in the text.

place as in the case of zero magnetic field. As the temperature falls below T_C, the cylinder wall material becomes ferromagnetic. The applied uniform magnetic field is strongly distorted in the neighborhood of the cylinder. The resulting magnetic forces deform the vapor layer surrounding the outer surface of the cylinder in different ways. The thickness of this layer, as well as the cooling rate for different points on the outer surface, depends strongly on θ. Of course, magnetic forces arise only when the cylinder undergoes a transformation from a paramagnetic to a ferromagnetic state as it cools and the cylinder begins to distort the applied uniform magnetic field. It is found that this kind of transition takes place at temperatures well below the Curie temperature of the cylinder wall material.

It is shown that after the transition, most rapid cooling occurs at those points on the outer surface of the cylinder which lie in the neighborhoods of its poles, where the magnetic forces press the fluid onto the surface of the cylinder. The thickness of the vapor layer between the cylinder and the fluid decreases and the heat exchange increases. Less rapid cooling takes place at the regions of the outer lateral surface of the cylinder in the neighborhood of $\theta = \pm 90°$, where the vapor layer becomes thicker as a result of the magnetic forces. Heat removal takes place even more slowly at the inner surface of the cylinder. This happens because the magnetic forces inhibit the penetration of the magnetic fluid into the hollow of the cylinder and push it out of the hollow if it has entered there at the time the cylinder was inserted into the fluid. Thus, the inner surface is cooled by contact with vapor or with a vapor-liquid flow, which also lowers the cooling rate.

The cooling of a hollow ferromagnetic cylinder in a magnetic field from an initial temperature T_0 below the Curie temperature T_C is substantially different from cooling for $T_0 > T_C$. Beginning with the first fractions of a second, cooling of the inner surface of the cylinder takes place at a much lower rate than at points on its outer surface, as opposed to cooling without a magnetic field or in a magnetic field when $T_0 > T_C$. To within the measurement error, the cooling rate is the same at all points on the interior surface of a hollow cylinder. This happens because the fluid is forced out of the cylinder hollow by the magnetic forces. The inner surface is cooled by contact with the vapor. The rate of cooling of the outer surface of the cylinder depends strongly on the angle θ. Most rapid cooling takes place in the neighborhood of the poles, where the magnetic forces press the fluid toward the cylinder surface, squeezing the vapor layer out. Cooling is much slower at the lateral surface of the cylinder, where the magnetic forces repel the fluid from the surface and the vapor layer is thicker.

The cooling of continuous magnetizable cylinders in magnetic fluids has been studied previously [1–4]. The cooling of plates in magnetic fluids has been studied in [5]. The effect of magnetic fields and of the properties of magnetic fluids on the cooling of magnetizable spheres in magnetic fluids has been discussed in [6–11].

1. Experimental Apparatus (Fig. 1). A hollow ferromagnetic cylinder *1* with an outer diameter of 25 mm, an inner diameter of 15 mm, and a height of 40 mm (to prevent horizontal displacements) was mounted in a hollow nonmagnetic shaft *2*. The shaft could move freely along guides *3*. The cylinder was heated in a laboratory electrical pipe furnace *4*.

After heating to a certain temperature and being kept in the furnace for 2–3 minutes in order to equilibrate the temperature over the wall thickness, the cylinder was rapidly submerged into a volume of magnetic fluid which filled a nonmagnetic cylindrical container *5* mounted between the poles of an electromagnet *6*. In all these experiments the external applied magnetic field,

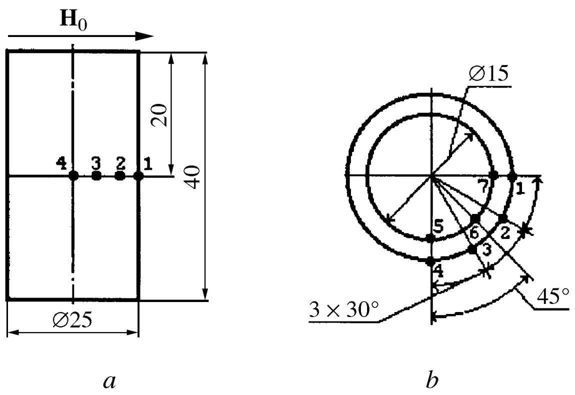

Fig. 2. Illustrating the location of the thermocouple junctions on the outer and inner surfaces of the hollow cylinder: *a*) side view, *b*) middle transverse cross section of the cylinder.

undistorted by the cylinder, was uniform and perpendicular to the generatrix of the cylinder. The diameter of the container was 100 mm and its height was 170 mm. With a pole piece end diameter of 100 mm and a distance between them of 110 mm, the inhomogeneity in the magnetic field within the gap of the electromagnet was less than 7%. The error in measuring the magnetic field was less than 3%. Chromel-alumel thermocouples with diameters of less than 0.5 mm were mounted at various points on the outer and inner surfaces of the cylinder to measure the temperature there. The thermocouple junctions were welded to surface of the cylinder with the aid of a copper electrode using a short ac pulse. The arrangement of the thermocouple junctions on the outer and inner surfaces of the hollow cylinder in one quadrant of its middle transverse cross section is shown in Fig. 2. Figure 2*a* shows a front view of the cylinder and Fig. 2*b*, a top view of the middle transverse cross section indicating the points where the thermocouples are mounted in this cross section. The direction of the uniform applied external magnetic field $\mathbf{H}_0$ is indicated with an arrow. The points 1–4 and 5–7 indicate the locations of the thermocouple junctions on the outer and inner surfaces of the cylinder, respectively. Thermocouples were mounted on the outer surface every 30°, so the angles θ between the direction of the external magnetic field and the radius vectors of points 1–4, respectively, are 0, 30, 60, and 90°. The angles θ for points 5–7 are 90, 45, and 0°. This choice of positions for the thermocouples was based on the symmetry of the problem relative to planes drawn along the diameters of the cylinder parallel and perpendicular to the applied magnetic field $\mathbf{H}_0$. In order to isolate them, the thermocouple electrodes were passed through channels of ceramic spaghetti installed along the inner part of the hollow nonmagnetic shaft used to hold the sample. The thermocouple outputs were recorded on an oscillograph *7*.

Preliminary experiments showed that cooling is substantially slower in a magnetic fluid than in water, so the inertia of the thermocouples was tested by cooling the sample in water. The measurements showed that all seven thermocouples are capable of detecting temperature changes at rates of at least 400°C/s. The test measurements showed that if deviations in the readouts from the thermocouples are observed during cooling of different points on the surface of the cylinder at rates less than 400°C/s, then these deviations are not caused by the different inertias of the thermocouples employed in the experiments. The error in the temperature measurements in these experiments was less than ±5°C. The confidence interval was determined from five-seven measurements to a confidence level of 0.9. In order to ensure constancy of the initial magnetic state of the cylinder before the start of each cooling event, the sample was placed in a variable magnetic field to demagnetize it.

The magnetic fluid used in the experiment was obtained by diluting water-based magnetic fluid with a saturation magnetization of 20.4 kA/m, density $\rho = 1.21\cdot10^3$ kg/m^3, kinematic viscosity $\nu = 3.99\cdot10^{-6}$ m^2/s, and absolute magnetic permeability $\mu_a = (2.5 \pm 0.3)\cdot10^{-6}$ H/m to half in water without introducing a stabilizer. Dilution reduced the density of the fluid to $1.106\cdot10^3$ kg/m^3 and the kinematic viscosity to $1.68\cdot10^{-6}$ m^2/s. The initial temperature of the magnetic fluid in this and the subsequent experiments was 24°C.

