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SURFACE COOLING BY AN IMPINGING WATER DROP

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ABSTRACT

We studied, using both experiments and a numerical model, the impact of water droplets on a hot stainless steel surface. Initial substrate temperatures were varied from 50°C to 120°C (low enough to prevent boiling in the drop) and impact velocities from 0.5 m/s to 4 m/s. Fluid mechanics and heat transfer during droplet impact were modelled using a "Volume-of-Fluid" (VOF) code. Numerical calculations of droplet shape and substrate temperature during impact agreed well with experimental results. Both simulations and experiments show that increasing impact velocity enhances heat flux from the substrate by only a small amount. The principal effect of raising droplet velocity is that it makes the droplet spread more during impact, increasing the wetted area across which heat transfer takes place. We also developed a simple model of heat transfer into the droplet by one-dimensional conduction across a thin boundary layer which gives estimates of droplet cooling effectiveness that agree well with results from the numerical model. The analytical model predicts that for fixed Reynolds number (*Re*) cooling effectiveness increases with Weber number (*We*). However, for large Weber numbers, when $We >> \sqrt{Re}$, cooling effectiveness is independent of droplet velocity or size and depends only on the Prandtl number.

INTRODUCTION

A liquid droplet projected onto a solid surface undergoes rapid deformation as it spreads into a thin film. If the substrate is hotter than the drop, the liquid will cool it. Predicting the degree of cooling requires knowledge both of the area wetted by the droplet and the heat flux from the hot surface to the liquid. Analysis of this problem is both fascinating and complex, coupling free-surface flow, motion of a liquid-solid-vapour contact line, and heat transfer in the liquid drop and solid substrate.

Widespread use of spray cooling in industrial applications such as cooling of turbine blades, fire suppression by sprinkler systems, and quenching of metal castings has motivated many experimental and analytical studies of droplets and sprays impinging on a hot surface. Bolle and Moreau (1982) have reviewed much of the early literature on spray cooling of hot surfaces. Mudawar and Valentine (1989) developed an extensive set of empirical correlations to predict heat transfer rates during quenching with water sprays. Yao and Choi (1987) studied the effect of varying spray droplet diameter and impact velocity by generating mono-dispersed sprays in which all droplets had uniform diameters and velocities. Halvorson et al (1994) measured heat flux from a hot surface on which a stream of water droplets was impacting. Chandra and Avedisian (1991) photographed impact of droplets on a heated plate.

Several numerical models of droplet impact on a surface, which including heat transfer between the solid and liquid, have been developed. Zhao, Poulikakos and Fukai (1996) formulated a finite-element model of droplets deposited on solid surfaces. Their study was part of an effort to develop a novel technique for depositing solder on circuit boards, and they focused on studying molten metal droplets impacting on cold surfaces. A number of other investigators, interested primarily in spray forming or coating applications, have also modelled impact, spreading and solidification of molten metal droplets (Trapaga et al 1992; Liu, Lavernia and Rangel 1993; Waldvogel & Poulikakos 1997). Pasandideh-Fard et al (1998) simulated impact of molten tin droplets on a steel plate, and compared model predictions with photographs of impacting droplets.

Little use has been made of numerical models of droplet impact in studying cooling of hot surfaces by impinging water droplets. DiMarzo et al (1993) developed a model of cooling under a droplet evaporating while resting on a hot surface. However, in many applications, droplets do not remain on the surface after impact but rebound (for example, when the surface is facing downwards or moving). All heat transfer takes place during the brief period when droplet touches the surface, and is due to convection and conduction within the drop rather than evaporation. Though most spray cooling studies have been principally concerned with boiling heat transfer, single-phase heat transfer is often the most important mode of heat transfer. This is true when the objective of spraying an object is to keep it cool and prevent overheating so that its temperature remains below the boiling point of the liquid.

The objectives of our study were: to simulate, using a numerical model, impact of water droplets on a hot steel plate; validate results from the model by comparing them with experimental observations; and develop a simple analytical model of heat transfer during droplet impact. The analytical model allows us to scale the results of this study