The propagation of temperature pulsations along the free surface of a liquid layer from a linear heat source

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Abstract. The evolution of the temperature field on the free surface of a fluid near a periodically heated wire is experimentally investigated. The wire was heated by rectangular current pulses with specified duration and pulse repetition period. The data on the spatial characteristics of thermal waves and the propagation velocity of a thermal wave are presented. Using digital video of the visualized fluid flow, the structure of the unsteady convective fluid flow was studied.

1. Introduction
Layers of fluid with a non-isothermal free upper boundary are typical natural and technological objects. Depending on the physical situation and characteristic sizes, the buoyancy forces and the thermocapillary effect make a different contribution to the formation of flows and, accordingly, to convective heat transfer processes [1–11]. The thermocapillary effect is manifested both in terrestrial conditions in the gravitational field and in zero gravity in the presence of a temperature gradient along the free surface of the fluid. The boundary conditions can be stationary when a constant temperature drop is maintained along the free surface of the fluid or unsteady with various functional time dependencies. It can be monotonously, suddenly or pulse-heated walls of various curvature and orientation. In technical devices, these are primarily fuel tanks of aviation and rocket technology. In technology, these are, for example, the processes of drawing single crystals from the free surface of melts by Czochralski methods and horizontal directional crystallization [6, 7]. In surface crystal growing technologies, in the presence of a free surface of melts, temperature control systems can create temperature fluctuations in the walls of crucibles and excite thermocapillary waves from the walls to the crystallization front. Continuing a series of works [3, 5–7], using thermal imaging scanning of the free surface of a liquid, thermocapillary and thermal gravitational-capillary flows excited by a pulsed heated wire located on a free surface or buried were studied.

Even when analyzing the results of experiments [3], the idea came up to use a pulse-heated linear heat source located on the free surface of a layer of ethanol to generate a thermocapillary flow. Those. eliminate the effect of buoyancy forces. Qualitative experiments were carried out and it was found that with short pulses and a large duty cycle, the fluid does not have time to warm in depth and a thermal wave of thermocapillary nature propagates along the surface. With a relatively low power of current pulses, the free surface practically does not deform. With the advent of thermal imaging technology, this type of flow can be studied without the disturbing effect of microthermocouple probes [3, 7] and the temperature field can be analyzed not at one point, but on the entire surface simultaneously. Modern thermal imagers and video cameras, computer processing of video films allow in one experiment measuring the temperature field on the surface of a fluid and studying hydrodynamics.
2. Model

The installation diagram is shown in Fig. 1. The cell in which the fluid (1) is located is a rectangular cavity made of transparent plexiglas with internal dimensions: length × width × height = 350x200x50 mm³. Two copper heat exchangers (2) are placed at the ends of the fluid layer. Water was pumped through the heat exchangers from thermostats (the water temperature was maintained with an accuracy of 0.1°C). A constantan wire is placed on the upper free boundary of the fluid in the center of the layer parallel to the end heat exchangers. The wire length l = 170 mm, diameter d=0.2 mm. Resistance (at Т = 27°C) R = 3.5 Ohm. The pulsed heated wire (3) is stretched horizontally on elastic holders and fixed on the coordinator (4). Using a microscrew, the wire could move vertically, the movement was controlled by a micrometer. The temperature of the copper plates of the heat exchangers was controlled by copper-constantan thermocouples. To control the heating mode of the wire, a controller was developed and manufactured, connected to a personal computer (PC) through a serial COM port. The developed software made it possible to control the parameters of wire heating (pulse repetition period — PRP, and pulse duration — PD). The temperature in the volume, on the surface and above the surface of the liquid was controlled by a thermocouple probe consisting of two nichrome-constantan thermocouples with joint diameters of 40 μm. The controller allowed to interrogate two Sch-300 digital voltmeters, which provided temperature measurement from thermocouple probes with an accuracy of 0.01°C and with a maximum sampling frequency of 25 Hz. The temperature field on the surface of the fluid was measured using an “Infraterm” (5) computer imager (developed by the Institute of Semiconductor Physics SB RAS) with a temperature resolution of 0.03°C and recording up to 20 frames per second. The temperature of the heat exchangers was set equal to the ambient temperature. In the presented series of experiments, the initial temperature of the working fluid was 21.5°C. The height of the fluid layer was maintained constant and equal to H = 24.0 mm. The wire was exposed so that there was no surface deformation. The heating parameters were set: voltage U = 8.5 V, current I = 2.4 A, pulse duration and pulse repetition period were set programmatically. After switching on the pulse heating of the wire, a time of 30 minutes was maintained before the start of thermal imaging. During this time, a heat balance was established between the heat generated by the wire and the heat removed by the heat exchangers. The
recording time of a thermal imaging film of a single steady state was 40-120 seconds, the frame rate was 19.5 Hz. To study the spatial form of the convective flow of the visualized fluid in a plane normal to the surface of the fluid and the wire, a digital video camera was used (frame rate 25 Hz). The visualization of the fluid was carried out by aluminum particles-flakes with sizes of 10-15 micrometers.