2. Cooling of a Hollow Cylinder in a Magnetic Fluid without a Magnetic Field. Figure 3 shows plots of the temperature as a function of cooling time for different points on the outer and inner surfaces of the hollow cylinder obtained by cooling the cylinder from an initial sample temperature of T_0 = 800°C in the magnetic fluid without turning on the magnetic field. In Fig. 3 and in all the following graphs the abscissa is the cooling time τ for different points on the surface of the hollow cylin-

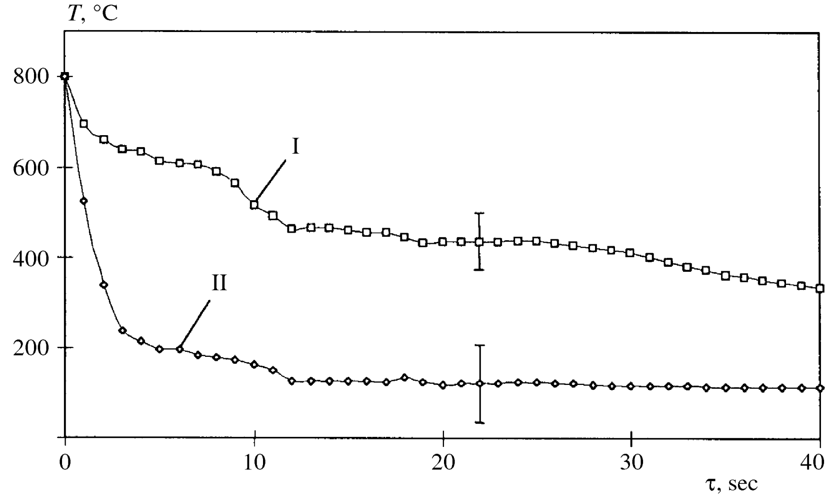

Fig. 3. The temperature T of different points on the outer and inner surfaces of the hollow cylinder as a function of cooling time τ during cooling from an initial temperature of 800°C in the magnetic fluid without a magnetic field. Curves I and II were obtained by averaging the readouts from the thermocouples mounted on the outer and inner surfaces, respectively, of the hollow cylinder.

der and the ordinate is the temperature T measured by the thermocouples mounted on the inner and outer surfaces of the cylinder. The readouts of all the four thermocouples mounted on the outer surface of the cylinder and of the three on its inner surface were averaged and plotted as curves I and II, respectively. The slight experimentally observed differences in the temperature plots at different points on the outer and inner surfaces of the cylinder were caused by natural fluctuations in the surface temperature owing to the rapid formation and destruction of the vapor film encircling the cylinder at high temperatures, the growth and detachment of vapor bubbles, and the resulting turbulent flows of the fluid.

It is evident that cooling is much more rapid in the cylinder hollow than on the outer surface at early times. Here and in the following the cooling rate is taken to mean the slope of the tangent to the cooling curve. The standard references on tempering cooling [12, 13] do not discuss experiments with hollow cylinders. Before offering a possible explanation of the observed phenomenon let us briefly analyze the boiling regimes for magnetic fluid on the inner and outer surfaces of a hollow cylinder at different cooling times in accordance with the curves in Fig. 3.

In the thermal physics of ordinary fluids, the boiling regimes are usually analyzed by means of various optical techniques [14]. The magnetic fluid is opaque, so its boiling cannot be analyzed by the traditional optical methods. It has, however, been observed [1, 2] that, when it comes into contact with a heated metal surface, magnetic fluid leaves behind a residue of stratified particles and surface-active material. The method developed in [1, 2, 8, 9] makes it possible to study the boiling regimes of magnetic fluids within one or another temperature interval in terms of the character of the residue of stratified magnetic fluids on cooled surfaces.

The following experiments were done in order to clarify the nature of boiling on the surfaces of a hollow cylinder cooled in a magnetic fluid in terms of the residue pattern. The hollow cylinder was heated to 800°C and immersed for cooling in a magnetic fluid contained in a cell, as shown in Fig. 1, without turning on the magnetic field. After a certain time, cooling was interrupted by rapidly removing the cylinder from the fluid.

Photograph *a* (Fig. 4) shows the cylinder with cooling interrupted after 3 s. The bulk of the cylinder's surface is free of any residue of stratified fluid, and a dense residue of stratified fluid can be seen only on the ends of the cylinder (the upper and lower parts of the picture). The deposits on the ends of the cylinder may be related to the special conditions under which they are cooled, e.g., more rapidly than at the lateral surface. In fact, the lower and upper ends of the cylinder are not only cooled at the inner and outer surfaces of the cylinder, but also at its end cross sections. The thickness of the end cross section of the cylinder wall is comparable to the height of the deposit at the ends of its outer surface. This may also be why a residue is deposited on the ends of the cylinder.

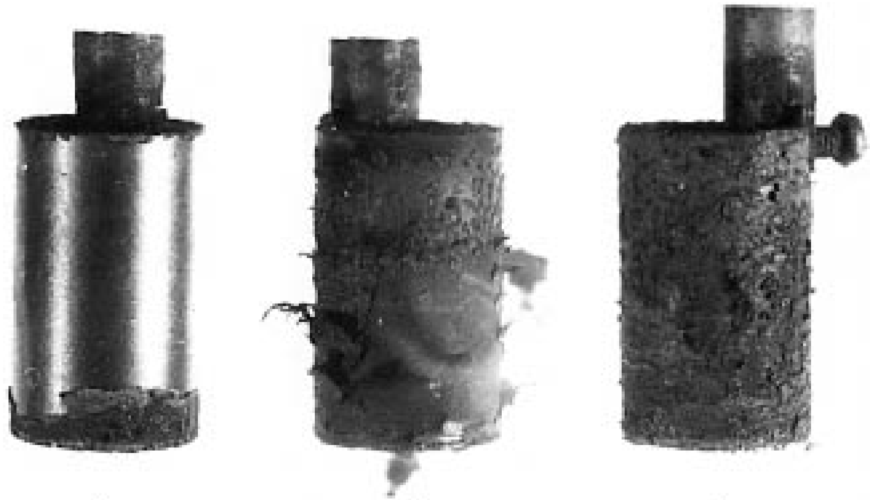

Fig. 4. Photographs of a hollow cylinder cooled in a magnetic fluid from an initial temperature of 800°C without a magnetic field. Cooling was interrupted 3 (*a*), 17 (*b*), and 35 s (*c*) after the onset of cooling.

The absence of a residue on the outer surface of the sample after 3 s of cooling can be explained by film boiling of the fluid during high temperature cooling. Here the magnetic fluid is completely separated from the heat transfer surface by a layer of vapor. Film boiling was observed on the outer surface of the cylinder until the first break in curve I of Fig. 3, which corresponds to 7–8 s of cooling. Then a switch from film to transition boiling takes place.

Picture *b* (Fig. 4) shows the surface of the hollow cylinder after cooling was interrupted at 17 s. The outer surface is clearly covered nonuniformly and randomly with a deposit of stratified magnetic fluid. This distribution of the deposit indicates that at the time the cylinder was removed from the volume of magnetic fluid, transition boiling of the fluid was taking place at its surface. Transition boiling is characterized [14] by gaps in the vapor film and contact between the fluid and the heat transfer surface. Portions of gaps in the vapor film are distributed randomly over the surface.

Picture *c* (Fig. 4) shows the surface of the hollow cylinder after cooling was interrupted at 35 s. Clearly, the sample is uniformly covered with a dense deposit of stratified magnetic fluid. The surface of the deposit is mottled with cavities from vapor bubbles. The observed character of the deposit indicates that at the time the cylinder was removed from the volume of fluid, nucleate boiling was taking place on its outer surface.

