Hydrodynamics and Warmth Trade in Cycles of Cooling of an Attractive Plate in an Attractive Fluid in the Attractive Field

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Abstract

The effect of the magnetic field on heat transfer processes of a magnetized steel plate cooled in a magnetic fluid is experimentally studied. Thermocouples were installed at six points on the surface of the plate along its length. The plots of temperature versus time are obtained in the absence of a magnetic field and in magnetic fields of different intensity. It is found that the intensity of heat exchange depends to a large extent on the magnitude of the magnetic field and on the location of points on the surface of the plate. In a magnetic field, cooling of the central part of the plate occurs with the same intensity as in the absence of a magnetic field and with a lower intensity in comparison with other points on the surface of the plate. Near the plate ends, the cooling rate of the surface is much greater in the magnetic field than in the absence of it. With increasing magnetic field strength, the cooling rate of points in the central part of the plate decreases and is less than in the absence of a magnetic field. The dependence of heat transfer on the magnitude of the magnetic field is explained by the distribution of the magnetic forces acting on the liquid surrounding the plate and the nature of the vapor-air cavities formed near its surface. Experiments on simulation of formation and the shape of vapor-air cavities in a liquid surrounding a magnetizing plate are described.

Key Words: Magnetic Fluid, Heat Transfer, Hydrodynamics, Steel Plate, Magnetic Field.

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Introduction

Magnetic fluids are stable the loid system. The dispersion medium in magnetic fluids is typically kerosene, organ silicon oils, or water. As the dispersed phase, particles of iron, cobalt or magnetite are used, due to which magnetic fluids have the ability to be highly magnetized in magnetic fields, while maintaining fluidity. The study of heat transfer during boiling of magnetic fluids is of interest both from a purely scientific point of view and in connection with the possible technical and technological use of the boiling process of a liquid magnetizing medium (Gogosov, V.V., and A. Ya Simonovskij, 1989 – Yanovskiy, Aleksandr A., et al, 2015). Thus, it was proposed to use magnetic fluids in heat exchangers and devices controlled by a magnetic field (Sundara, L. Syam, Manoj K. Singha, and Antonio CM Sousa, 2013–Yanovskii, A.A., A. Ya Simonovskii, and E.M. Klimenko, 2014), and also as a quenching medium for cooling magnetized bodies (Gogosov, V.V., and A. Ya Simonovskij, 1989 – Mirkin, L.I., S.A. Shesterikov, and A. Ya Simonovski), (Khoshmehr, Hamed Habibi, et al, 2014 – Abdollahi, Ali, Mohammad Reza Salimpour, and Nasrin Etesami, 2017).

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It was shown (Gogosov, V.V., and A. Ya Simonovskij, 1989, Yanovskiy, Aleksandr A., et al, 2015 - Gogosov, V.V., A. Ya Simonovskii, and R.D. Smolkin 1990) that the use of magnetic fields with a given spatial distribution and varying with time it according to given laws allows you to control the hardening processes. In this case, it is possible to conduct inhomogeneous cooling and obtain a locally heterogeneous structure and various hardness in different parts of the surface of the hardened products. In this regard, it is of interest to study the processes of heat and mass transfer during cooling of heated magnetizing bodies in magnetic fluids in the presence of a magnetic field. The purpose of this study is to study the effect of magnetic fields on the intensity of heat transfer processes of a magnetized plate immersed in magnetic fluid, as well as the shape of the vapor-air cavities formed during its cooling.

Materials and Methods

The heat transfer parameters were determined on the experimental setup, the diagram of which is shown in Figure 1. A plate 1 made of ferromagnetic steel was attached to a non-magnetic cylindrical rod 2. The rod could freely move vertically along the guides 3. The plate was heated in a tubular electric furnace 4. Cooling was carried out by rapid immersion of the sample in a magnetic volume liquid filling a non-magnetic cylindrical container 5 located between the poles of the electromagnet 6. With a diameter of the pole tips of the electromagnet 100 mm and the distance between 107 mm poles field heterogeneity in the gap of the electromagnet did not exceed 7%. The error in measuring the magnetic field did not exceed 2%. The direction of the magnetic field in all experiments coincided with the plane of the plate. Plate length L = 45 mm, height h = 50 mm, thickness b = 5 mm. At six points on the surface of the plate in the middle part along the height, thermocouples were installed. Point 1 is located in the center of the plate, point 6 at the end of the plate.

