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Investigation of grid-enhanced two-phase convective heat transfer in the dispersed flow film boiling regime

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HIGHLIGHTS

- Experiments were done in the RBHT facility to study the droplet flow in rod bundle.
- The presence of a droplet field was found to greatly enhance heat transfer.
- A second-stage augmentation was observed downstream of a spacer grid.
- This augmentation is due to the breakup of liquid ligaments downstream of the grid.

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ABSTRACT

A two-phase dispersed droplet flow investigation of the grid-enhanced heat transfer augmentation has been done using steam cooling with droplet injection experimental data obtained from the Penn State/NRC Rod Bundle Heat Transfer (RBHT) facility. The RBHT facility is a vertical, full length, 7 × 7-rod bundle heat transfer facility having 45 electrically heated fuel rod simulators of 9.5 mm (0.374-in.) diameter on a 12.6 mm (0.496-in.) pitch which simulates a portion of a PWR fuel assembly. The facility operates at low pressure, up to 4 bars (60 psia) and has over 500 channels of instrumentation including heater rod thermocouples, spacer grid thermocouples, closely-spaced differential pressure cells along the test section, several fluid temperature measurements within the rod bundle flow area, inlet and exit flows, absolute pressure, and the bundle power. A series of carefully controlled and well instrumented steam cooling with droplet injection experiments were performed over a range of Reynolds numbers and droplet injection flow rates. The experimental results were analyzed to obtain the axial variation of the local heat transfer coefficients along the rod bundle. At the spacer grid location, the flow was found to be substantially disrupted, with the hydrodynamic and thermal boundary layers undergoing redevelopment. Owing to this flow restructuring, the heat transfer downstream of a grid spacer was found to be augmented above the fully developed flow heat transfer as a result of flow disruption induced by the grid. Furthermore, the presence of a droplet field further enhanced the heat transfer as compared to single phase conditions. From the RBHT steam cooling with droplet injection data, it was found that a second-stage augmentation occurs under wet grid conditions at a distance of approximately 10 diameters downstream of the grid. This second-stage augmentation, which is a direct consequence of a sharp increase of the droplet interfacial area due to the breakup of liquid ligaments downstream of the grid, was not observed under dry-grid conditions nor was it observed in single-phase steam cooling tests. It was also found that the general practice of classifying a grid as wet or dry based solely on the thermocouple temperature is insufficient, as a large scatter was observed in the data.

1. Introduction

Spacer grids are a significant part of the fuel assembly design in light water nuclear reactors (LWRs). The grids maintain a constant distance between rods in a tight lattice, secure flow passage, and prevent damage of the fuel assembly from flow-induced vibration. The grid spacers also represent a flow blockage in the channel causing the flow to redevelop downstream of each grid. This has been found to induce turbulent mixing in the flow field, thus increasing

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the local heat transfer. In addition to the local enhancement of convective heat transfer, spacer grids can also induce droplet breakup in a dispersed droplet field which further improves the overall heat transfer and enhance the rate of cooling of the fuel rods.

In the present study, data from a series of two phase induced steam cooling with droplet injection tests performed at the Penn State/NRC Rod Bundle Heat Transfer (RBHT) facility over a range of Reynolds numbers and droplet injection flow rates were used in an attempt to capture the effect on the grid-enhanced heat transfer at a spacer grid as well as downstream of the grid. During a reflood transient under low flooding rate conditions, the region above the quench front is a two-phase flow mixture of bulk steam flow with entrained droplets referred to as the dispersed flow film boiling (DFFB) region. Significant research and experiments have been completed focusing on the characteristics of DFFB with several observations and measurements being attempted.

Ganic and Rohsenow (1977) derived a correlation for dispersed droplet heat transfer using results from experiments performed with nitrogen. The correlation included heat transfer mechanisms for radiation, single-phase vapor convection, and droplet wall contact. The radiation heat transfer was modeled using the model of Sun et al. (1975), while the convection heat transfer was modeled using the Dittus–Boelter (1930) correlation. The droplet wall contact heat transfer was modeled using the trajectories of the droplets in the thermal boundary layer, the drop deposition flux, and the droplet mass cumulative deposition factor.

Yao and Sun (1980) developed DFFB considering two regions. The regions include an entry region where droplet wall contact occurs and a second region with homogeneous non-slip droplet flow. The entry region was modeled using an augmented heat transfer, while the second region model was developed using low reflooding test data which indicated a dependence on the vapor velocity. Lee et al. (1982) utilized data from the FLECHT-SEASET experiments for modeling DFFB. Their analysis indicated that depending on the time and elevation, the radiation heat transfer could account for as much as 75% of the total heat flux. Additionally, the results showed that droplets will play a significant role in the heat transfer enhancement due to increased interfacial shear between the droplets and the vapor phases.