This is the way the outer surface of the cylinder cools. An extremely thin deposit of stratified magnetic fluid was observed on its inner surface during all these time periods, so it was impossible to evaluate the succession of boiling regimes for the fluid, despite the fact that a succession undoubtedly does occur. The fluid comes into contact with the hot surface. In the cavity hollow, however, rapid flows of vapor-liquid mixture develop which prevent firm sticking of the precipitate of stratified magnetic fluid on the inner surface of the sample.

The state of the free surface of the magnetic fluid in the cylinder hollow and outside the cylinder can be observed conveniently by immersing the cylinder, heated to 800°C, half way into the fluid. At the initial time, the free surface of the fluid is calm, both inside the volume of the hollow and outside it. Then, the free surface begins to bubble within the cylinder hollow. After a short time, an intense, foaming, vapor-liquid mixture that increases with time begins to escape from the opening in the cylinder and carry large droplets of magnetic fluid out of the cylinder. Figure 5 shows photographs of the escaping vapor-liquid flow and foam from the upper opening of the cylinder at different times after cooling starts. The free surface of the fluid remains calm at the outer surface of the cylinder during this period and afterward. The differences in the deposits of stratified magnetic fluid on the inner and outer surfaces could be observed by interrupting the cooling of the cylinder. The deposit is distributed uniformly on the outer surface, while the inner surface is free of a deposit. Apparently, the rapid vapor-liquid flow in the cavity of the cylinder washes its inner surface and frees it of the deposit of stratified fluid.

The following explanation is proposed for these phenomena. When the temperatures of the heat transfer surfaces on the outer and inner surfaces of the cylinder are high, the fluid boils explosively [15]. After a short time the liquid is separated from the walls of the cylinder by a layer of vapor [14]. Bubbles of vapor grow and detach from the surface of the vapor

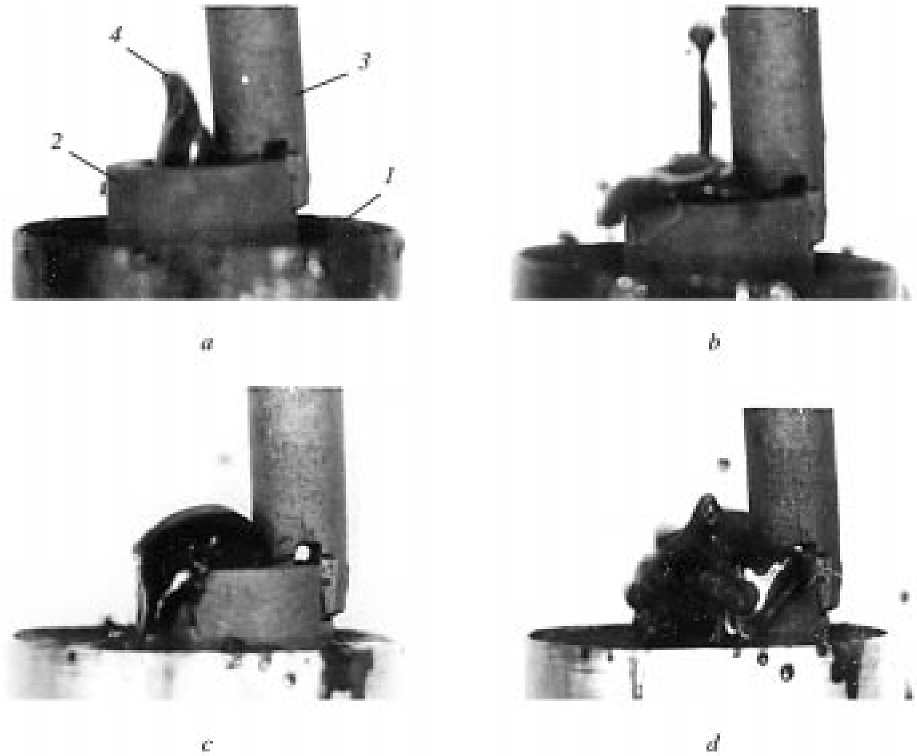

Fig. 5. Pictures illustrating the rapid removal of vapor-liquid mixture and foam from the upper hole in a cylinder heated to 800°C at different times following the onset of cooling. *1*) Cell with the magnetic fluid, *2*) the cylinder undergoing cooling, *3*) shaft, *4*) emerging vapor-liquid flow.

layer, thereby making the liquid surrounding the cylinder turbulent. This process of high-temperature heat and mass transfer at the heated wall is different at the inner and outer surfaces of the cylinder. On the outside surface boiling takes place in a layer near the wall within a large volume of fluid that is far from heated to its saturation temperature. Vapor bubbles which detach from the surface of the vapor film on the outside of the cylinder enter the volume of cold fluid and collapse as a result of condensation.

Boiling at the inner wall of the cylinder takes place within a limited volume of fluid in the cylinder hollow. Probably the liquid in the hollow is heated rapidly owing to intense turbulent mixing. Vapor bubbles that detach from the vapor film do not collapse as they enter the interior of the heated fluid. Perhaps, because of the presence of a large amount of surface active substances in the fluid, the vapor bubbles are able to form conglomerates, i.e., aggregates of bubbles, and thereby create something like a foam. Acted on by the extruding forces associated with the difference in densities of the vapor and liquid, the conglomerates of bubbles are pushed out of the cylinder hollow and capture adjacent volumes of fluid, thereby creating the intense flows of vapor-liquid mixture which emerge from the inner hollow of the cylinder and are shown in Fig. 5.

The emerging flow is replaced by new portions of unheated fluid which enter through the lower opening of the cylinder and boil upon contact with the wall. New bubbles are formed which push the foam out, and so on. Thus, the more rapid cooling of the inner cylinder wall compared to the outer wall takes place as a result of its being washed by new portions of fluid which enter the hollow from the bottom opening of the cylinder. Note that a water-based magnetic fluid was used in all the experiments, although in ordinary water this kind of formation and movement of a vapor-liquid flow does not occur in the inner hollow of the same cylinder as it cools.

These remarks can be generalized by saying that the more rapid cooling at points on the inner surface of the cylinder compared to the outer points when there is no magnetic field is caused by intense flows of vapor-liquid mixture within the volume of the hollow and by the absence of deposits of stratified magnetic fluid on the inner surface, which, since it is friable and flaky, enhances the thermal resistance of the outer wall and inhibits heat transfer between it and the fluid.