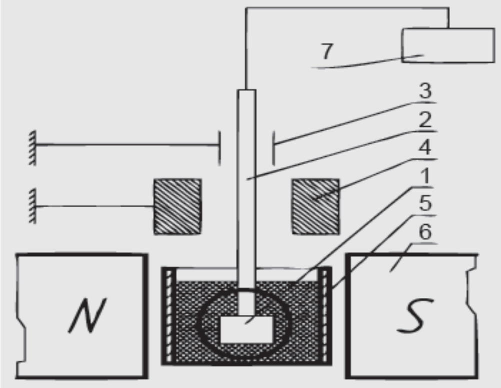

Fig. 1. The experimental setup

The dimensions of the plate and the locations of the thermocouple installation points are shown in Fig. 2. The thermocouple electrodes for insulation were routed along the ceramic straw channels and laid along the surface of the guide rod. The thermocouple readings were recorded by the board of the analog-to-digital converter 7. In the experiments, we used a water-based magnetic fluid with the following parameters: absolute magnetic permeability μ = (2.5 ± 0.4) • 10^{-6} GN / m; density ρ = 1.21 • 10^{3} kg / m^{3}, kinematic viscosity ν = 3.99 • 10^{-6} m^{2} / s. The cooled plate was made of 40X steel. The choice of mother the sample size is explained by the wide distribution of this steel grade and the well-known temperature dependence of its thermophysical properties. The choice of the ratio of sample sizes L to thickness b, L / b ~ 10, is due to the following. Experiments on finding the shape of the free surface of a magnetic fluid surrounding a cold magnetizing plate showed that at L / b ~ 10, depending on the magnitude of the applied external magnetic field, two or four cone-shaped air cavities can form near the surface of the plate in the volume of the surrounding magnetic fluid plate. The dimensions of the cavities depend nonmonotonically on the magnitude of the magnetic field. With this field effect on the shape of the free surface of the magnetic fluid, we can analyze the dependence of the thickness of the vapor film of the magnetic fluid surrounding the magnetized plate cooled in it on the field magnitude. Thus, it is possible to simulate the effect of the field on the heat transfer of a plate with a magnetic fluid, the intensity of which depends on the thickness of the vapor film. Thermocouples were installed at six points on the surface of the plate (Fig. 2). During the experiments, the sample was heated to a temperature of 625°C. Thus, the heating temperature of the sample in all measurements was lower.

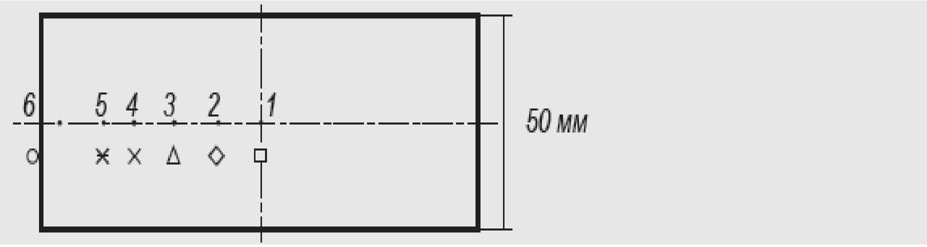

Fig. 2. Layout of thermocouples on the surface of the plate in its middle part in height, top view

