Parameters of temperature disturbance triggering the propagation of the quench front on an extremely overheated surface

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Abstract. The results of computational experiments simulating the triggering of the quench front propagation on the superheated vertically oriented metal plates are presented. The plates are quenched by a gravitationally flowing down liquid nitrogen film. The temperature of the test samples at the beginning of the process was higher than the critical temperature and the Leidenfrost temperature, which means that direct long-term liquid-solid contact is impossible. For this reason, the front is initially motionless. As a result of numerical simulation, a dynamic pattern of the quench front propagation on a high-temperature surface was obtained. Analysis of the results allowed to find the realistic values of heat sink into the cooling medium, as well as the parameters of the local temperature disturbance, its spatial extent and amplitude, at which the conditions are created for triggering the process of quench front propagation on the high-temperature surface. Direct comparison of the numerical simulations results with experimental data on the velocity, geometry of the quench front and on the dynamical pattern of the process confirmed the reliability of the results obtained.

1. Introduction
One of the promising and actively applied methods of intensive cooling of overheated surfaces is cooling with the gravitationally flowing down liquid films. The least studied issue, which has not yet been resolved, is the issue of the contact of the coolant with the surface at temperatures significantly exceeding $T_{th}$ (thermodynamic limit of superheat temperature). From a thermodynamic point of view, at such a temperature level, direct liquid-solid contact is impossible. As far as we know, today there is no reliable knowledge about how and when at a very high surface temperature the first stable liquid-solid contact occurs and how the dynamic pattern of the expansion of the local contact area looks like. Although a large number of experimental and theoretical works have been devoted to the study of various aspects of the quenching phenomenon, many issues remain open.

In addition to theoretical interest, the research in this area has obvious practical value. The study of quenching regularities is important for solving the problems of safety of nuclear reactors, for metallurgy, for cryopreservation of biological tissues, for ultrafast cooling of high-performance graphics processors and others powerful electronics.

The heat transfer mechanism during quenching, the effect of the surface structure on the quenching efficiency, the quench front initiation mechanism are still poorly understood due to the complexity of the physical pattern of this essentially non-stationary phenomenon.
In present work, a number of computational experiments were carried out to determine the parameters of the local temperature disturbance, its spatial extent and amplitude, at which the conditions are created for triggering the process of quench front propagation on the high-temperature surface. Results are presented for a technically smooth thin copper slab and for a multilayer copper slab with a structured capillary-porous coating.

2. Numerical simulation

In this paper, a numerical model of quenching by a flowing down film of a cryogenic fluid (LN$_2$) for vertically oriented smooth and capillary-porous-coated copper plates is implemented. The results of computational experiments are shown in comparison with the experimental data presented in work [1] for a smooth surface and in [2] for a surface with a structured capillary-porous coating. As a cooling medium, we used a downward flowing liquid nitrogen film LN$_2$ at atmospheric pressure on the saturation line. In the case of the coated surface, the quenched object was a high-temperature vertical slab consisting of four layers with a total thickness of 3.595 mm. The thickness of the copper layer is 2.5 mm, the size is $55 \times 80$ mm. The slab was heated by a direct current passing through a constantan foil with a thickness 0.025 mm. A three-dimensional capillary-porous coating 0.57 mm thickness was created on the surface by the method of directed plasma spraying. A bronze powder was used for spraying. The experimental setup and experimental parameters are presented in detail in [1, 2]. The initial temperature of the sample under study, $T_0 = 218$ K, was higher than the $T_{LFP}$ (Leidenfrost temperature) and even higher than the critical temperature $T_c$. At such high temperatures, direct long-term liquid-solid contact is impossible from the standpoint of thermodynamics. The film Reynolds number was $Re = 350$. Analysis of high-speed video recording showed that the quench front at the first stage of the process is located above the upper boundary of the high-temperature specimen and its velocity is zero. Heat transfer at this stage occurs in the regime of turbulent free convection in the vapor phase with a very low heat transfer coefficient. While the front is still immobile, thermocouples begin to show that the surface temperature begins to decrease from a certain moment faster than it would decrease in the regime of turbulent free convection. The reason for this phenomenon is unknown, since nothing has changed visually - the front still located over the upper boundary of the plate. We assumed that at the moment when the surface temperature begins to decrease faster than in the free convection mode, a concave temperature disturbance arises at the upper boundary of the plate as a result of the local contact of the liquid with the superheated surface. The task was to find the parameters of this disturbance capable of starting the process of propagation of the quench front. In addition, the disturbance parameters should be such that, as a result, the entire dynamic pattern of the process, the front velocity and its geometry coincide with the experimental data. It can be seen from the Fig. 1a and Fig. 1b that 2D wedge-shaped quench front propagates along the hot surface after initiation the liquid-solid contact.

