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A hydrodynamic model for subcooled liquid jet impingement at the Leidenfrost condition

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ABSTRACT

Stable film boiling occurs in the stagnation region of an impinging subcooled liquid jet during quenching of very hot steel plates. During film boiling the liquid is separated from the surface of the plate by a continuous vapor layer. The minimum surface temperature required to support film boiling is referred to as the Leidenfrost temperature. The present work is devoted to the development of a theoretical model for determination of vapor layer thickness, wall heat flux and wall superheat at the Leidenfrost condition. The model is developed for the jet impingement region with a strong transverse pressure gradient, i.e. within the stagnation and the acceleration regions. For convenience, the entire stagnation and acceleration region is referred to as the stagnation region in this article. Due to the pressure gradient in the impingement region, both the vapor and the liquid flow outwards from the stagnation point. In the current model, it is assumed that the Leidenfrost condition corresponds to zero shear stress at the vapor–liquid interface in the entire stagnation region. Our analytical model is developed for both planar and circular jets, assuming that the entire stagnation region satisfies this condition. The model is based on a solution of the momentum equation in the vapor layer, and the energy equation in the liquid. For a planar jet, the predicted vapor layer thickness is in good agreement with the experimental data of Bogdanic et al. [1]. A vapor film thickness of 8 ± 2 μm for stable film boiling close to the Leidenfrost state has been measured, while the current model predicts a film thickness of 6.31 μm at the stagnation point for the same conditions. The wall heat flux is under-predicted by about 5–47% compared to the experimental data available in the literature, while the wall superheat is under-predicted by up to 70%. In the present analysis, the entire stagnation region has been considered to be at the Leidenfrost condition, which is unrealistic for experiments. In the published experiments, no spatially resolved heat transfer and wall temperature measurements were performed. It is possible that in the experiments transition and film boiling might occur simultaneously in the stagnation region at the minimum heat flux condition. Hence, the wall superheat estimations in this study deviate more than the heat flux estimations. Accurate experimental data are required to validate the model over a wider range of parameters.

1. Introduction

Rapid cooling of hot metal parts with liquids is an important material processing technique. This cooling process, frequently referred to as quenching, affects the mechanical properties of the finished product. A good example is the hot rolling process used to reduce thick steel billets into thin strips. After rolling, the steel strip has a temperature of about 800–1000 °C and is then cooled at controlled rates by direct contact with water. Commonly the coolant (subcooled water) is distributed on the hot surface by an array of impinging jets (planar or circular). Since the initial temperature of the steel plate is too high for stable wetting of the surface by water, film boiling occurs in the stagnation region. In this regime, an insulating vapor blanket is rapidly formed over the hot surface. Due to the lack of direct contact between the cooling liquid and the solid, the heat transfer rate in the film boiling regime is low. The lower temperature limit of the film boiling regime is referred to as the *Leidenfrost point* (LFP) or the *minimum film boiling temperature*. The thermohydraulic condition corresponding to the LFP is referred to as the Leidenfrost condition. As the surface temperature

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