Bajorek and Young (2000) used the Thermal Hydraulic Test Facility data to show the importance of drop-wall direct contact heat transfer. Through the analysis, modifications to the Forslund and Rohsenow (1968) drop-wall contact heat transfer coefficient were made. The modifications accounted for the effect of turbulence and boundary layer thickness. Ganic and Mastanaiah (1981) studied droplet deposition from a turbulent gas stream. The model considered a dimensionless deposition velocity which is dependent on the Reynolds number and a dimensionless relaxation time. A vapor generation source function was developed by Unal et al. (1991). This source function was formulated using both single tube and rod bundle data.

The presence of a grid spacer within the DFFB region is further complicated due to the impacting of droplets on the grid spacer itself. The effects of a droplet colliding with another object have been studied for several decades. In the investigation by Engel (1955), work was conducted to try and determine the deceleration and deformation of the apex of an impinging droplet. Additionally, Engel investigated the flow that developed as a result of the impact in the radial direction. Savic and Boult (1957) derived an expression for the velocity potential within a droplet. Levin and Hobbs (1971) completed research on the crowning that is observed when a droplet impinges and expels “daughter” droplets back away from the surface in a circular pattern around the outer edges of the point of impact. During their research, Levin and Hobbs also studied the ability for these daughter droplets to conduct electricity away from the surface. The work of Stow and Stainer (1977) investigated the effects that velocity and droplet radius have on the production of secondary droplets. Similar work was done by Mundo et al. (1995) where an empirical model was developed to describe the deposition and splashing process. In their study, the initial conditions of the droplet diameter, velocity, surface tension, viscosity, and angle of impingement were studied for their effects upon a flat surface.

As one can observe, much of the work for impaction of droplets with a surface has focused on a flat surface such that the droplet diameter is smaller than the surface. However, the impact on grid spacer geometry has a surface which is of a thickness much smaller than the droplet diameter. Due to this much thinner surface, an additional cutting or slicing of the droplet is introduced. Yao et al. (1988) studied the dynamics of droplet impaction on thin heated strips. It was observed that the “rebounding” droplets that were created with impact on a large flat surface would instead flow away from the impaction site at an angle that can be related to the impact angle with the thin strip. If one now looks at the flow characteristics through a grid spacer, it can be observed that the local velocity profile is drastically altered due to the significant flow area reduction, as was studied by Campbell (2003).

The above studies do not investigate local heat transfer augmentation present at and downstream of the grid spacer. Similar to single-phase conditions investigated by Miller et al. (2011), the grid blockage ratio and Reynolds number may affect the local heat transfer which can be enhanced further due to the presence of liquid droplets. Physically, the flow is disrupted at each spacer grid as the hydrodynamic and thermal boundary layers are stripped away and must redevelop. Owing to this flow redevelopment, the heat transfer tends to significantly increase at the grid and then decrease with downstream distance from the grid. However, the extent of heat transfer enhancement at the grid and the rate of decay of the grid-enhanced heat transfer in the downstream locations depend strongly on the flow restructuring process. The latter, in turn, may vary significantly from one flow Reynolds number to another. The presence of a liquid droplet field provides additional cooling to the bulk steam flow which enhances the heat transfer compared to single-phase steam flow conditions. Furthermore, as the droplet density within the flow increases the grid spacers will provide the first locations of local quenching and liquid de-entrainment. The grid spacers appear to become a source of re-entrained droplets and a second local heat transfer enhancement is observed downstream of the grid. In the present study, data from a series of two-phase steam cooling with droplet injection tests performed at the Penn State/NRC Rod Bundle Heat Transfer (RBHT) facility over a range of Reynolds numbers and droplet injection mass flow rates were used to capture the Reynolds number and droplet effects on the grid-enhanced heat transfer at a spacer grid as well as downstream of the grid.

2. Experimental method

The experimental data employed in this study was obtained at the Rod Bundle Heat Transfer (RBHT) test facility that was designed to conduct systematic separate-effect reflood tests under well-controlled laboratory conditions. The RBHT facility is heavily instrumented that meets all the instrumentation needs for measuring the quantities characterizing the reflood transients including the dispersed flow film boiling regime. The facility shown in Fig. 1 has a full-length rod bundle with 45 heater rods that are electrically heated and four unheated corner rods to support the bundle grids and the instrumentation lines. The rods have a diameter of 9.5 mm arranged in a 7 × 7 array with a 12.6 mm pitch. Each rod is instrumented with eight 0.508 mm diameter ungrounded thermocouples. The rod bundle has seven mixing vane grids similar in design of a pressurized water reactor