When the initial temperature of the cylinder is reduced, the rates of heat removal to its outer and inner surfaces approach one another, and more rapid cooling of the outer surface can be observed. Figure 6 shows plots of the temperature variation

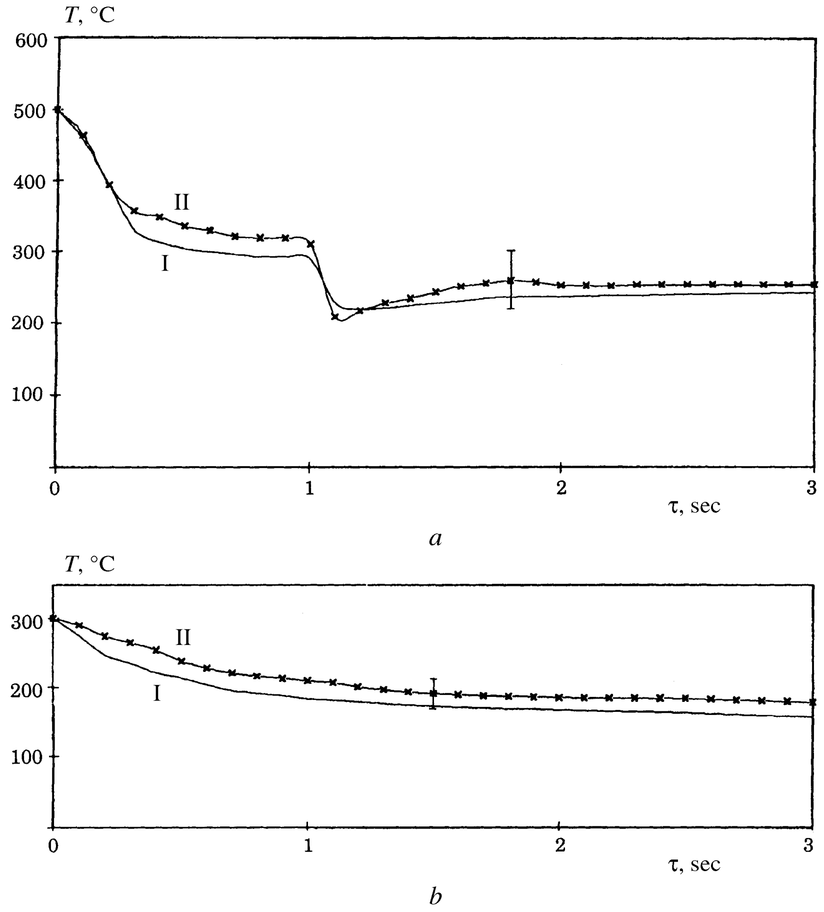

Fig. 6. The temperature T as a function of the cooling time τ for different points on the outer and inner surfaces of the hollow cylinder in the magnetic fluid without a magnetic field for initial cylinder temperatures of 500 (*a*) and 300°C (*b*). Curves I and II were obtained by averaging the readings from the thermocouples on the outer and inner surfaces, respectively, of the hollow cylinder.

with time during cooling of the outer and inner surfaces of a cylinder cooled in a magnetic fluid from initial temperatures T_0 = 500 (*a*) and 300°C (*b*) without a magnetic field. The cooling of the cylinder was interrupted after 3 s in these experiments, as well as in the experiments shown in Figs. 9 and 10. The curves to not change later in time to within the experimental error. Curves I and II were obtained by averaging the readouts of the thermocouples on the outer and inner surfaces of the hollow cylinder, respectively. Figure 6a shows that in the first fractions of a second after cooling begins from a temperature of 500°C, the rates of heat removal are essentially the same at the inner and outer walls of the cylinder. Over the first 0.25 s, the temperature of both walls falls significantly, reaching 350°C. At these temperatures for the outer and inner wall surfaces, film boiling of the magnetic fluid is observed. This is confirmed by observations of the state of the deposit of stratified magnetic fluid on the sample surface, when cooling is interrupted at times up to 0.8 s after the onset of cooling. A large fraction of the surface of the sample removed from the magnetic fluid is free of deposits.

The transition from film to nucleate boiling on both the outer and inner surfaces sets in at times of 0.9 to 1.2 s after the onset of cooling (Fig. 6*a*). A sharp drop in temperature to about 200°C is observed on both surfaces. Then the temperature of both surfaces of the hollow cylinder increases somewhat with time owing to the arrival of heat from the inner layers of the cylinder wall; stable nucleate boiling is observed on the inner and outer surfaces. This is confirmed by observations of the state of the deposits of stratified magnetic fluid on the surfaces of the cylinder when cooling is interrupted after 2 s. The entire outer surface is covered with a uniformly distributed deposit of stratified magnetic fluid which is mottled with cavities from vapor bubbles. With time, there is a drop in the foam production in the hollow of the cylinder and in the rate at which the vapor-liq-

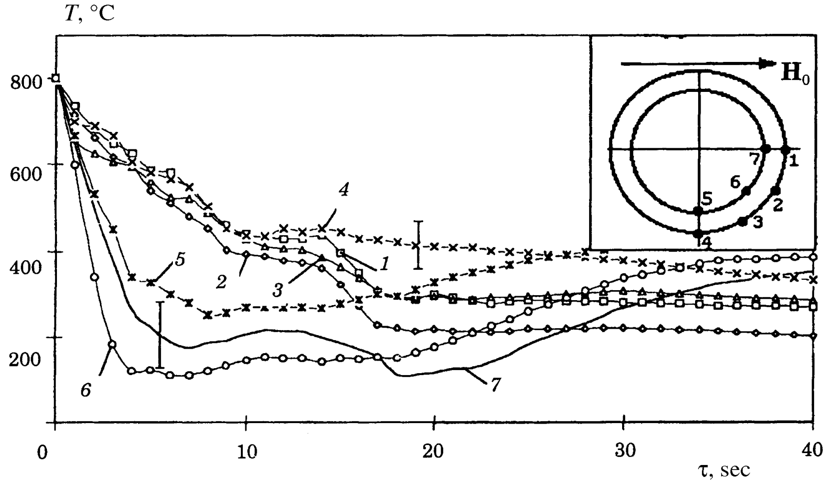

Fig. 7. The temperature T of different points on the outer and inner surfaces of the hollow cylinder as a function of cooling time τ when it is cooled from an initial temperature of 800°C in the magnetic fluid in a magnetic field of 105 kA/m.

uid mixture is removed from the hollow. When the initial sample temperature is reduced, there is less stratification of the magnetic fluid and less precipitation on the outer surface.

When the cylinder is cooled in the magnetic fluid from an initial temperature of 300°C without a magnetic field (Fig. 6*b*), no significant temperature oscillations associated with changes in the boiling regimes for the coolant can be seen in the cooling curves. Observations of the state of the deposits of stratified magnetic fluid show that nucleate boiling of the liquid develops on the inner and outer surfaces of the hollow cylinder at these temperatures. When the cylinder is withdrawn from the liquid volume at any time, a thin layer of precipitate that is mottled with cavities from the vapor bubbles can be observed on both surfaces.

3. Cooling of a Hollow Magnetizable Cylinder in a Magnetic Fluid in a Magnetic Field for Initial Cylinder Temperatures above the Curie Temperature. Cooling proceeds quite differently at different points on the surfaces of a hollow cylinder in a magnetic field. The cooling rate at different times depends not only on the angle θ between the radius vector of the point and the magnetic field direction, but also on whether the initial temperature of the cylinder is greater or less than the Curie temperature. In this section we describe experiments on cooling a cylinder when its initial temperature T_0 is 800°C and exceeds the Curie temperature T_C, which is 768°C for the ferromagnetic steel [16] used to fabricate the hollow cylindrical sample.

Figure 7 shows plots of the temperature as a function of time for cooling of a heated cylinder in a magnetic field of 105 kA/m. Here and in all the following graphs the numbers on the curves correspond to the numbers of the points where thermocouple junctions are located on the outer (1–4) and inner (5–7) surfaces of the hollow cylinder as indicated in Figs. 2 and 7. At point 1, the angle θ between the direction of the magnetic field and the outward normal to the surface is zero, and at point 4, θ = 90°. The figure shows that the cooling rate for the different points on the inner and outer surfaces of the cylinder for temperatures of 800–650°C are the same to within the limits of error of the measurements. For temperatures below 650°C, the cooling rate for points 5–7 is substantially higher than that for points 1–4. The slope of the cooling curves for the inner surface of the cylinder is steeper at these times. More rapid cooling at points 5–7 compared to points 1–4 is observed until 4–6 s after cooling starts. The temperature of the points on the inner surface of the cylinder falls to an average of 200°C over this time. At later times the temperature of the points on the inner surface rises slowly owing to the arrival of heat from the inner layers of the cylinder wall until the time when the cooling process is cut off in these experiments, i.e., until 40 s. By this time the temperature of the points on the inner surface of the cylinder has risen above that of the points on its outer surface.