3. Results and discussion

The initial temperature information is stored as a matrix of instantaneous temperature values at 128x128 = 16384 points. Processing this information on a computer, it is possible to obtain a temperature field in the form of a tone picture, in the form of a three-dimensional graph of $T(x, y)$ or the distribution of isotherms on the surface of a fluid. In Figure 2 shows a selection of individual frames of a thermal imaging film in the form of tone patterns in bmp format (256 gray gradations). The evolution of the temperature field on the surface of the alcohol layer in time is shown in the regime with the duration of the heating interval — DI = 1s, pulse repetition period PI = 5s. The first three frames correspond to the warm-up period, the next three frames to the cooling interval. Light areas near the wires correspond to a higher temperature, dark - low. After turning on the heating, the temperature in the immediate vicinity of the wire increases sharply and reaches 24.8°C (a temperature jump of 3.3°C). A large local temperature gradient that has arisen sharply leads to a dispersal of the heated fluid along the surface. The front of the heat wave is formed. On frame 2, this is a strip about 4 mm wide, which broadens over time. Removing the heated front is accompanied by pulling the fluid from the lower layer to the wire. After the heating is turned off, a surface region with a reduced temperature is formed (in frame 4, the temperature decrease is 0.1 K). The width of the region of reduced temperature increases and reaches ~ 10 mm by the end of the fifth second - towards the end of the heating interval of the wire (frame 6). After the heating is turned off, the region near the wire rapidly cools by about ~ 1 K, this is caused by the removal of cold liquid to the surface from the lower layers, which has arisen by the convective flow that has formed during heating (frames 4-6). It can be seen that in the next stage, the sharp temperature contrast and the cooled region disappear quickly (frame 6). This is because the superheated liquid spreads in two directions: to and from the wire along the surface. In order to trace the propagation of thermal waves over the free surface of a fluid, it is possible to plot the temperature distribution along the X axis perpendicular to the wire for a specific value of the longitudinal Y coordinate versus time in the form of a tone (or color) photograph.

Details of the formation and propagation of heat waves in the pulsed heating mode with RPR = 1s and DP = 5s are shown in Figures 3-7. In Figure 3 shows an example of such a representation of the temperature distribution along the X axis for the regime for which selective frames are presented in Fig. 2. Figures 3 and 4 show the temperature distribution averaged over the Y coordinate in the 10 mm
band. Figure 3 clearly shows the symmetry in the propagation of heat waves from the wire in both directions along the surface in the direction normal to the wire. In Figure 4, these data are presented in three-dimensional form. Local overheating at the wire and cooling for one period are clearly shown here.

The propagation velocity of the leading edge of the heat wave and its position at various points in time are shown in Figure 5. The propagation velocity along the free surface depends on the local temperature gradient. At the initial moment, heating the wire creates a maximum gradient and a thin layer of liquid is ejected from the heat source at high speed. At the following time points, a cold liquid is drawn from below, flowing onto the

![Figure 5](image)

**Figure 5.** The time dependence of the coordinate of the wave front along the normal to the wire (1) and its advancement speed (2).

![Figure 6](image)

**Figure 6.** The structure of convective flow near the wire.

Moments of time: 1 – t=0.2s; 2–1s.; 3 – 2s; 4 – 3s; 5 – 4s;

1 – vertical component of velocity, 2 – horizontal component.

![Figure 7](image)

**Figure 7.** Profiles of velocity components near the wire.
heated wire. Figures 6, 7 show this process in dynamics. The failure in the distribution of the horizontal velocity component in Figure 7 is explained by the fact that, when processing the video, the velocity averaged in a layer 0.9 mm thick was built. Estimates of the velocity of individual particles moving in a thin layer near the surface give 28-32 mm/s. The thermal imager (Figure 5) measures the speed on the free surface directly.

