Experimental Thermal and Fluid Science 94 (2018) 246–257

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

# Experimental study of droplet sizes across a spacer grid location under various reflood conditions

Yue Jin[a,*], Faith R. Beck[a], Brian R. Lowery[b], Douglas J. Miller[a], Fan-Bill Cheung[a], Stephen M. Bajorek[c], Kirk Tien[c], Chris L. Hoxie[c]

[a] Department of Mechanical & Nuclear Engineering, Pennsylvania State University, University Park, PA 16802, United States
[b] Applied Research Laboratory, Pennsylvania State University, University Park, PA 16802, United States
[c] Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC 20555, United States

ARTICLE INFO

*Keywords:*
Droplet breakup
Reflood
Rod bundle
Spacer grid
Heat transfer augmentation

ABSTRACT

Droplet size and distribution across a spacer grid in a heated rod bundle during reflood stage of a postulated design basis accident loss of coolant accident (LOCA) are studied experimentally using the Rod Bundle Heat Transfer (RBHT) test facility. Effects of spacer grid conditions, quench front location during reflood, and inlet water subcooling on droplet field are investigated. Experimental results show that the droplet sizes decrease when they pass through a dry spacer grid due to cutting and shattering effects at the lower edges of the spacer grid. On the other hand, for a wet grid, the droplet sizes downstream of the grid could be larger than those at the upstream locations, as the droplet generation mechanism, for a wet grid, is due to the formation of liquid ligaments at the trailing edge of the spacer grid and the subsequent aerodynamic breakup of these ligaments into relatively larger droplets induced by instabilities. It is found that, as the quench front propagates upward, sizes of incoming droplets increase correspondingly as a result of the droplet-vapor thermal-hydraulic interactions along the flow channels. The experimental results also indicate that larger droplet diameters occur when the inlet water subcooling is higher. Results of the present study can be utilized to develop models for droplet field behavior under accident scenarios. These models can be incorporated into nuclear reactor thermal-hydraulic safety analysis codes such as COBRA-TF and TRACE.

## 1. Introduction

Under a postulated Loss of Coolant Accident (LOCA), the primary reactor coolant system inventory is lost due to a break on the loop boundary. The nuclear fuel rods located inside the reactor pressure vessel (RPV) can be completely exposed to single-phase heat transfer between the bare rods and steam, which not only has a poor heat transfer capability but, under certain circumstances, would result in significant increase in the cladding temperatures. In order to ensure that the peak cladding temperature (PCT) is well below the regulatory limit of 1477 K (2200 °*F*), the Emergency Core Cooling System (ECCS) must provide sufficient coolant to reflood and cool the core.

During reflood, the dispersed flow film boiling (DFFB) regime is expected to occur within the rod bundle assemblies. DFFB is generally characterized by dispersed liquid droplets entrained by the superheated vapor, which is the continuous phase [1]. The mechanisms of cooling under reflood are complex and several heat transfer mechanisms occur, including laminar and turbulent convection between single-phase vapor and the rod surface, enhancement of heat transfer between liquid droplets and the superheated rod surface (dry wall contact), and radiation heat transfer from the rod to the steam, droplets and surrounding structure. During reflood, water is injected into the bottom of the active core. The quench front propagates upward along the fuel rod surface whose temperature is well above the Leidenfrost point. The quench process is accompanied by a large amount of heat transfer from the cladding to the coolant, resulting in vigorous steam generation in which the liquid droplets are often entrained. These entrained liquid droplets are expected to de-superheat the steam which, in turn, will reduce the PCT as a result. These multi-phase heat transfer mechanisms have significant effects on the evolution of the accident scenario. Many studies have been conducted in the past on the rod bundle quenching behavior and the thermal-hydraulic response. Patil et al. [2] experimentally investigated the quenching behavior in a 54-rod bundle geometry. Based on the RBHT test facility, Miller et al. [3] studied the two-phase heat transfer augmentation due to spacer grid in the DFFB regime. Significant heat transfer enhancement was observed at the

* Corresponding author.
*E-mail address:* yuj118@psu.edu (Y. Jin).

https://doi.org/10.1016/j.expthermflusci.2018.02.017
Received 20 February 2017; Received in revised form 11 January 2018; Accepted 11 February 2018
Available online 12 February 2018

downstream of a spacer grid. Riley et al. [4] experimentally studied the spacer grid thermal-hydraulic behavior in the DFFB regime. In the study performed by Mohanta et al. [5], a new correlation predicting the Nusselt number was proposed for the IAFB and ISFB regimes. Good agreement with the experimental data was achieved. Beside these experimental investigations, Seo et al. [6] numerically studied the reflood transients using MARS 1D and 3D modules. They found that the code shows a good predicting capability in calculating the rod bundle PCT.

Spacer grids are generally used in fuel assembly design in order to maintain structural integrity of the fuel rods as well as to prevent flow-induced vibrations during normal operating conditions of the reactor power plant. It has been observed from previous RBHT experiments that the spacer grid plays an extremely important role in droplet breakup and liquid re-entrainment processes under postulated reflood transients. Effects on droplet generation and subsequent heat transfer behavior significantly differ according to the different wetting conditions of the spacer grid. As reported by Srinivasan [7], dry spacer grids are found to serve as an effective method for breaking large droplets into smaller ones, thus substantially increasing the interfacial heat transfer area between the liquid droplets and the vapor. In previous studies on droplet breakup [8], the reduction in droplet size is considered to be dependent upon the Weber number ($We$) of the incoming droplets, the blockage ratio of the spacer grid, and the volume fraction of droplets in the dispersed phase as well as the energy transformation process. Once the spacer grids rewet, however, the grids appear to act as a potential source for droplets having de-entrained onto the grid surface. Under wet-grid conditions, a liquid film exists on the spacer grid surface which may be sheared off by the vapor flow to form liquid ligaments and subsequently break up into large droplets downstream of the grid. Such phenomena have been observed in the RBHT reflood tests as well as in several other experiments [9,7,10].