A numerical simulation of the observed quenching phenomenon was implemented. The direct two dimensional non-steady problem of heat conduction was solved numerically. The multilayer slab was considered as a thin slab with an effective properties and uniform in z-direction temperature. Estimates of the temperature change in the z-direction were made (Biot's number, Burggraf's approach [3] and direct calculation). The temperature estimates made it possible to conclude that the temperature distribution in the z-direction under the conditions of our problem is insignificant, and therefore, to simulate the dynamics of front propagation, we can solve the 2D heat conduction problem. Changes in temperature fields in space and time are described by a non-steady differential heat conduction equation:

$$\frac{\partial T_y}{\partial \tau} = \alpha \left( \frac{\partial^2 T_y}{\partial x^2} + \frac{\partial^2 T_y}{\partial y^2} \right) - \frac{1}{\delta_x \rho c_p} q_y (T_y)$$  (1)
Where \( a = \frac{\lambda_h}{(c_h \rho_h)} \) is thermal diffusivity of test sample; subscript \( h \) refers to the object to be cooled; \( T \) is the temperature, \( \tau \) is the time, and \( \delta_h, c_h, \rho_h \) are the total thickness of the slab, the efficient specific thermal capacity, average density of the slab material. The computational scheme is based on the method of transverse directions [4] and after reducing the differential equation to finite-difference equation can be represented in 2D case as follows:

\[
\begin{align*}
(T_{x,y}^{n+1})_i - T_{x,y}^n &= a(T_{x+1,y}^{n+1/2} - 2T_{x,y}^{n+1/2} + T_{x-1,y}^{n+1/2})/h_x^2 + a(T_{x,y+1}^{n+1/2} + 2T_{x,y}^{n+1/2} + T_{x,y-1}^{n+1/2})/h_y^2 + f_{x,y}^{n+1/2} \\
(T_{x,y}^{n+1})_i - T_{x,y}^n &= a(T_{x+1,y}^{n+1/2} - 2T_{x,y}^{n+1/2} + T_{x-1,y}^{n+1/2})/h_x^2 + a(T_{x,y+1}^{n+1/2} + 2T_{x,y}^{n+1/2} + T_{x,y-1}^{n+1/2})/h_y^2 + f_{x,y}^{n+1/2}
\end{align*}
\]

Here

\[ f_{x,y}^{n+1/2} = 1/(\delta_x \delta_y \rho_h) (q_x - q_y (T_{x,y}^n)), \]

\( \tau \) is time step, \( \tau' = \tau/2; h_x, h_y \) are the grid steps in the \( x \) and \( y \) direction, respectively. An additional source term \( q \) is introduced to take into account the heat flux removal into the cooling media. The temperature dependence of the heat sink into the cooling media in a substantially unsteady quenching process is unknown. We found this dependence by trial and error method by setting the condition for the coincidence of the calculated cooling curve \( T_{\text{calc}}(\tau) \) in the point of thermocouple location with the experimental thermogram \( T_{\text{exp}}(\tau) \). The condition of satisfactory coincidence of the calculated velocity of the quench front with the experimental data was used as a criterion for the correctness of the solution. As a result of solving the system of equations together with the initial and boundary conditions, we obtain a temperature field in a 2D domain corresponding to the slab size, at different time layers. The analysis of the evolution of the temperature field allows one to obtain a dynamic pattern of the running quench front.

### 3. Results and discussion

Fig. 1 clearly demonstrates the features of the dynamics of the quench front propagation on the modified surface of the copper plate. The surface modification was carried out by the method of directed plasma spraying. The presented fragments of a high-speed digital video [2] shows that the shape of the front is essentially two-dimensional, wedge-shaped. Within about 100 seconds from the start of the process, the quench front is immobile, then it begins to move. Observation with a high-speed video camera Phantom v7.0 allows drawing a conclusion about the features of the flow pattern and the dynamics of cryogenic quenching. During a short time interval, the front accelerates and then moves at an almost constant velocity.

When the quench front is immobile, the temperature of the entire surface is uniform. For this stage of the process, equation (1) can be solved analytically, since the second derivatives in the equation are zero:

\[
T(\tau) = (T_0 - T_i) e^{-\frac{\alpha_{\infty}}{\delta x^2 \rho h}} + T_i, \tag{4}
\]

where \( \alpha_{\infty} \) is the heat transfer coefficient for turbulent free convection. \( T_0 \) corresponds to the initial surface temperature and \( T_i \) corresponds to the temperature of the cooling media.