According to Fig. 7, the cooling rates for points 1–4 are the same to within the experimental error until about 13 s after cooling starts. After 13 s of cooling, a sharp drop in the temperature from on the order of 400 to 250°C is noticeable in curves *1–3*. The temperature at point 4 undergoes no sharp changes and by the time cooling has ended it is higher than the temperatures of the other points on the outer surface.

In order to explain the variation in the time dependences of the temperature at different points on the inner and outer surfaces of the cylinder in Fig. 7, it is necessary to calculate the distribution of forces acting on the magnetic fluid in the neighborhood of the magnetizable cylinder. A cylinder in a ferromagnetic state distorts a uniform applied magnetic field. The force acting on the magnetic fluid is proportional to the gradient of the magnitude of the field. Appropriate calculations of the distribution of the field and force diagrams in the neighborhood of an infinitely long hollow cylinder have been done, but are not presented in this paper. It was shown that in the hollow of a ferromagnetic cylinder the magnetic field is lower and outside the cylinder the field is higher than the external applied field, and that it depends strongly on θ. The situation is similar in the neighborhood of a finite cylinder: the field is lower in the hollow than outside, and the force acting on the magnetic fluid is proportional to the gradient of the magnetic field. Thus, during the transition from a paramagnetic to a ferromagnetic state in the neighborhood of the ends of a hollow cylinder, including in the hollow, magnetic forces begin to act on the magnetic fluid which inhibit the penetration of the fluid into the cylinder hollow when it is immersed in a container of fluid and extrude the magnetic fluid and vapor-liquid mixture out of the cylinder hollow if any liquid should enter it. Thus, by 4–6 s after the onset of cooling, heat removal from the inner wall essentially ceases. The magnetic fluid that has not been able to boil off is extruded from the cylinder hollow and its inner surface is cooled to 200°C through contact with strongly superheated vapor, i.e., very slowly. Because heat is transferred from the inner layers of the cylinder mass, the temperature of its inner surface increases with time and by 40 s, it exceeds that of the outer surface. This effect can also be seen in curves *5–7* of Fig. 7, beginning 5 s after the onset of cooling.

The nonuniform distribution of the cooling rate over different points on the outer surface of the cylinder, which has been observed in the experiment and is illustrated by curves *1–4* of Fig. 7 after about 13 s, when the cylinder has already acquired ferromagnetic properties, can also be explained in terms of the distribution of ponderomotive forces acting on the magnetic fluid near different points on the outer surface. Plots of the distribution of magnetic forces (see [1, 2, 9], as well) show that in the neighborhood of point 1 and at the point diametrically opposite it, in the neighborhood of the poles, the magnetic forces press the fluid toward the surface of the cylinder. The vapor layer is squeezed out and heat exchange is enhanced, entirely consistently with the behavior of curves *1–3*. Near point 4 and its diametrally opposite point, on the side surface, the magnetic field is pressed away from the surface, the vapor layer thickens and heat transfer is reduced, as implied by the behavior of curve *4*.

Of course, the forces acting on the magnetic fluid in the neighborhood of a cylinder develop only when the cylinder material undergoes a transition from a paramagnetic to a ferromagnetic state as it cools, thereby distorting the uniform applied magnetic field. It seems that this transition should take place by the time the cylinder has cooled to the Curie temperature T_C = 768°C [16]. In the experiment, on the other hand, the cylinder cools the same way as without a field or as if the cylinder were in a paramagnetic state, all the way down to temperatures of 200–300°C.

We propose the following possible explanation of the cooling processes. Since the initial temperature of the cylinder, T_0 = 800°C, exceeds the Curie temperature T_C, the cooled cylinder is in a paramagnetic state. A temperature of 800°C for the steel of which the sample was made is higher than the austeniting temperature, the temperature at which the ferromagnetic α-phase of the steel undergoes a transition to the paramagnetic γ-phase. The distortions produced in the external applied magnetic field by a hollow cylinder in a paramagnetic state are negligible. The magnetic field in the neighborhood of the cylinder differs little from the uniform external field. The magnetic forces acting on the magnetic fluid near different points on the inner and outer surfaces of a paramagnetic hollow cylinder are small. In addition, an equilibrium transition of the steel from a paramagnetic to a ferromagnetic state, which usually takes place at the Curie temperature, may set in at substantially lower temperatures in the case of rapid cooling because of a delay in the appearance of the ferromagnetic phase (pearlite or martensite) [16, 17]. Note that the temperatures of different layers in the wall of the hollow cylinder are quite different during cooling. The rates of cooling of the ferromagnetic layers were also different. Thus, the transition from the paramagnetic to the ferromagnetic state (appearance of the ferromagnetic phase) at different points in the volume of the wall of the cylinder may take place at different times. For this reason, it is difficult to specify the exact times over which the cylinder wall will undergo a transition from a paramagnetic to a ferromagnetic state.

This delay in the transition of the cooling cylinder from a paramagnetic to a ferromagnetic state probably also affected the experimentally observed (Fig. 7) distribution of the cooling rate at different points on the outer and inner surfaces of the hollow cylinder during the initial cooling period. Here, as in the field-free experiments, the cooling at the outer surface of the hollow cylinder is independent, to within the experimental error, of θ until times τ on the order of 13 s. The inner surface of the cylinder is cooled during this time in a way similar to the field-free experiments, i.e., the inner surface is cooled more rapidly than the outer surface. Curve II of Fig. 3 and curves *5–7* of Fig. 7 reveal rapid cooling of the inner surface down to tempera-

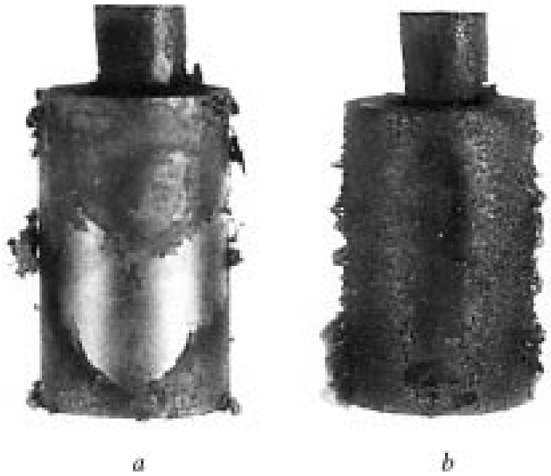

Fig. 8. Photographs of a hollow cylinder cooled in magnetic fluid for 3 (*a*) and 10 s (*b*) from an initial temperature of 800°C in an applied magnetic field of 105 kA/m.

tures on the order of 200°C. Here, however, it should be noted that even when the cylinder is in a paramagnetic state the magnetic field can affect the stability of the vapor-magnetic fluid interface. In addition, this influence will depend on the angle θ between the magnetic field and the boundary of the vapor–magnetic fluid interface. Here heat and mass transfer with and without a magnetic field will proceed differently, even when $T_0 < T_C$. This may explain the different behavior of the cooling curves *5–7* in Fig. 7, especially during the initial cooling period, up to 15 s. Without a field the cooling rates at points 5–7 are the same to within the experimental error.

