Peculiarities of the initialization and dynamics of the quench front on an extremely overheated plate cooled by a falling film of a cryogenic fluid

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Abstract. Quenching is a generally accepted term for the process of rapid cooling of a solid body that is superheated above the temperature of the thermodynamic limit of a liquid superheat. The paper presents the results of computational experiments simulating the quenching of a high-temperature vertical copper plate by a gravitationally flowing film of liquid nitrogen. The peculiarities of the initialization and dynamics of the quench front in the transition process are investigated. The initial temperature of the test sample was higher than the Leidenfrost temperature and even higher than the critical temperature, which excluded the possibility of long-term stable liquid-solid contact. An improved numerical model of quenching is implemented, which assumes at the time of the quench front initialization an unsteady local contact of the liquid with the extremely overheated surface in the vicinity of the upper boundary of the heater. A dynamic pattern of the running quench front was obtained numerically, which satisfactorily correlates with that observed in cryogenic experiments by the high-speed digital video camera. The reliability of the results obtained numerically is confirmed by direct comparison with experimental data on the velocity and the shape of the quench front.

1. Introduction
Rapid cooling of high-temperature solids in saturated and subcooled liquids (quenching) is actual for many technologies and attracts the attention of researchers. Studies affecting the theory of heat transfer during unsteady cooling of high-temperature bodies are carried out in research centers in Japan, USA, Korea, India, Russia, Israel, Netherlands, Great Britain, and Germany. Several main research areas are devoted to this problem: cooling of high-temperature bodies in a bulk of liquid; jet and spray cooling; cooling by flowing down liquid films; and the interaction of liquid droplets with a superheated surface.

The interest in the quenching of extremely overheated surfaces is mainly due to its role in light water reactor safety. A comprehensive understanding of this transient process is required to analyze emergency in core cooling systems after a loss of coolant accident (LOCA) in a nuclear reactor. Knowledge of the quench front velocity and the total time of the transient process is required for solving practically important problems of the safety of the nuclear reactors.

A similar problem arises when the fast cooling of the superconducting magnets is necessary at a local loss of the superconducting state and the normal zone propagation. A clear understanding of quenching peculiarities is required for the cooling of high-power electronics, advanced spacecraft thermal control, cryogenic, and other industrial processes.
The film flows of liquids, being an effective method of heat and mass transfer, are widely used in various modern heat exchangers. Evaporation and boiling in thin liquid films ensure a high heat transfer rate at low coolant flow rates and low-temperature heads. The urgent problem is the creation of effective compact film cooling systems for microelectronic equipment and high-performance processors, whose speed and durability depend essentially on the power dissipation efficiency. It is promising to use cryogenic liquid films as a coolant in technologies using high-temperature superconducting ceramic elements.

Due to the complexities in the physical pattern of quenching from phase transition to chaotic processes, the mechanism of heat transfer during quenching is still not sufficiently understood. Different cooling modes such as film boiling, transient from film to nucleate boiling, and nucleate boiling coexist on the surface, and these modes change with time during quenching.

To our best knowledge, no information is available on when and how the first stable liquid-solid contact occurs at extremely high surface temperature and how the local contact area begins to extend. Here we have more models and hypotheses than authentically established facts. Despite a large number of published papers devoted to the study of different aspects of the quenching phenomena, many questions remain open and there is no generally accepted theory of the quenching process.

Analysis of the literature reveals insufficient knowledge of heat transfer processes during quenching, the mechanism of quench front initialization, and the influence of the surface structure on the quenching efficiency.

The paper presents the results of computational experiments simulating the quenching of a high-temperature vertical copper thin slab by a gravitationally flowing film of liquid nitrogen. Special attention is paid to the peculiarities of the quench front initialization.

2. Cryogenic quenching experiment and numerical simulation

Fragments of high-speed video recording of cryogenic quenching experiment, peculiarities of the flow pattern, and dynamics of the quench front propagation over a surface with capillary-porous coatings are shown in figure 1. The observation was performed by the high-speed digital video camera Phantom v7.0. The experimental technique is described in detail in the article [1].

![Figure 1](image-url)

**Figure 1.** Visualization of quenching dynamics. Fragments of a high-speed video camera recording. a – $\tau = 0.5$ s, ($\tau$ is the time from the start of rapid quench front propagation); b – 1.5; c – 3.5 s.

In the present study, the falling film of liquid nitrogen on the saturation line at atmospheric pressure has been considered as the quenching media. The quenched object was the hot vertical multilayered slab composed of four layers of different thicknesses. The copper slab with a thickness of $\delta_3 = 2.5$ mm and $55 \times 80$ mm in size was heated by a constantan foil of a thickness $\delta_1 = 0.025$ mm, through which a direct current was passed. The foil was firmly pressed against the back of the slab. Between the copper layer and the constantan foil, there was a dielectric spacer made of oxidized duralumin of the thickness $\delta_2 = 0.5$ mm. The three-dimensional capillary-porous coating on this surface was applied by directional plasma spraying. The average thickness of the structured capillary-porous coating was $\delta_4 = 0.57$ mm. The total
slab thickness was $\delta_0=3.595$ mm. The quenching media was falling film of liquid nitrogen LN$_2$, the film Reynolds number $Re=350$.

