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Heat transfer during quenching of high temperature surface by the falling cryogenic liquid film

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ABSTRACT

Contact between a liquid and an extremely superheated solid surface is restored during quenching. The cryogenic experiment and numerical simulation were performed to study the peculiarities of heat transfer during quenching of hot vertical copper plate being much higher than the Leidenfrost temperature by the falling film of liquid nitrogen. An anomalous behavior of heat transfer has been found in the vicinity of the quench front. The results revealed that the maximum heat flux into the liquid during quenching is significantly higher than the average in the quasi-stationary conditions. The dynamic pattern of quench front propagation has been obtained in the numerical experiment. It was found that the quench front initialization occurs after lowering the surface temperature to the thermodynamic limit of superheat for liquid nitrogen. The correlation to determine the time of quench front stagnation is proposed. The numerical model allows us to quantify the quench front velocity and temperature fields in the heater, which are variable in space and time. The reliability of the simulation results has been confirmed by direct comparison with the experimental data on the quench front geometry and velocity as well as on the surface temperature change over time.

1. Introduction

Rapid cooling of superheated surface is a transient process known as a quenching. The interest in quenching is caused mainly due to its role in the light water reactor safety. Comprehensive understanding of this transient process is required for analysis of emergency in core cooling systems after a loss of coolant accident (LOCA) in a nuclear reactor, for metallurgy.

at metal treatment, in the cooling of high-power electronics, for thermal control of advanced space craft, for cryogenic and other industrial processes. There are situations where it is necessary to cool rapidly the superconducting magnets at a local loss of the superconducting state and the normal zone propagation.

The physical pattern of quenching phenomenon is extremely complex. Quenching is a non-stationary process. A liquid phase cannot exist beyond the temperature T_{tls} (maximum thermodynamic limit of superheat). A phase transition occurs when a liquid contacts with a high temperature surface.

The vapor layer emerging on the surface prevents the contact between the solid and liquid phases. The rate of heat removal from the surface in this case is relatively small due to the low thermal conductivity of the vapor layer that acts as an insulator. As the surface cools off, the vapor film reaches the point where it can no longer be sustained. At this point the vapor film collapses and the solid-liquid contact is reestablished that increases the heat transfer coefficient (HTC) sharply. The velocity of the three-phase contact line is called the quenching velocity, or rewetting velocity. The temperature at the solid-vapor-liquid contact line is designated as the rewetting temperature T_r, or quenching temperature. When the temperature drops below T_r, heat transfer can be increased by as much as two orders of magnitude. This stage is characterized by violent bubble boiling with a maximum cooling rate. The final stage of quenching occurs when the surface temperature reduced below the boiling point of the quenchant. During the last stage, nucleate boiling stops and heat transfer occurs directly by surface-liquid contact. The rate of heat removal is low in this case.

A physical mechanism of heat transfer in the area of dynamical three-phase contact line is insufficiently understood up to the present day. The quenching phenomenon involves a great number of extremely complicated processes: fluctuations; chaotic processes in the vicinity of quench front; intermolecular forces; non-equilibrium processes; hydrodynamic instability on the liquid-

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vapor interface; phase transition; dynamical contact angle and so on. The problem is related to the Leidenfrost phenomenon. While the fluid droplets levitation was discovered 250 years ago, the fundamental physics of this phenomenon has not been studied yet. The Leidenfrost temperature is defined historically as the surface temperature corresponding to the highest droplet evaporation time. However, many researchers employ presently the term Leidenfrost phenomenon to describe the boundary between transition boiling and film boiling of a large liquid volume.

There is a large number of experimental and theoretical works, where an attempt was made to understand various phenomena associated with the quenching [1–14]. Some works are devoted to the influence on the quenching dynamics of various factors such as the film flow rate, the subcooling of the fluid, the initial temperature, different geometries of the surface, heat capacity, thermal conductivity of the surface and so on. Some works are devoted to the effect of quenching medium on the heat transfer efficiency. A systematic comparison of cryogenic quenching experiments with liquid nitrogen and liquid hydrogen has been presented in the paper [15].

Because of the complexity and non-linear nature of the quenching phenomena the possibilities of analytical solution of the problem are limited by the simpliest cases. A comprehensive state-of-the-art review of the available analytical models is presented in paper [3]. The basic estimated correlation for rewetting front velocity in one-dimensional formulation is known as the Yamanouchi model [1]:

$$V_{fr} = \sqrt{\alpha_w \lambda_h / \delta_h} \Big/ (c_h \rho_h) \times (T_r - T_l) \Big/ \sqrt{(T_0 - T_r)(T_0 - T_l)} \tag{1}$$