The video of the flow in the plane normal to the free surface and to the wire helps to decipher the features of the temperature distributions along the surface at various points in time after heating is turned on. Video processing allows you to get the velocity field and determine the direction and intensity of the flow at different points in time (Figure 7). Figure 6 shows analogs of shutter-speed photographs obtained by adding 25 frames of a movie. They give an idea of the scale and spatial form of the flow. The upper image in Figure 7 corresponds to the time instant 0.2 s after the heating of the wire is turned on. It can be seen that at the initial moment a rising flow is formed, the velocity of which increases during the heating time (Figure 7). After the heating is switched off after 1s, the lift flow practically decays. Then for a short time a downward return flow is formed.

An example of the temperature distribution along the X axis at different points in time for other parameters of heating the wire is shown in Figure 8. The graph shows the local temperature values averaged over a 10 mm strip in the central section along the length of the wire. Temperature distributions over a sequence of three heating pulses are shown. The fields of isotherms are shown, which are reproduced with great accuracy in this batch process. At a qualitative level, the sequence of events described above does not change. The time intervals vary in the development of ascending and descending fluid flows under the wire and the parameters of the heat waves running away from the heated wire. The temperature in the region immediately adjacent to the wire increases with increasing pulse duration. For example, with DI = 5s and PI = 10s, the temperature in the region is from about 32°C on the wire to 26°C at a distance of 2.5 mm from the wire. In addition, the wave front loses...
stability in the longitudinal direction. The question of the degree of surface deformation has so far remained open.

![Image](image.png)

**Figure 10.** The temperature field on the surface of the liquid near the pulse-heated wire immersed in the liquid to a depth of $H = 5$ mm in the mode with PD = 0.28s, PRP = 5s at different points in time: 1 – 1.42s; 2 – 1.84s; 3 – 2.26s; 4 – 2.95s; 5 – 5.26s; 6 – 6.42s; 7 – 6.84s; 8 – 7.37s; 9 – 8.16s; 10 – 10.26s.

In the modes described above, the influence of buoyancy forces was negligible. Ascending and descending flows were formed due to continuity conditions, since in regime of thermocapillary convection the continuity equation is also fulfilled. How much fluid escaped from the heated wire along the free surface, the same should have surfaced. After turning off the heating of the wire, the surface around it is colder than at the trailing edge of the heat wave. Therefore, a return flow occurs at a lower speed. If the wire is buried a few millimeters under the free surface, then buoyancy forces are included.

Figure 9 shows the evolution in time of the temperature field over a pulse-heated wire immersed to a depth of 7.5 mm. Here it is very clearly seen that the heated liquid floating up on the free surface breaks up into separate streams. The selection of the perturbation wavelength along the longitudinal coordinate is clearly expressed. Figure 10 shows the temperature distribution on the free surface above the wire at different points in time. Shows frames of a thermal imaging film for two periods of pulsed heating of the wire. An unsteady two-dimensional plane jet rising above a heated wire (linear heat source) loses stability. Disturbances with a clearly defined wavelength develop along the longitudinal coordinate. An analogy can be drawn with the Rayleigh-Benard type of instability of a horizontal layer heated from below. An interesting feature is the development of upward flows during the next impulse with a shift to the place of lowering flows in the previous cycle of the periodic process. This can be seen in the thermal imaging frames in Figure 10 on the left and the temperature distributions on the free surface above the wire in
Figure 10 on the right. This feature is observed over a sequence of many periods (Figure 11). As can be seen in Figures 9 - 11, the process of the formation of spatial flow forms has a quasiperiodic three-dimensional character.

4. Conclusion
The evolution of the spatial form of thermal waves generated by a pulse-heated wire located on the free surface of a layer of ethanol is studied. When pulsed heating a wire located on the surface of a liquid, a heat wave is generated that propagates perpendicular to the wire along the surface of the liquid. The dependences of the wave velocity are obtained depending on the distance from the wire and depending on the heating parameters. It is shown that for short pulses of low power the flow has a purely thermocapillary nature. The processes of generation and attenuation of disturbances of a thermal gravitational-capillary nature are studied. At the same heat pulse power, the velocity and propagation distance of a disturbance of a thermal gravitational-capillary nature are lower than in the case of a thermocapillary flow. This is explained by the fact that in the case of gravitational-capillary flow, hot thermals, before they surface, lose some of the energy to overcome viscous friction and due to heat transfer to the surrounding fluid. The formation and propagation of thermocapillary waves has a strictly deterministic character. In the case of the generation and propagation of gravitational-capillary waves, coherent spatial structures first appear, and then the process becomes chaotic, due to the instability of pop-up extended thermals.

Acknowledgments
This research was realized under the project III.18.2.5, number of state registration AAAA-A17-117022850021-3/

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