With increased cooling time and the transition of the cylinder material from a paramagnetic to a ferromagnetic state, the way the inner and outer surfaces of the cylinder cool becomes significantly different from the field-free case. At the outer wall, after 13–15 s the temperature continues to fall, with the cooling rate depending strongly on θ. The temperature of the inner wall begins to increase after 7 s and by 40 s it exceeds that of the outer wall.

We now present some results from experiments on the state of the deposit of stratified magnetic fluid on the outer surface of the hollow cylinder at different cooling times in a magnetic field; these data yield a qualitative explanation of the mechanism for the redistribution of the cooling mechanism at different points on the outer surface in accordance with a plot of the distribution of forces acting on the magnetic fluid in the neighborhood of the cylinder.

The experiment involved heating the hollow cylindrical sample to 800°C and then cooling it in magnetic fluid with an applied magnetic field of 105 kA/m. The cooling of the sample was interrupted rapidly at different times. Figure 8 shows a photograph (*a*) of the outer side surface of the hollow cylinder after 3 s cooling in the magnetic fluid from an initial temperature of 800°C with an applied magnetic field of 105 kA/m. It is evident that there is a uniformly distributed (over the perimeter of the cylinder) dense deposit of stratified magnetic fluid on the ends of the cylinder, its upper and lower parts (Fig. 8*a*). The bulk of the outer surface of the sample is clean, without a deposit of stratified magnetic fluid, in a curvilinear pattern which uniformly encircles the outer surface of the cylinder around its perimeter. A similar distribution of the deposit on the cylinder surface was observed for cooling without a magnetic field (photograph *a* in Fig. 4). Thus, cooling of a cylinder in a paramagnetic state in a magnetic fluid when a magnetic field is present is essentially the same as without a magnetic field. This cooling regime continues until temperatures substantially below the equilibrium point for the appearance of the magnetic phase in the steel used to make the sample, i.e., below T_C = 768°C.

Unlike the state of the sample surface without a magnetic field shown in Fig. 4*a*, the picture in Fig. 8*a* shows a low density deposit of stratified magnetic fluid in the upper part of the side of the cylinder. This is consistent with the above remarks to the effect that, within this period of time, the side surface of the sample in Fig. 8*a* was uniformly surrounded by a vapor film. The deposit on the surface may be caused by diffusive transport of particles of stratified magnetic fluid by Brownian motion through the vapor layer and onto the cylinder surface, as well as to the direct contact of magnetic fluid with the cylinder surface and to stratification of the fluid and its precipitation into a deposit. In addition, although the same sample was used in these experiments and it was demagnetized and its surface was degreased and carefully cleaned before each cooling event, it is difficult to guarantee that the states of the sample surface before each cooling event were completely identical. From one measurement to the next, the adhesion or adsorption properties of the sample surface might, in general, have changed.

There is yet another difference in the states of the deposits of stratified magnetic fluid on the sample surfaces subjected to cooling without a magnetic field (Fig. 4*a*) and with a magnetic field (Fig. 8*a*). In the latter case, flakes of stratified magnetic fluid can be seen on the left and right hand sides of the cylinder in the shape of thin films with an irregular geometric outline. The planes of these flake-films lie in the plane of the photograph and are oriented along the external applied magnetic field. It is possible that the magnetic fluid stratifies in the volume of the boiling magnetic fluid, as well as at the hot cylinder surface. Stratified particles whose shell of surface-active material has been destroyed by the magnetic forces form flaky conglomerates. These conglomerates are carried toward the cylinder surface by the turbulent flows of vapor-liquid mixture that wash the cylinder and settle on the surface by adhesion or adsorption, orienting themselves along the direction of the applied magnetic field.

Figure 8*b* is a photograph of the lateral outer surface of the hollow cylinder obtained by cooling it in a magnetic fluid from an initial temperature of 800°C in an applied magnetic field of 105 kA/m with rapid removal from the coolant after 10 s. After 10 s of cooling, the entire outer surface of the cylinder is coated with a dense deposit of stratified magnetic fluid. The density of this deposit, however, is different at different parts of the surface. Thus, near the poles of the cylinder the deposit is denser. These are the parts of the cylinder surface lying in the left and right regions near the poles (Fig. 8*b*). In the central portion of the outer lateral surface along its generatrix, there is a dark band which becomes narrower in the direction of the acceleration of gravity and is coated with a less dense precipitate of stratified magnetic fluid. This shows that within this time period the cylindrical sample has already acquired ferromagnetic properties and has significantly distorted the external applied field. In the neighborhood of the generatrix of the cylinder that passes through point 1 on its surface, the magnetic forces press the magnetic fluid to the surface. The fluid stratifies and sticks in a thick layer onto the left and right hand sides of the surface of the cylinder, in the neighborhood of the poles (Fig. 8*b*). The cooling rates for different points (1–4) on the outside surface, however, are still the same to within the experimental error after 10 s of cooling (Fig. 7). A significant difference develops in the cooling rates at points 1 and 4 somewhat later, when nonuniform precipitation has begun, roughly 13 s after cooling has begun, as can be seen from the behavior of curves *1–3* in Fig. 7.

Of course, it should be kept in mind that the friable deposit of stratified magnetic fluid on the surface of the cylinder can change the rate of the heat transfer process, obviously reducing it. Thus, heat exchange at point 1 may take place at a somewhat lower rate than at point 2, although this difference lies within the experimental error.

In the neighborhood of the generatrix passing through point 4 of the cylinder surface, the magnetic fluid is repelled from the surface. In this region the vapor layer is thicker owing to the masses of vapor moved to there after being pushed out of the regions adjacent points 1–3 on the surface. As a result, heat exchange between the liquid and the surface is reduced, in full accord with the behavior of curve *4* in the lower plot of Fig. 7. A thin layer of precipitate develops on this part of the cylinder surface, and is visible in Fig. 8*b*, as a result of diffusive processes— transport of magnetic particles of stratified magnetic fluid by turbulent flows of vapor-liquid mixture and the transport of magnetic particles owing to their brownian motion. Particles of stratified magnetic fluid attach to the side portions of the outer surface of the cylinder owing to adhesion or adsorption.

4. Cooling of a Hollow Magnetizable Cylinder in a Magnetic Fluid in Magnetic Fields of Various Strengths for Initial Cylinder Temperatures below the Curie Temperature. The cooling of a hollow ferromagnetic cylinder in a magnetic fluid from an initial temperature $T_0 < T_C$ is qualitatively different from cooling when $T_0 > T_C$.

Figure 9*a* shows the time variation in the temperature at different points on the inner and outer surfaces of a hollow cylinder as it cools in a magnetic fluid from an initial temperature T_0 = 500°C, i.e., $T_0 < T_C$, in a magnetic field of 31 kA/m. Even within the first fractions of a second, points 5–7, which lie on the inner surface of the cylinder, cool less rapidly than points 1–4 on its outer surface. To within the experimental error, the cooling rate is the same at all points on the inner surface of the cylinder. This result is easily explained as follows: at 500°C the hollow cylinder is in a ferromagnetic state and, when it enters the external magnetic field between the poles of the electromagnet, it magnetizes essentially instantaneously. When the hollow cylinder is rapidly immersed in the container of magnetic fluid, small portions of fluid may enter the hollow of the hot cylinder, despite the countering effect of the magnetic forces which attempt to push the liquid out of the hollow, and the fluid is vaporized essentially instantaneously. Thus, the inner wall of the cylinder is cooled through contact with the vapor or with a vapor-liquid medium. The rate of cooling in this case is low and is independent of the angle θ.