At the top of Fig. 1a is presented the so-called "cooling curve" or experimental thermogram or temperature-time history obtained using the thermocouple technique. We can assume that at the moment when the experimental thermogram begins to deviate from the solution with turbulent free convection, the first local contact of the liquid with the high-temperature surface occurs. The surface temperature at this moment is about 150 K, which is significantly higher than the Leidenfrost temperature. Liquid-solid contact under these conditions is thermodynamically impossible, because the liquid instantly turns into the vapor. Hypothetically, such a liquid-solid contact at an extremely high temperature can arise as a result of local contacts of the ridges on a complex modified surface with wave crests at the liquid-vapor interface near the upper boundary of the superheated test sample.
For a falling down liquid film, the wave flow is energetically more favorable than a flow with a smooth surface, it was shown in [5]. The possibility of direct liquid-solid contacts at such high temperatures is evidenced by the experimental data obtained by Bradfield [6], where the detection of an electrical contact between a water droplet and a solid showed that at a surface temperature much higher than $T_{tls}$, a direct liquid-solid contact was observed. Experimental evidence for the presence of liquid-solid contacts in the film boiling regime was also presented by Yao and Henry [7].

As a result, such a contact creates a concave temperature disturbance with an amplitude $A_T$ and a spatial extent $\delta_T$ in a temperature field.

Figure 1. a - Cooling curve $T(\tau)$ and cooling rate $|dT/d\tau|$ for the copper slab with a structured capillary-porous coating. Lower graph: Dynamics of the quench front. Experimental data and numerical simulation results. b - The pattern of quench front propagation on a smooth surface. Simulation results are shown with the white dashed lines.

Heat from adjacent parts of the overheated sample begins to flow into the region with a low temperature. When the local heat flux into the cooling media exceeds the heat flux into the local area with a low temperature, this area begins to expand, and eventually develops into the running quench front. Fig. 1a presented the experimental thermogram in comparison with the analytical solution for
turbulent free convection and the cooling rate (dT/dt). Lower graph shows the numerical simulations results on dynamical pattern of the quench front propagation. Shown are the quench front coordinates observed in the cryogenic experiment in comparison with those found in the process of numerical simulation.

As a result of a series of computational experiments, the parameters of the temperature disturbance that can initiate the propagation of the quench front were found: the amplitude of temperature disturbance $A_T \approx 62$ K and the spatial extent $\delta_T \approx 1$ mm. The spatial extent of the $T$-disturbance correlates well with the size of the inhomogeneities on the modified surface with the structured capillary-porous coating. The spatial extent of the $T$-disturbance, which can trigger the propagation of the quench front on the hot smooth surface, $\delta_T \approx 0.1$ mm. The dynamic pattern of quench front propagation obtained numerically with these parameters correlates satisfactorily with the pattern observed in the cryogenic experiment [2] with a capillary-porous-coated surface, (Fig. 1a), and the pattern, observed in the experiment [1] with a smooth surface, (Fig 1b). The velocity of quench front movement along the surface, obtained numerically, correlates well with the experimental data obtained by processing high-speed video recording (lower graph 1a). Figure 1b also demonstrates satisfactory agreement between the calculated shape of the quench front and that observed in the experiment.

4. Conclusion
The results of computational experiments simulating the triggering of the quench front propagation on the superheated vertically oriented metal plates cooled by a gravitationally flowing down liquid nitrogen film are presented.

The appearance of waves of large amplitude, comparable with the vapor film thickness, can initiate contacts between the liquid and protrusions on an extremely superheated solid even if the average temperature of the solid is much higher than the Leidenfrost temperature or the critical one. The geometry of the protrusions can also be the prime factor influencing the occurrence of contacts, which allow accelerate the quenching process and, thus, shorten the total quench time.

The analysis of the results allowed us to find the realistic values of heat flux into the cooling media, as well as the parameters of the local temperature disturbance, its spatial extent and amplitude, at which conditions are created for triggering the process of propagation of this disturbance on a high-temperature surface. The spatial extent of the temperature disturbance, which can trigger the process of propagation of the quench front, is comparable to the size of the inhomogeneities of the surface.

Direct comparison of the numerical simulations results with experimental data on the velocity, geometry of the quench front and on the dynamical pattern of the process confirmed the reliability of the results obtained. To construct a more advanced physical model of the quenching phenomenon, it is promising to study the initialization of the quench front on the microscale.

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