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Film boiling collapse in solid spheres immersed in a sub-cooled liquid

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ABSTRACT

The present study examines the thermal reaction phenomenon associated with the penetration of a hot metal solid sphere into a cold liquid reservoir. The effect of various parameters on the sudden collapse of the vapor film around the sphere is studied. A pre-heated metal sphere, made of aluminum, copper, or steel having different dimensions and a variable initial temperature, has been immersed in a varied degree of sub-cooled water. The evolution of the time-dependent temperature of the solid body has been recorded. Simultaneously, the film collapsing process has been recorded with a video camera. It is observed that above a certain sub-cooling degree, film collapsing noise (vapor explosion) and higher heat transfer rates are involved. The temperature, at which the film collapses, the quenching temperature, seems to be dependent on the sub-cooling degree, on the sphere material, and on the sphere size.

We found that the steam explosion is followed by an apparent "golf-ball" like boiling period. This occurs between the transition and the film boiling regimes. During the "golf-ball" boiling period, the sphere surface appears to be covered by a large number of concaved cells having a characteristic dimension of about 3 mm.

In order to explore the possible effect of the hot surface curvature of the immersed body, generalization of the pool boiling hydrodynamic theory for MHF conditions has been developed for arbitrarily curved heater geometries. The MHF is related to the mass rate of the vapor leaving the vapor film under these conditions. An account for the excess pressure acting on the base of the bubble arises from the excess pressure of the vapor film, due its curvature, has been added. The applicability of this model is presented for a horizontal plate, horizontal cylinders, and spheres. The model seems to fit well available experimental data for the different systems.

1. Introduction

Vapor explosion occurs when special conditions lead to sudden overheating and rapid phase transition of the liquid into vapor. The pace of vaporization and gas acceleration are of a magnitude and strength far greater than that occurs under normal boiling process. It occurs within a time frame of milliseconds, which is similar to the characteristic delay time of a self-ignition process, thereby accounting for the name "steam explosion". Vapor explosions are known in some of the major industries [1], among these are metal foundries, paper production, and transport of cryogenic liquefied gas. Depending on the system configuration, vapor explosion may occur in various geometric arrangements: hot liquid is introduced into a cold liquid surface [2–4], cold liquid is introduced into a hot liquid surface [5–7], hot and cold liquids are mixed in a stratified structure [8], and hot solid is introduced into a cold liquid surface. The latter is the subject of the present study.

Fig. 1 shows the general behavior of the heat flux from an immersed solid when introduced to a moderate sub-cooled pool. It shows how the heat flux depends on the temperature difference between the solid surface and the pool saturation temperature. When the temperature difference is low, the heat transfer is dominated by natural convection. For higher temperature difference, nucleate boiling enhances the heat transfer up to a critical value (CHF, critical heat flux) where further temperature increase results in more and more surface area that is covered by vapor films around the sphere, thermal isolators, thus reducing the heat flux (transition boiling). At a certain temperature difference (MHF, minimum heat flux, or Leidenfrost point), the sphere is wrapped by a vapor film through which the heat is transferred to the sphere

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