The cooling rate at the points on the outer surface is the same, to within the experimental error, until τ = 0.5 s after the onset of cooling. At later times, some reduction in the removal of heat from point 1, which is at a pole of the cylinder, can

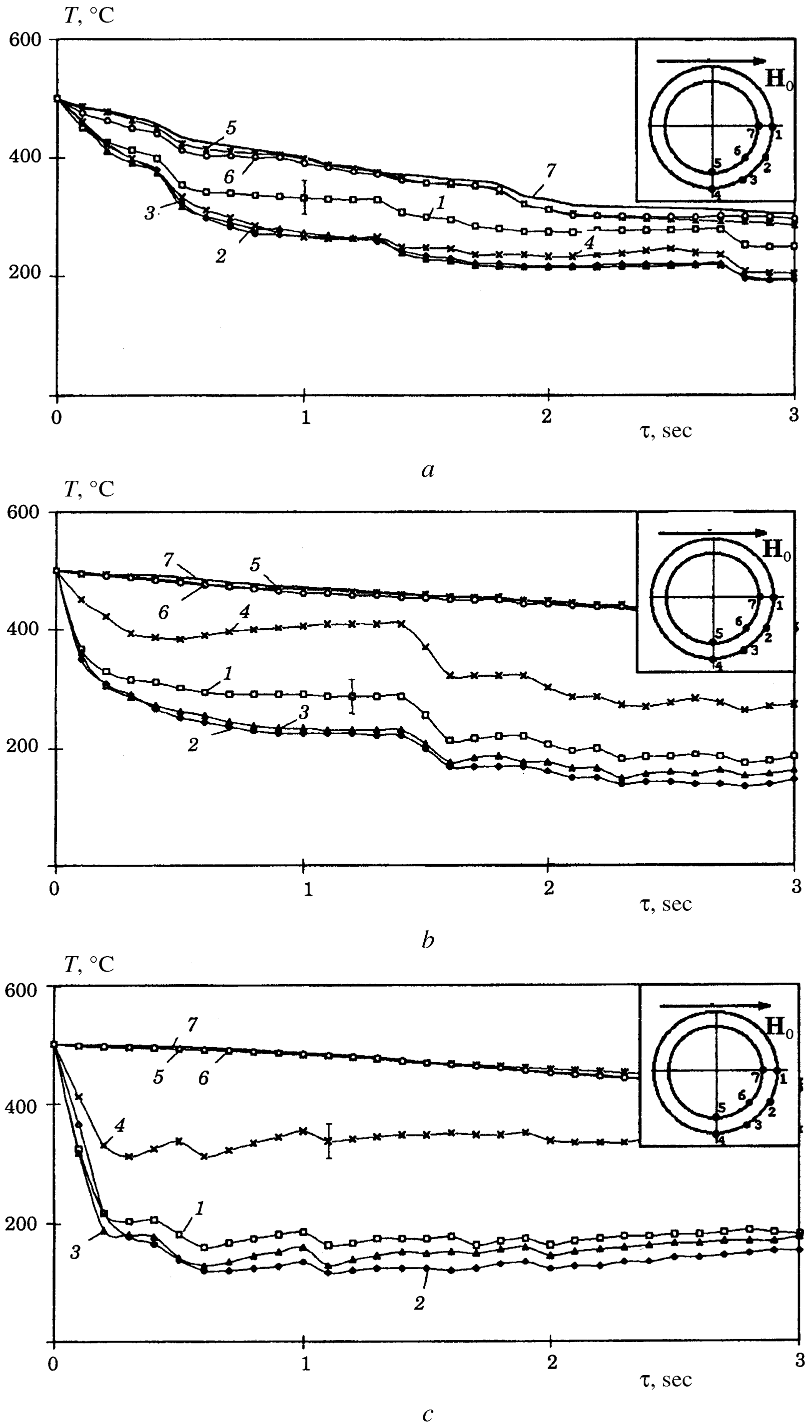

Fig. 9. The temperature T at different points on the outer and inner surfaces of the hollow cylinder as a function of cooling time τ during cooling from an initial temperature of 500°C in magnetic fields of 31 (*a*), 83 (*b*), and 105 kA/m (*c*).

be seen. A possible explanation for this is the following: the forces which push the magnetic fluid from the outer surface of the sample near points on the lateral surface of the cylinder (point 4 and the point diametrally opposite it) are weak in the low external applied magnetic field H_0 = 31 kA/m. The forces which press the magnetic fluid toward those points on the surface which lie near the poles of the cylinder (point 1 and the point diametrally opposite it) are also weak. Because the magnetic forces acting on the magnetic fluid in the neighborhood of different points on the outer surface of the hollow cylinder are weak, these points cool at essentially the same rate to within the measurement error. The slight drop in the cooling rate on the outer surface near the poles of the cylinder may be caused by deposits of friable precipitate of stratified magnetic fluid at these sites owing to the weak magnetic forces which push the magnetic fluid and magnetic particles in the stratified magnetic fluid toward the poles of the cylinder.

As the applied magnetic field is increased, a substantial redistribution of the cooling rate over the outer surface of the cylinder can be seen. Figure 9*b* shows some plots of the temperature as a function of cooling time for different points on the outer and inner surfaces of the hollow cylinder as it cools in the magnetic fluid from 500°C in a magnetic field of 83 kA/m.

Figure 9*b* shows that the cooling rate at points 5–7 on the inner surface of the hollow cylinder is lower than for the same points in the lower magnetic field, 31 kA/m, of Fig. 9*a*. This probably happens because, as the magnetic field is raised, there is an increase in the magnetic forces tending to push the fluid out of the cylinder hollow and preventing penetration of the fluid into the hollow. As a result, the rates of cooling and heat removal from the inner surface of the cylinder wall, which is mainly in contact with the vapor, decrease substantially.

Heat exchange at the outer lateral surfaces of the cylinder also is substantially different in a magnetic field of 83 kA/m compared to a field of 31 kA/m. Figure 9*b* shows that within the first fractions of a second the rate of heat removal at point 4 is much lower than at points 1–3. This also corresponds to the distribution of forces acting on the magnetic fluid. In the neighborhood of the poles and in the neighborhood of the lateral portions of the cylinder surface these forces push the fluid toward the surface and, correspondingly, push it from the surface. Hence, at the poles the vapor layer becomes thinner and heat transfer increases, while at the lateral surface the vapor layer thickens, so heat transfer is reduced. This is confirmed by observations of the state of the deposits of stratified magnetic fluid on the outer surface of the cylinder.

The plots of Fig. 9*b* show that at point 1, which lies at a pole of the cylinder, the cooling rate is somewhat lower than at the points 2 and 3 adjacent to the pole. This can be explained by the greater thickness of the friable deposit of stratified magnetic fluid in the neighborhood of the poles, which reduces heat transfer and develops as a result of magnetic forces which press the conglomerate of stratified magnetic particles onto this part of the cylinder surface.

Further increases in the strength of the applied magnetic field cause even more rapid cooling of points 1–4 on the outer surface of the hollow cylinder during the initial cooling period than for cooling in a field of 83 kA/m. This effect can be seen in Fig. 9*c*, which shows plots of the temperature at different points on the outer and inner surfaces of the cylinder as a function of time during cooling in the magnetic fluid from an initial sample temperature of 500°C in a magnetic field of 105 kA/m. It is evident that the cooling rate for points 5–7 on the inner surface of the cylinder is essentially unchanged from that with a field of 83 kA/m. Curves *1–3* also fall much more rapidly within the first fractions of a second after the onset of cooling than with a field of 83 kA/m. The cooling rate of the lateral surface of the cylinder, in the neighborhood of point 4, also increases in the first 0.2 s compared to cooling with a field of 83 kA/m. This may be explained by the fact that heat is removed from point 4 in the azimuthal direction, as well as radially, because of the rapid temperature drop at the adjacent point 3. For times $\tau > 0.3$ s, the cooling rate at point 4 again falls below that at points 1–3 which lie closer to the pole of the cylinder. Cooling in this fashion at various points on the outer surface of the hollow cylinder is explained by the increased magnetic forces acting on the magnetic fluid surrounding the cylinder as the magnetic field is raised, which, as noted above, either enhance or reduce the thickness of the vapor layer between the cylinder and the fluid.