System analysis codes, such as COBRA-TF and TRACE, are used to simulate nuclear reactor system thermal-hydraulics. In order to better simulate the postulated accident scenarios and to provide more accurate and reliable predictions of key parameters, models for droplet generation and breakup processes as well as the subsequent heat transfer augmentation under reflood transients must be developed and incorporated into these thermal-hydraulic codes. Due to their significant effects on the nuclear reactor core thermal-hydraulic behavior, interactions between the droplets and spacer grid and the subsequent grid induced heat transfer augmentation have been the focus of investigation by previous researchers [11–15]. Recent works include Ireland et.al. [16]], Cheung and Bajorek [8], Cho et al. [10], etc.

Adams and Clare [11] carried out a photographic study of droplet grid interactions using an air-water system to provide a basis for modeling heat transfer in the vicinity of a spacer grid in the DFFB flow regime. In their study, effects of dry and wet grids on droplets were investigated. However, no correlation was proposed to relate the up- and down-stream droplets.

In the work performed by Lee et al. [12], dynamics and subsequent heat transfer augmentation induced by a droplet mist flow across a spacer grid were investigated experimentally for a 2 × 2 electrically heated fuel rod assembly. A Laser-Doppler anemometry was used to obtain the droplet size and velocity distributions as well as the flow conditions of the superheated steam. In this study, the droplet sizes were correlated to the incoming droplet Weber number for both dry and wet spacer grids.

In another study by Sugimoto and Murao [13], experiments were performed to clarify the effect of spacer grids on reflood heat transfer. They investigated the flow pattern, the thermal responses and the droplet behavior near the spacer grid location and proposed spacer grid models for both dry and wet grids.

Later, Paik and Hochreiter et al. [14] proposed a spacer grid heat transfer and droplet breakup model for a subchannel code, COBRA-TF. Similar to Lee's work, they correlated the droplet size to the incoming droplet Weber number based upon which the droplet breakup criteria were established. Their model is compared with the current available RBHT data in this paper.

Yao et al. [15] experimentally studied the water droplet breakup upon impacting on a thin strip which were heated well beyond the Leidenfrost temperature. In their study, high-speed movies were recorded to analyze the shattered droplet size distribution. Experimental results were verified by theoretical analysis and were correlated to the incoming droplet Weber number for various droplet diameter and strip thickness ratios. Their work also provided information for the volume ratios, velocity ratios, and angles of the injected large and small droplets.

Ireland et al. [16] optically measured droplet sizes using a high-speed camera and analyzed the data using the VisiSize system for the RBHT tests. Experimental results for droplet size distribution were presented. The results showed that a 29% decrease in the mean droplet diameter was produced by spacer grids at given experimental conditions.

In the study by Bajorek and Cheung [9], the spacer grid rewet conditions and the corresponding droplet size were investigated experimentally using the RBHT test facility. It was found that the droplet distribution at the downstream of a spacer grid is significantly different from that of a dry grid. New models addressing the wet grid droplet generation process were recommended.

In the work by Cheung and Bajorek [8], a dry grid droplet breakup model was proposed from a fundamental physical point of view and the model was verified by the RBHT experimental data. In their work, the droplet Sauter mean diameter (SMD) ratio was derived by considering effects including conservation of mass and energy, incoming droplet Weber number, blockage ratio of the spacer grid, and the fraction of kinetic energy being transferred to surface energy during droplet breakup.

Cho et al. [10] carried out an experimental study using a 6 × 6 rod bundle assembly. The steam-droplet flow system was adopted. In order to reproduce the reflood transients in a LWR, the steam was supplied by external boiler and the droplets were generated using a droplet injection nozzle. This method is different with experiments carried out by Bajorek and Cheung [9], Cheung and Bajorek [8], which were based on the RBHT test facility. Cho's work focused on droplet sizes and distributions under different spacer grid conditions.

From the literature survey above, it is known that though much effort has been directed to the study of reflood transients and the thermal-hydraulic response, there lacks a detailed and comprehensive understanding on the behavior of entrained liquid droplets during reflood. To date, the droplet dynamic behavior related to its size distribution, variation of its size with respect to the quench front, and the droplet breakup process across a spacer grid is still unclear. The major motivation for this study is to seek a better understanding of the droplet dynamics during reflood transients. In this work, the droplet sizes and distributions are investigated using the data obtained at the RBHT test facility. The droplet behavior across a spacer grid captured by the Oxford Lasers Firefly Imaging System is analyzed using the VisiSize software for the entire reflood transients focusing specifically on the effects of quench front location, spacer grid conditions, and inlet liquid subcooling on the droplet sizes and distributions up- and down-stream of the spacer grid. The experimental data obtained provides detailed information on the droplet size variation and the breakup process over a spacer grid, thus providing a useful basis for new model development and verification.

## 2. RBHT test facility

### 2.1. General configuration

The Rod Bundle Heat Transfer (RBHT) test facility was designed and built by The Pennsylvania State University (PSU) under the sponsorship of the United States Nuclear Regulatory Commission. This facility is