Curie temperature, equal for steel 768°C. As a result, the residual magnetization of the cooled plate in a magnetic field could vary from measurement to measurement. To ensure the constancy of the initial magnetic state, the sample was placed in an alternating magnetic field for demagnetization before each change in the applied magnetic field mode. It was found that when the plate was cooled from 625°C to room temperature, all boiling regimes of magnetic fluid — film, transition, bubble, and convective cooling — can be observed. In particular, it was found that when the plate is cooled, a film boiling mode is realized in the temperature range 700–400°C. It should be noted that at heating temperatures above 625°C, a significant acceleration of decarburization and delamination of the surface of the cooled sample is observed; the formation of scale. Since thermocouple junctions were welded to the surface of the plate by spot welding with a copper electrode, a decrease in the heating temperature below traditionally used in technological processes of steel quenching (850–900°C) during thermophysical measurements made it possible to increase the number of cooling without damaging the joints of thermocouple junctions with the surface cooled sample. To equalize the temperature over the cross section of the sample before the turn- By changing the field, a three-minute exposure was realized in order to evaluate the systematic measurement error associated with the difference in the inertial properties of the temperature sensors, the plate was cooled in air. The measurements showed that when the plate is cooled in air, the temperature changes with time at different points on the plate surface in the same way. This is due to the fact that cooling in air occurs due to convective heat removal. Phase transitions in this case do not occur. The identical behavior of the cooling curves of various points on the surface of the plate in air indicates that the inertia of the thermocouples does not differ significantly (there is no lag during any curve compared to the others) with a small cooling rate.

When cooling in a liquid, phase transitions cause significant temperature fluctuations on the heat-transfer surface, and the cooling intensity is greater than when cooling in air. At higher cooling intensities, delays may occur during the cooling curves due to differences in inertial properties of thermocouples. To determine the value of this difference, the plate was cooled in water. Measurements showed that the course of the cooling curves at different points on the plate surface is almost the same. The differences in the course of the cooling curves are associated with natural fluctuations due to the boiling processes of the cooling medium during heat and mass transfer. In repeated experiments, the course of the curves changed arbitrarily. Measurements showed that the inertia of the thermocouples used in the experiment does not differ significantly. Thus, the difference in the course of the curves due to the inertia of the thermocouples is less than the difference in the course of the curves due to temperature fluctuations of the heat-transfer surface. In the absence of a magnetic field, it was assumed that the cooling rate is the same at all points on the plate surface. The measurement data were averaged over six measurements every 25°C. This means that at each point six measurements were taken. As a result, we obtained six temperature dependences that are slightly different from each other. On each curve, a given temperature corresponded to six different times τ. These times were summed up and the sum was divided by six. The obtained value was considered a characteristic time corresponding to the selected temperature value. Such a procedure was carried out over the entire range of the cooling temperature with an interval of 25°C. The error in determining the temperature did not exceed ± 5°C. The relative error in determining the time intervals did not exceed 20%.

Results and Discussion

Figure 3a shows the averaged curve of the dependence of temperature *T* on time *τ* obtained by cooling the plate in a magnetic fluid without a magnetic field. The graph shows that cooling occurs most intensively in the initial period (up to about 465°C). Then the cooling rate decreases. At temperatures of approximately 400°C, a kink in the curve is observed. The appearance of a break point is associated with the destruction of the vapor film surrounding the plate during the film boiling regime of the cooling medium, which corresponds to the beginning of the transition boiling regime. The earlier observations of the surface state of the cooled plate showed that at a temperature of the plate above 400 ° C the film mode of boiling of the cooled medium occurs. Below 400 ° C (curve of Fig. 3a), the cooling is initially intensified, then at T ~ 300°C it weakens again.