When the initial temperature of the sample is reduced to 300°C, there is not much change in the way the different points on the outer and inner surfaces of the hollow cylinder cool compared to cooling from an initial temperature of 500°C. Figure 10*a* shows plots of the temperature as a function of cooling time at different points on the outer and inner surfaces of the cylinder obtained during cooling in the magnetic fluid from an initial temperature of 300°C in a magnetic field of 31 kA/m. These curves show that the cooling rate at points 5–7 on the inner surface of the hollow cylinder is slightly lower than that at points 1–4 on the outer surface. The difference in the variation of the cooling curves for points 5–7 lies within the limits of experimental error. The same is true of the differences in the cooling curves for points 1–4.

It is probable that in low magnetic fields the cooling fluid is able to penetrate into the cylinder hollow and cause rather rapid cooling of the inner surface. This may be related to a number of factors which determine the cooling process. Penetration of the magnetic fluid into the cylinder cavity is inhibited by the magnetic forces tending to push it outward. However, in a low external applied field these forces are not strong enough to keep some of the magnetic fluid from entering the cylinder hollow as the sample is rapidly lowered into the container of magnetic fluid. In addition, during cooling of the cylinder from 300°C the magnetic fluid starts to boil on coming into contact with the heated metal surface. A vapor-liquid mixture with reduced magnetic properties is formed, and this also attenuates the effect of the extruding magnetic forces. At the same time, low magnetic fields do not affect the rate of heat removal at different points on the outer surface of the cylinder. Apparently, the combination

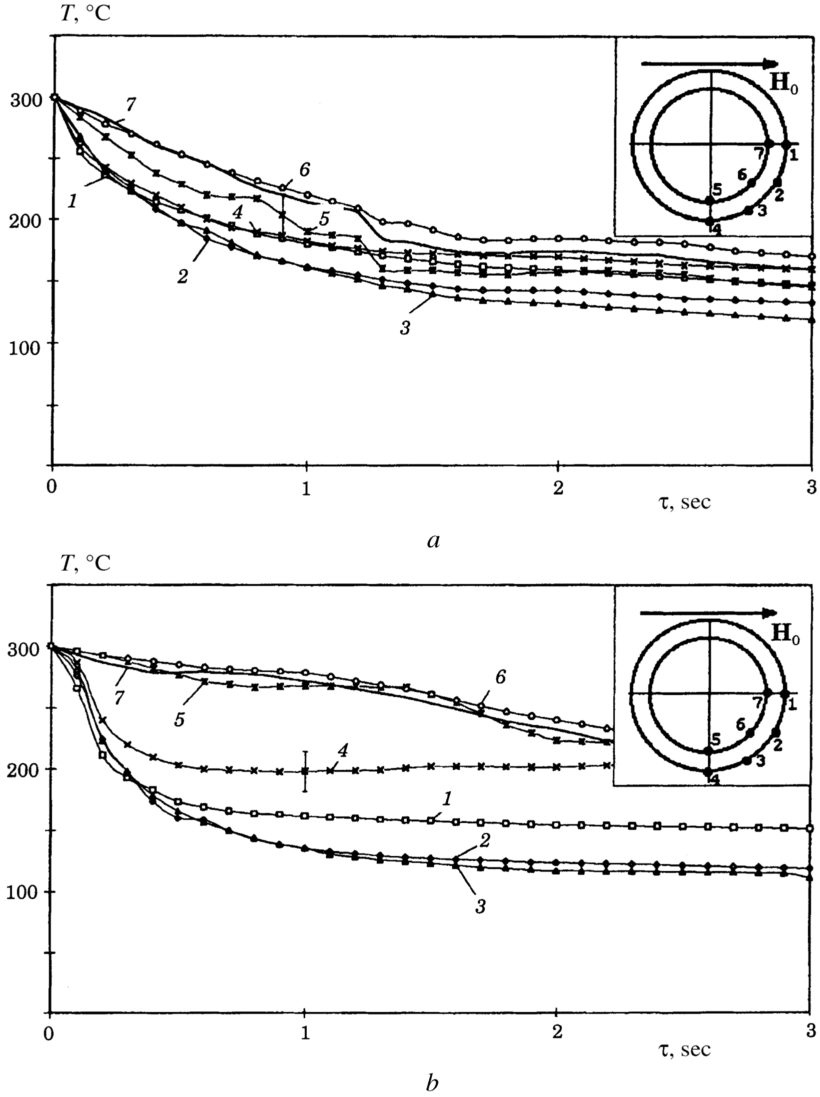

Fig. 10. The temperature T as a function of cooling time τ at different points on the outer and inner surfaces of the hollow cylinder as it is cooled in the magnetic fluid from an initial temperature of 300°C in magnetic fields of 31 (*a*) and 83 kA/m (*b*).

of these factors ensures that the fluid can penetrate the hollow of the cylinder, create conditions for heat removal from the inner surface, and ensure that the difference between the cooling rates at the inner and outer surfaces of the cylinder is small.

When the cylinder is heated to 300°C and then cooled in a magnetic field of 83 kA/m, the magnetic forces tending to push the magnetic fluid out of the cylinder hollow become substantial. They are also substantial in the neighborhood of the outer surface. Thus, as the measurements show, the cooling rates for points located on the inner surface of the cylinder are substantially lower (Fig. 10*b*) than those for a magnetic field of 31 kA/m (Fig. 10*a*). According to Fig. 10*b*, the cooling rate for points located on the outer cylinder surface at different angles θ are substantially different, as also happens during cooling of the cylinder in the same field from an initial temperature of 500°C. Cooling is most rapid at points 2 and 3 on the outer surface. At point 1, which lies at a pole of the cylinder, the cooling rate for times τ close to 0.5 s is somewhat lower than at points 2 and 3, which can apparently be explained by the presence of a deposit of stratified magnetic fluid at point 1 that impedes heat removal. The cooling rate at point 4, which lies on the lateral surface of the cylinder, is already noticeably lower than that for the other points on the outer surface by 0.25 s. This result can be explained with the aid of experiments for observing the distribution of the deposit of stratified magnetic fluid over the outer surface of the cylinder by interrupting the cooling process at different times. Photographs of the outer surface show that a deposit of stratified magnetic fluid, which is mottled with vapor bubble cavities, develops on the left and right sides of the cylinder in the neighborhood of its poles. Cooling at the poles of the cylinder takes place through nucleate boiling, i.e., the surface is cooled rapidly in the neighborhood of the poles. During cooling, the lateral surface of the cylinder is separated from the fluid by a vapor layer; a trace of the vapor layer is visible on the side surface of the cylinder as a bright strip in the central portion of the cylinder surface which is free of deposits of stratified magnetic fluid. Because of the rapid cooling of the lateral portion of the outer cylinder surface, the cooling rates near the poles are substantially lower.

Because the magnetic forces which push the magnetic fluid out of the cylinder hollow are rather large for an applied field of 83 kA/m, the fluid is no longer able to penetrate into the cylinder hollow, and the low cooling rate for the inner surface is explained by heat transfer through the vapor. As the experiments showed, these effects are enhanced by increasing the applied magnetic field.

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