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Influence of Structured Capillary-Porous Coatings on Cryogenic Quenching Efficiency

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Abstract : Quenching is a term generally accepted for the process of rapid cooling of a solid that is overheated above the thermodynamic limit of the liquid superheat. The main objective of many previous studies on quenching is to find a way to reduce the total time of the transient process. Computational experiments were performed to simulate quenching by a falling liquid nitrogen film of an extremely overheated vertical copper plate with a structured capillary-porous coating. The coating was produced by directed plasma spraying. Due to the complexities in physical pattern of quenching from chaotic processes to phase transition, the mechanism of heat transfer during quenching is still not sufficiently understood. To our best knowledge, no information exists on when and how the first stable liquid-solid contact occurs and how the local contact area begins to expand. Here we have more models and hypotheses than authentically established facts. The peculiarities of the quench front dynamics and heat transfer in the transient process are studied. The created numerical model determines the quench front velocity and the temperature fields in the heater, varying in space and time. The dynamic pattern of the running quench front obtained numerically satisfactorily correlates with the pattern observed in experiments. Capillary-porous coatings with straight and reverse orientation of crests are investigated. The results show that the cooling rate is influenced by thermal properties of the coating as well as the structure and geometry of the protrusions. The presence of capillary-porous coating significantly affects the dynamics of quenching and reduces the total quenching time more than threefold. This effect is due to the fact that the initialization of a quench front on a plate with a capillary-porous coating occurs at a temperature significantly higher than the thermodynamic limit of the liquid superheat, when a stable solid-liquid contact is thermodynamically impossible. Waves present on the liquid-vapor interface and protrusions on the complex micro-structured surface cause destabilization of the vapor film and the appearance of local liquid-solid micro-contacts even though the average integral surface temperature is much higher than the liquid superheat limit. The reliability of the results is confirmed by direct comparison with experimental data on the quench front velocity, the quench front geometry, and the surface temperature change over time. Knowledge of the quench front velocity and total time of transition process is required for solving practically important problems of nuclear reactors safety.

Keywords : capillary-porous coating, heat transfer, Leidenfrost phenomenon, numerical simulation, quenching
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