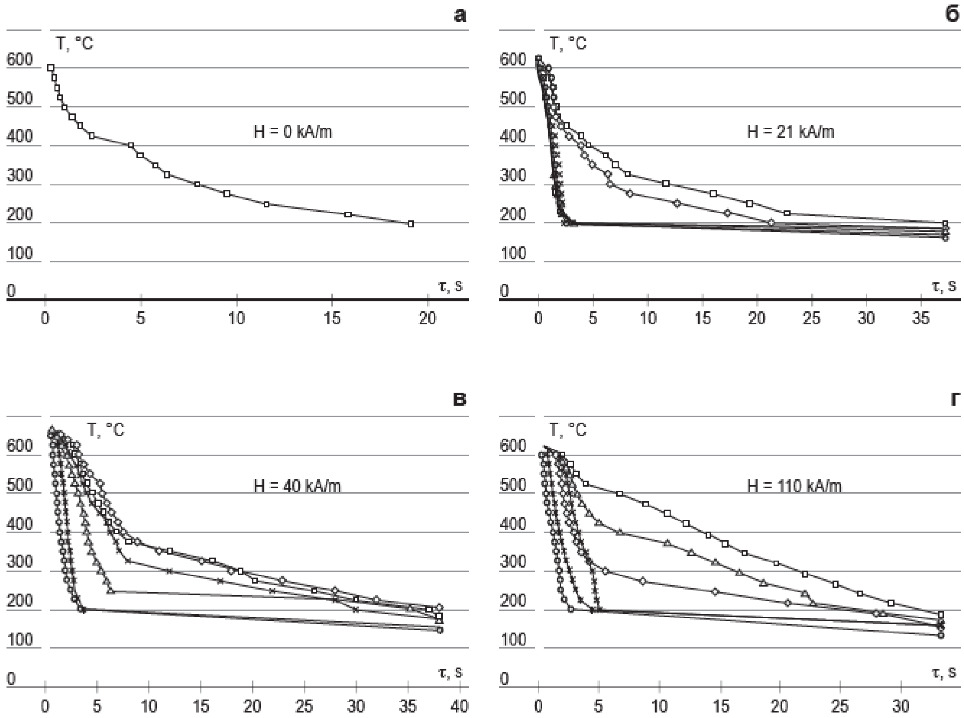

Fig. 3. The dependence of temperature T °C, on time τ, s, when laying the plate in the absence of a magnetic field (a) and in magnetic fields 21, 40, 110 kA / m (b, c, d).