The initial temperature $T_0$ of the test sample was taken to be higher than the Leidenfrost temperature when a long stable liquid-solid contact is thermodynamically impossible. Visual observation and high-speed video recording revealed that the quench front during the first stage of the process is immobile and located over the upper boundary of the superheated sample. This is the stage of quench front stagnation, the quench front velocity $U_f = 0$. During this stage, the high-temperature surface is cooled at free turbulent convection in the vapor phase with a low heat transfer coefficient, and, therefore, with a low cooling rate.

From figure 1 it is clear that essentially two-dimensional wedge-shaped quench front moves along the surface at a certain velocity after restoring the liquid-solid contact.

Objectively, the problem considered is an inverse one, since the boundary condition at the cooled surface is unknown. Factually, the direct 2D non-steady problem of heat conduction considering the real four-layer slab as a thin plate with a temperature, uniform in the $z$-direction, and effective properties was solved. The temperature estimates according to the Burggraf approach [2] in various heat transfer modes allow concluding that the temperature distribution in the $z$-direction is negligible in the present situation. Thus, we can assume that the surface temperature of the slab is slightly different from the thermocouple readings. We have implemented a numerical simulation of the observed transient phenomena. Spatial and temporal changes of the temperature fields in the heater are described by the non-stationary differential equation of thermal conductivity:

$$\frac{\partial T_h}{\partial \tau} = \alpha \left( \frac{\partial^2 T_h}{\partial x^2} + \frac{\partial^2 T_h}{\partial y^2} \right) - \frac{1}{\delta_h c_h \rho_h} q(T_h)$$

(1)

Subscript $h$ refers to the heater. Here $T$ is the temperature, $\tau$ is the time, $\alpha$ is thermal diffusivity, and $c_h, \rho_h, \delta_h$ are the efficient specific thermal capacity, the average density of the slab material, and the total thickness of the slab, respectively.

The relevant differential equation is reduced to the finite-difference equation. The construction of a computational scheme is based on the method of transverse directions [3]. Equation (1) accompanied by the initial and boundary conditions allows simulating the evolution of the temperature fields over time in the 2D computational domain and receiving as a result the dynamical pattern of the moving quench front. To take into account the cooling effect, an additional source term (heat sink into the liquid nitrogen) with an unknown surface heat flux $q$ is introduced, whose value is determined by trial and error method. In this case, the condition is set for the coincidence of the calculated cooling curve with the experimental thermogram.

This approach allows getting quite interesting results satisfactorily describing the experimental data on quench front propagation. The main objective of the present numerical simulation is to develop a theoretical model to describe the dynamic pattern of the quenching phenomenon.

3. Results and discussion

Until the moment of the first liquid-solid contact, the equation (1) is solved analytically with a heat transfer coefficient corresponding to the regime of turbulent free convection. Cooling until the moment of quench front initiation is described by the function:

$$T(\tau) = (T_0 - T_l) \exp(-\alpha_{free\ turb\ con}\tau (\delta_0 c_0 \rho_0)) + T_l,$$

(2)

which is an analytical solution of the equation (1) at the absence of the running quench front. Here $T_0$ is the initial surface temperature, and $T_l$ is the liquid temperature, $\alpha_{free\ turb\ con}$ is the heat transfer coefficient at turbulent free convection in the vapor phase.
The thermocouple technique allows for a detailed analysis of the surface temperature-time history. The deviation of the experimental cooling curve from the free convection mode solution (figure 2a) after reaching the temperature $T_{1st\text{-}s\text{. cont}}$ means the beginning of the quench front incipience at this point.

![Diagram](image)

**Figure 2.** Temperature-time history during quenching $T(\tau)$ and its derivative $|dT/d\tau|$ for the test specimen with a capillary-porous coating. 1 – calculation with stationary local liquid-solid contact. 2 – calculation with non-stationary local liquid-solid contact. Lower diagram: Dependence of the quench front coordinate on time.

A small local wet patch on a superheated surface generates the appearance of a concave temperature disturbance in the temperature field. If the local heat flux into the LN$_2$ exceeds the heat flux due to the non-stationary heat conduction from adjacent parts of the superheated specimen to the high intensive cooling area, then this area will expand. Finally, the concave temperature disturbance eventually develops into the moving quench front.
Figure 2a shows the experimental data on temperature-time history in comparison with the present numerical simulations results. Figure 2b shows the results of a computational experiment simulating the quench front dynamics. The quench front runs the distance of 50 mm in ~3.5 seconds. The dynamic pattern of quench front propagation obtained numerically satisfactorily correlates with that observed in the experiments.