where: T_r is the temperature at the boundary of the wetting front; T_0 is the initial temperature of the overheated surface; T_l is the liquid temperature; c_h is the specific thermal capacity; λ_h is the thermal conductivity; ρ_h is the density; δ_h is the surface thickness. Subscript h refers to the heater. In this model, the heat transfer coefficient in the wetted area α_w is assumed to be a some constant value, and in the drained region it equals zero. The calculation results have inevitably qualitative character only because the model contains very strong assumptions (in particular, the heat flux on dry area sets to zero). An essential disadvantage of similar models is also the uncertainty of parameters α_w and T_r, the absence of the quench front stagnation and initialization stages. However, we believe it is very important to take into account the finite length of the surface and to describe the initial stage of the transient process. Most of the quenching models developed in the last 50 years require the assumption of an a priori value for the wet-side heat transfer coefficient α_w and the rewetting temperature T_r as the input parameters. However, the uncertainty of these parameters is too high, therefore such models predicts the front velocity with the partial success only. It should be noted that all existing theoretical correlations give an infinite value of the front velocity at the initial surface temperature equal to the rewetting temperature T_r, a singularity in Eq. (1) arises when $T_0 = T_r$. Moreover, there is an internal contradiction in the correlation (1). The front velocity is determined by the initial surface temperature, while the liquid cannot come into the contact with the surface until the temperature drops to T_r, i.e. the quench front is immobile within this time interval. There is no consensus upon the determining method for T_r and α_w despite the great number of attempts, which leads to different predictions of the quench front velocity for the same liquid-solid systems.

The main goal of most studies on quenching is to find a way to reduce the total quench time. Recently, there are many works [10–12] that investigate the possibility of using nanofluids instead of traditional fluids and nanoporous surface [13] in order to intensify heat transfer processes that probably will also allow to improve the quenching efficiency. The paper [14] presents the effect of the surface characteristics (roughness, wettability, and porosity) on the boiling critical heat flux (CHF). An experimental study of cooling in liquid nitrogen of overheated copper plate coated with a low thermoconductive coating was performing in work [24]. It is shown that the low thermoconductive coating has a significant effect on the character cooling curves and total time of plate cooling. Comparison of cryogenic flow boiling in liquid nitrogen and liquid hydrogen chilldown experiments is presented in paper [15]. The work [16] deals with the study on development of crisis phenomena in the falling liquid film at stepwise heat generation. The insulating vapor layer significantly degrades heat transfer and leads to surface dryout that causes equipment failure. The crisis development relates to the expansion of a dry spot over the surface. Reducing the heat flux initiates the rewetting process. Much attention has been devoted to transient cryogenic chill down process in horizontal and inclined pipes [17]. Rewetting model proposed by A. Dorfman [22] is applicable for semi-infinite hot plate cooled by flowing liquid film. An analytical solution for rewetting of an infinitely extended vertical slab with a uniform heating has been obtained, employing the Wiener-Hopf technique, in the Satapathy & Sahoo [23] research paper. The model assumes constant but different heat transfer coefficient for the wet and dry regions on the flooded side.

There is no doubt that such a long-continued interest in the study of the physics of quenching phenomenon reflects the lack of generally accepted theory of the process.

2. Cryogenic quenching experiments and modeling

In the present study, the falling film of liquid nitrogen has been considered as the quenching media. The quenched object was the hot vertical copper plate with a thickness of $\delta_h = 2.5$ mm and 50×75 mm in size. The experiments were done for initial temperature range from 153.7 to 201.5 K, which was beyond the thermodynamic limit of superheat T_{tls}=110 K for liquid nitrogen LN_2 [19].

2.1. Experimental setup and measurement technique

The scheme of experimental setup to study the quenching phenomena by the falling liquid film is shown in Fig. 1. Experiments are carried out with the liquid nitrogen as working fluid at saturation line (T_{sat} = 77.4 K) and atmospheric pressure. The optical cryostat in the form of a cryogenic vessel with an inner diameter of 0.2 m and the height of 1.25 m served as the working volume. For an exception of evaporation of a liquid film on an experimental plate (due to inflows of heat through a side surface of an internal volume of the cryostat) working volume is protected by the vacuum chamber and an external nitrogen shield. Constant level tank with liquid nitrogen also protected the working section from the heat inflows from the upper side of the cryostat.

The constant flow rate of liquid nitrogen to the constant level tank is provided with the set excessive pressure in an additional helium vessel with a capacity of 0.1 m^3 which is set by evaporation of nitrogen in the overpressure reservoir with a capacity of 0.04 m^3. Control of the excessive pressure in the overpressure reservoir is performed with a calibrated differential pressure transducer with temperature compensation. The pressure in the reservoir is maintained by a resistive heater which is powered by a voltage source with an external remote control. The liquid flow rate from the additional helium vessel by regulation of power supply was selected so that the volume of liquid nitrogen in a constant-level tank remained invariable within each series of experiments. The