In fig. Figures 3b-d show the lines of the cooling rate of points on the plate surface obtained in experiments on cooling in magnetic fluid in applied magnetic fields of 21, 40, and 110 kA / m, respectively. From fig. 3b shows that in a magnetic field with a strength of 21 kA / m in the initial cooling period in the temperature range 625–475 ° C; the cooling rate of all points on the plate surface within the experimental error is the same. At points 1 and 2 adjacent to the central part of the plate, cooling at temperatures below 475 ° C occurs much less intensively than at other points on the surface nosti. At these points, the cooling intensity did not change compared to cooling without a field. The cooling of points 3–6 at temperatures from 600 to 200 ° C is much more intense than without field. An increase in the heat transfer rate in a magnetic field with a strength of 21 kA / m compared to heat transfer without a magnetic field at the points of plate 3–6 located closer to its ends at surface temperatures from 625 to 200 ° C can be explained as follows. Magnetizable the plate distorts the applied uniform magnetic field. As a result, forces caused by distortion of the magnetic fields proportional to the gradient of the field. It can be shown (Yanovskii, A. A., A. Ya Simonovskii, and E. M. Klimenko, 2014) that these forces press the fluid to the surface of the plate in the vicinity of its thorns. In the film and transitional modes of boiling of a magnetic fluid, as a result of the action of these forces, the thickness of the vapor layer decreases. Heat exchange hot steam plates are significantly lower than with liquid. Therefore, a decrease in the thickness of the vapor layer leads to an increase in heat transfer in the vicinity of points near the ends of the plate. In addition, instability of the magnetic liquid-vapor interface can occur. As a result, the magnetic fluid may come into contact with the surface of the plate. All this can lead to intensification of heat transfer. Near points 1 and 2, in the central part of the plate, magnetic forces, caused by distortion of the magnetic field of the magnetized plate, repel the liquid from the surface of the plate. In a magnetic field with a strength of 21 kA / m, the repulsive forces are small and do not lead to a significant thickening of the vapor film, and possibly to the development of instability of the phase boundary. As a result of this, there is no noticeable change in the heat transfer intensity in the vicinity of points 1 and 2 compared with cooling without a magnetic field. In fig. Figure 3c shows the cooling curves of various points on the surface of the wafer obtained as a result of cooling the wafer in a magnetic fluid in a magnetic field of 40 kA/m. The figure shows that the difference in the course of the cooling curves is noticeable even in the high-temperature cooling region. In this case, a significant change in the heat transfer rate at point 6 on the plate end and point 5 adjacent to the end face as compared to cooling in a magnetic field of 21 kA / m does not occur. At the same time, at points 1–4 of the plate surface, a significant decrease in the cooling rate is observed in comparison with cooling in magnetic fluid in a field of 21 kA / m (Fig. 3b). Apparently, at points 5 and 6, the heat transfer intensity did not increase compared to the field of 21 kA / m, since the magnetic forces pressing the liquid to the poles of the plate in the vicinity of these points did not change significantly. At points 1–4, the magnitude of the magnetic forces repelling the magnetic the liquid from the surface of the plate has increased significantly. There was an increase in the thickness of the vapor layer separating the plate from the liquid. The heat sink from the indicated points of the plate surface also decreased. For the same reason at points 1, 2, 4 on the surface of the plate, the cooling rate significantly decreases compared to the cooling rate without a field. However, at point 3, such a decrease in the cooling rate is observed only in the temperature range rats from 625 to 450°C. At lower temperatures, cooling at point 3 in a field of 40 kA / m is still more intense than without field. It should be noted that point 4 is closer to the end of the plate than point 3, and the forces that press the fluid to the plate at point 4 are greater than in the physical and mathematical sciences Hydrodynamics and heat transfer in the processes of cooling of a magnetized plate. Point 3. It would seem the vapor layer at point 4 should be thinner than at point 3. However, heat transfer at point 4 is less intense than at point 3. A possible explanation for the increase in cooling rate at point 3 compared to point 4 in a magnetic field of 40 kA / m will be given below. A further increase in the magnetic field leads to new interesting effects on the distribution of the cooling intensity along the length of the cooling the wafer Figure 3d shows the cooling curves of various points on the surface of the plate obtained by cooling the plate in a magnetic fluid in a magnetic field of 110 kA / m. The graph shows that in the high-temperature cooling region of 625–550°C, a significant decrease in the cooling intensity occurs at points on the surface of the plate 1–5. The cooling intensity decreases at point 6 at the end of the plate as compared with the cooling intensity in a magnetic field of 40 kA / m. The cooling rate at center point 1 is slightly increased compared to the cooling intensity of this point in a magnetic field of 40 kA / m and the cooling intensity at point 2. Apparently, the magnetic liquid-vapor interface in the vicinity of points 1, 2 becomes unstable. There is a leakage of magnetic fluid to the plate in the center of the plate in the vicinity points 1. As a result, the thickness of the vapor layer in this region decreases, and the heat transfer increases. In addition, it is noticeable that the cooling intensity at point 3 of the plate surface becomes larger than the cooling intensity at point 5. Apparently, as a result of the instability the boundary between the magnetic liquid – vapor interface liquid flows to the plate also in the vicinity of point 3. As a result, the heat transfer rate at point 3 increases. For the same reason, an increase in the heat transfer rate occurs at point 3 compared with point 4 in a magnetic field of 40 kA / m. Cooling significantly slows down at point 3 of the plate surface, but at the same time intensifies at points 4–6 in the vicinity of the plate end. An analysis of the dependence of the change in the cooling rate on the magnitude of the magnetic field allows us to conclude that the field magnitude determines the hydrodynamics of the formation of vapor cavities at various parts of the surface of the cooled magnetized plate and the shape of the cavities and, as a consequence, the heat transfer rate of the plate with magnetic fluid.