The abrupt temperature drop indicates a rapid increase in heat flux which reaches the maximum approximately at the maximum slope of the $T(\tau)$ curve. The arrow in figure 2a indicates the maximum slope of the cooling curve. The subsequent slow drop of the temperature is associated with a single-phase convection regime. The analysis and comparison of experimental data with the analytical solution at free convection mode showed that the temperature of quench front incipience can be significantly higher than the thermodynamic limit of superheat for liquid nitrogen $T_{tls}$.

The first decreasing part of the $T(\tau)$ curve corresponds to free turbulent convection mode with low heat flux values. We assume, that the deviation of the experimental cooling curve from the free turbulent convection mode solution after reaching the temperature ~150 K means the occurrence of the first local liquid-solid contact, the beginning of the quench front incipience at this point. The cooling acceleration from this moment means the appearance of a small local "wet patch" near the upper part of the heater, on initially dried surface. There is no other reason for increasing the cooling rate, because the boundary of the liquid nitrogen film is above the upper edge of the slab, and, the quench front is immobile until the moment $\tau \sim 103$ s. Information is obtained from the analysis of synchronized measurement of the test sample temperature and high-speed video recording of a transient process. The onset of a hypothetical local wet patch could be due to the presence of the asperities on the cooled surface and the waves on the liquid-vapor interface. In work [4] it was shown that for a falling-down liquid film, the wave flow is energetically more favorable than flow with a smooth surface.

In present work, an improved numerical quenching model is implemented (calculated curve 2 in figure 2a), which assumes at the time of the quench front initialization an unsteady local contact of the fluid with the high-temperature surface in the vicinity of the upper boundary of the heater. The model with a non-stationary liquid-solid contact better describes the experimental data compared with the approach of a stationary local contact (curve 1 in figure 2a). The frequency of the contacts corresponds to the frequency of the waves in the falling cryogenic liquid film. The surface microstructure can be the most important factor triggering the liquid contact with an extremely overheated surface. To accelerate quenching, to create ultra-fast systems for cooling high-temperature bodies, it is promising to look for ways to organize local contact of a liquid with a surface at the highest temperatures.

The set of obtained experimental and numerical simulation results makes it possible to propose a hypothesis on conditions of initialization of the quench front. The presence of the waves on the liquid-vapor interface and the protrusions on the complex microstructured surface causes destabilization of the vapor film. A local liquid-solid micro-contact appears even though the average integral temperature of the sample is much higher than the thermodynamic liquid superheat limit $T_{tls}$. This phenomenon is, in general, contrary to the thermodynamics. From a standpoint of thermodynamics, contact at such high temperatures is impossible, because the liquid instantly turns into the vapor. However, in favor of the possibilities of this paradoxical phenomenon are the experimental data reported by W.S. Bradfield in [5], where the study of high-speed video recording and the detection of the appearance of the electrical contact of a water drop with a solid body, showed that at a surface temperature much higher than the homogeneous nucleation temperature there was direct liquid-solid contact. Experimental evidence of liquid-solid contacts in the film boiling regime was reported also by Yao & Henry [6].

In our calculations, the liquid-solid contact at temperatures above the thermodynamic limit of liquid superheat is confirmed by the deviation of the cooling curve from the calculation for free turbulent convection. It should be noted that on a smooth surface without coating, the initiation of the quench front occurs when the surface temperature drops to the temperature $T_{tls}$ [1].
Conclusion
The numerical simulation results in comparison with the experimental data on cryogenic quenching by the falling liquid nitrogen film of a high-temperature vertical copper slab with the capillary-porous coating are presented. An improved numerical model of the cryogenic quenching process is implemented, which assumes at the time of the quench front initialization an unsteady local contact of the fluid with the extremely overheated surface. The peculiarities of the initialization and dynamics of the quench front in the transition process are investigated. For a falling-down liquid film, the wave flow is energetically more favorable than flow with a smooth surface. The emergence of waves of large amplitude, comparable with the thickness of a vapor film, can lead to short-term discontinuous contacts between a liquid and asperities of a strongly superheated solid. Local liquid-solid micro contact appears even though the average integral temperature of the sample is much higher than the thermodynamic liquid superheat limit $T_{ls}$. The microstructure of the surface, the geometric aspects of the protrusions can be a prime factor affecting a triggering the liquid-solid contact at extremely high temperatures, which makes it possible to accelerate the quenching process.

The reliability of the results obtained numerically is confirmed by direct comparison with experimental data on the dynamics of the quench front, the velocity, and the shape of the front. Realizing the full potential of cryogenic quenching requires a detailed understanding of the physics governing the process. To create a more advanced model of a quenching, it is necessary more fundamental experimental and computational studies, for example, studying the initialization of the quench front at the micro-scale.

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