The effect of a magnetic field on the free form the surface of the magnetic fluid surrounding magnetizable plate to determine the effect of a magnetic field on the formation and the shape of the vapor cavity surrounding the magnetizing plate was carried out by the following experiments. A cold plate was mounted in a non-magnetic cylindrical cell placed between the poles of an electromagnet. The cuvette was filled with magnetic fluid. Volume ratio magnetic fluid V_{mf} to the plate volume $V_{mf} / V_{pl} = 51$. The direction of the magnetic field is parallel to the plane of the plate. The experimental design is similar to that shown in Figure 1. Figure 4 a shows a photograph of a plate without magnetic fluid (top view). In the presence of a magnetic fluid and an applied external magnetic field H = 76 kA / m in the volume of the magnetic fluid in the vicinity of the central part of the plate, two air cavities are formed, one each on each side of the plate. It can be seen from the experiment that the formed air cavities have the shape of cone-shaped funnels tapering in the direction of gravity from the upper free surface of the magnetic liquid to the bottom of the cell. Two bright spots in the center of the plate in photograph b (Fig. 4, top view) are traces of cone-shaped funnel air cavities at the bottom of the cell in an applied magnetic field of 76 kA /m. With further increase total volume of magnetic fluid at constant plate sizes.

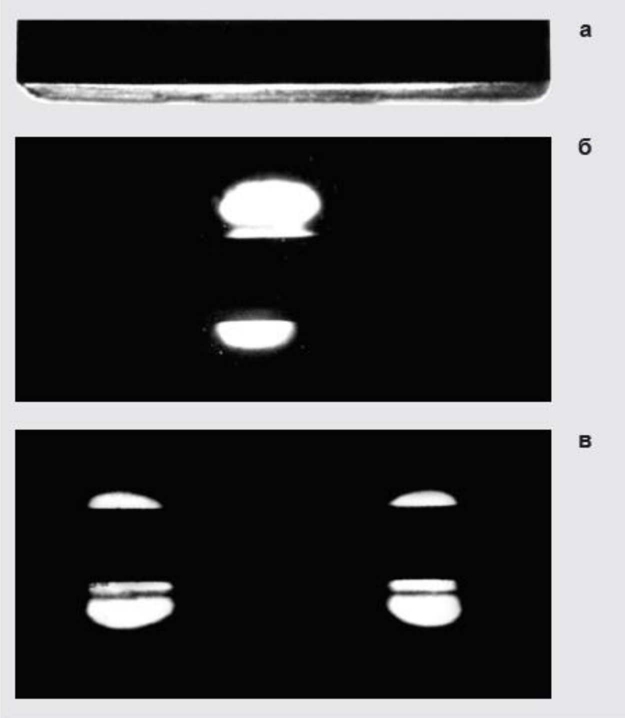

Fig. 4. Photos of the plate without magnetic fluid (a) and traces on the bottom of the plate of cone-shaped funnel air cavities appearing in the volume of magnetic fluid in magnetic fields of 76 kA / m (b) and 190 kA / m (c)

The volume of air cavities near the central part of the plate decreases. The lumen of the cavities at the bottom of the cuvette also decreases — a part of the plate surface that is free of magnetic fluid narrows. Note that for magnetic fields less than 76 kA / m for a given ratio V_{mf} / V_{pl}, and with the dimensions of the plate, air cavities are not formed. The fluid is in contact with the plate everywhere. Near the ends of the plate, the height of the liquid column, comparable with the height of the plate, is observed at a distance from the plate almost to the borders of the cell. As was clear from the previous one, the formation of air cavities can be explained by the action of magnetic forces on the magnetic fluid surrounding the magnetized plate. These forces result from distortion of the applied uniform magnetic field by a magnetized plate. It can be shown (Yanovskii, A.A., A. Ya Simonovskii, and E. M. Klimenko, 2014) that near the ends of the plate, magnetic forces press the fluid to the plate. In the center of the plate, magnetic forces repel the magnetic fluid from the plate. As a result, air cavities are formed in the central part of the plate. Similar wide vapor cavities can form near the central part of a hot plate cooled in magnetic fluid. As a result, heat transfer between the plate and the liquid in these areas of the plate decreases. As the magnetic field increases to 138 kA / m, the liquid touches the central part of the plate and instead of two conical cavities in the center of the plate, four conical funnel cavities are formed, two on each side plates. Cavities are displaced from the central part of the plate to its ends. With a further increase in the magnetic field to 165 kA / m, the dimensions of the cavities decrease, and the traces of the cavities at the bottom of the cell also decrease. Cavities are shifted in the direction of the ends of the plate. In a magnetic field of 190 kA / m, the cavities again increase in volume; a photograph of their traces at the bottom of the cell is shown in Figure 4c. The formation of air cavities in the center of the plate, their shape, dimensions and the transition from two cavities to four depend, all other things being equal (plate dimensions, type of magnetic fluid, etc.) not only on the magnitude of the magnetic field, but also on the ratio of the volume of the magnetic fluid in the V_{mf} cuvette to the full volume of the V_{pl} plate immersed in the liquid. This statement is also true when the height of the plate exceeds the height of the cell with magnetic fluid. Perhaps this is due to the fact that near the ends of the plate in an applied magnetic field, the magnetic fluid rises under the action of magnetic forces along the entire height of the ends to the upper face of the plate, regardless of its height. Thus, with a ratio of

V_{mf} / V_{pl} = 32, two air cavities with a stable magnetic liquid-air interface are observed in the entire range of the magnetic field from 110 to 190 kA / m. Liquid does not leak to the plate and does not pass from two to four funnel air cavities (Ahmed, Ali M., Qasim Shakir Kadhim, and Ibrahim A. Ali, 2021). The axonometric drawing of the free surface of the magnetic fluid in this case corresponds to that shown in Figure 5a. However, the volume of the cavities increases with increasing field. Traces of air funnel cavities at the bottom of the plate also increase. V_{mf} / V_{pl} = 32. The magnetic fluid-air interface is stable at all field values. With field values less than 110 kA / m, air cavities absent - the liquid is everywhere in contact with the plate. Thus, with an increase in the V_{mf} / V_{pl} ratio, instability of the magnetic liquid – air interface, the formation of two air cavities in the liquid volume in the region of the central part of the plate, and the transition from two to four air cavities in the vicinity of the ends of the plate arise at lower values of the magnetic field. An analogy can be found between the shape of the free surface of the magnetic fluid surrounding the cold magnetizing plate and the shape of the vapor cavity in the volume of magnetic fluid surrounding the heated plate. So, in a magnetic field of 21 kA / m in the central part thickened vapor film may form on the cooled plate on each side of the magnetic fluid. With an increase in the magnetic field, thickenings of the vapor film can capture plate adjacent to the central part of the plate, extending to its ends. Then there are four thickenings of the vapor film near the ends of the plate, two on each of its sides. With a further increase in the field, each of the four thickenings first decreases, and then increases in size, migrating along the length of the plate. Such a change in the shape of the vapor cavity corresponds to the formation of two funnel air cavities in the central part of the cold plate surrounded by a magnetic fluid at a certain value of the magnetic field. As the field increases, the size of the funnel air cavities increases, extending along the length of the plate. With a further increase in the field, four air cavities arise in the vicinity of the ends of the plate, the thickness and size of which change with the germ of the field, capturing one or the other surface areas of the plate. An increase or decrease in the thickness of the vapor film leads, respectively, to a decrease or increase in the intensity of heat transfer between the magnetic fluid and the plate. In experiments on cooling the plate, the volume of magnetic fluid in the cell is large, the V_{mf} / V_{pl} ratio is 160, so that the plate is completely immersed in the liquid. It can be assumed that the transition from two to four thickenings of the vapor cavity occurs at lower field values with respect to compared with the transition from two to four air cavities arising in experiments when studying the forms of the free surface of a liquid surrounding a cold plate.

Conclusions

As a result of the studies obtained graph-the time dependences of the temperature of various points on the surface of a magnetizing plate in magnetic fields of different strengths. It is shown that the heat transfer intensity between the plate and the liquid substantially depends on the magnitude of the applied magnetic field and the location on the plate of the elements of its surface. It was found that in a magnetic field with a strength of 21 kA / m, at the ends of the plate, the heat transfer intensity is much higher in a magnetic field than without a field. With an increase in the applied magnetic field, the heat transfer the central part of the plate is reduced compared with the same cooling in the absence of a field. An analysis of the described experiments allows us to conclude that the magnitude of the magnetic field affects the hydrodynamics of the formation of vapor cavities near various parts of the surface of the cooled plate.

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