The 6th ASME-JSME Thermal Engineering Joint Conference, March 16-20, 2003

TED-AJ03-624

Droplet Size and Velocity Measurements in a Heated Rod Bundle

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Keywords

droplet breakup, spacer grid, grid strap, rod bundle

Abstract

The phenomena of droplet shattering on spacer grids is an important consideration in two-phase heat transfer in rod bundle geometries. Droplet breakup over grid straps enhances the downstream heat transfer be increasing the available surface area for evaporation to occur.

A rod bundle geometry consisting of 49 rods connected with mixing-vane spacer grids and an overall length of 3.7 m (144 in) was used to quantify the behavior of droplets as they pass over a spacer grid. The experiment involved the use of a system called VisiSizer, which is a digital imaging system, to determine the droplet diameter distributions upstream and downstream of a spacer grid.

The results show that the spacer grids produced a 29% decrease in the mean diameter of the droplets at the given experimental conditions. This compares well to previous experiments conducted on droplet shattering.

Nomenclature

D_I	diameter of impacting droplet
W	grid strap thickness
We_D	droplet impact Weber number
d_o	diameter of un-shattered droplet
d_{en}	diameter of shattered droplet
ρ_l	droplet liquid density
σ	droplet surface tension

Introdution

The Pennsylvania State University/US Nuclear Regulatory Commission sponsored Rod Bundle Heat Transfer Facility (RBHT) has been designed to investigate reflood heat transfer in an electrically heated rod bundle which simulates a nuclear fuel assembly. The objective is to obtain basic two-phase flow and heat transfer data in the dispersed flow film boiling regime where the peak fuel rod temperatures are calculated to occur for a postulated reactor design basis accident. The information and data required includes: the entrained liquid droplet sizes and velocity, vapor temperature, steam flow rate, and the interfacial heat and mass transfer.

The dispersed flow film boiling region is extremely complex since the dispersed droplets act as heat sinks and alter the vapor superheat temperature such that the film boiling is a two-step process, that is, heat is transferred to the continuous vapor phase from the heated walls, then heat is transferred to the entrained water droplets by interfacial heat and mass transfer [1-3]. As a result, the vapor temperature is a dependent parameter which is a function of both the wall heat transfer and the interfacial heat transfer. In addition to being a source of interfacial heat transfer, the entrained droplets can also affect the continuous vapor heat transfer from the heated wall by increasing the turbulence level in the flow, due to the additional interfacial drag in the flow. The droplets also as act as distributed heat sinks within the vapor flow. The spacer grids, that are used to support the rod arrays, can also effect the dispersed flow film boiling within the rod bundle. The spacer grids provide subchannel blockage which can act to shatter entrained droplets, thereby increasing the interfacial heat transfer between the drops and superheated vapor.

Best estimate safety analysis computer codes are widely used to predict nuclear fuel rod temperatures for postulated accidents. The most limiting accident is the

Loss of Coolant Accident in which the calculated peak cladding temperatures for the reactor occur in the dispersed flow film boiling region [2]. These codes rely on models to accurately describe the physical processes in the dispersed two-phase flow heat transfer regime as described above. To date, the existing models have large uncertainties and do not capture all the physical phenomena that have been observed in various experiments. In particular, most of the best-estimate computer codes do not model the effects of the spacer grids on the flow in the dispersed flow film boiling regime. As a result the safety analysis calculations and associated method logics have large uncertainties and conservative calculations must be performed to insure that the calculated peak cladding temperatures are within the licensing limits for the reactor [3].

One of the key features of the RBHT program is to provide improved data and analysis such that the analytical models that are used to represent the physical phenomena for the two-phase dispersed flow film boiling region can be improved such that the calculated uncertainty is reduced. The RBHT does model the effects of the spacer grids and special instrumentation is used to determine the grid effects. The experimental approach in the RBHT work is to separate the different phenomena, as best as possible, such that it is easier to develop component models for the more complex dispersed flow film boiling region. Toward this end, a RBHT test facility has been constructed to study reflood heat transfer in rod bundles to obtain data for improving the heat transfer model for Best-Estimate computer codes.

This paper will focus on the shattering of droplets on spacer grids as analyzed by the VisiSizer system during two-phase reflood tests on the RBHT test facility.

Facility Description

The RBHT facility consists of a 7x7 bundle with 45 heated full length electrical heater rods which simulate a 17x17 similar fuel rod. There are also four support rods, one in each corner, which provide structural support for the bundle. The axial power shape has a peak power at the 2.74 m (108 in) elevation. The spacer grids, which are used in the bundle, have mixing vanes, which promote improved heat transfer downstream of the grids. These grids have high blockage (39%) of the rod bundle flow area such that the flow is accelerated through the grids and entrained droplets can be shattered by the grids. The grids are comprised of straps which are 0.508 mm (0.02 in) thick.

Quartz windows are located on opposite sides of the Inconel housing for viewing the flow within the rod bundle. There is one pair of quartz windows for each spacer grid on the bundle, which allows for a comparison of droplet distributions upstream and downstream of the grid. A layout of the rod bundle, as well as an overall view of the housing are shown in Figs. 1 and 2 respectively.

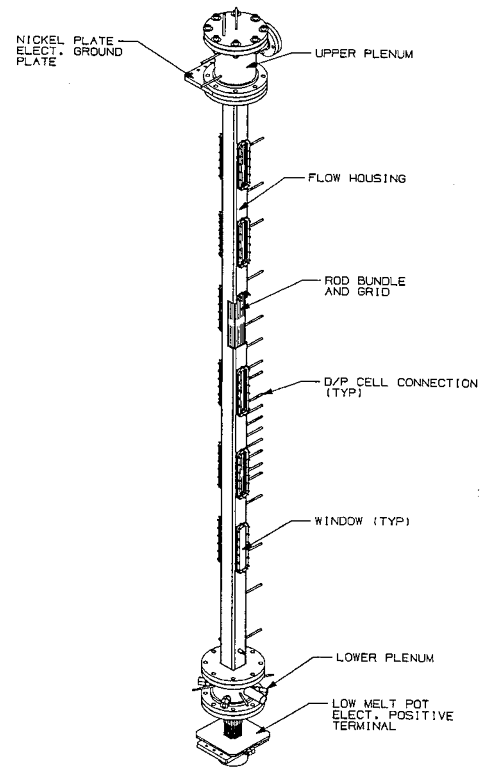

Figure 1. Schematic of Test Facility Housing.

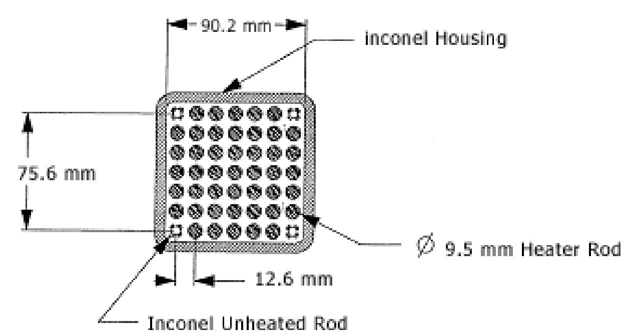

Figure 2. Rod Bundle Layout.

VisiSizer Description

The method of analyzing the droplet distributions in the rod bundle involves the use of a system known as VisiSizer [4,5], which is capable of real-time analysis of droplet size and velocity distributions. The system consists of a high-resolution digital camera, infrared laser, data analysis software, and associated computer and control equipment.

The camera, a Kodak Megaplus™ digital camera, has a resolution of over 1.0 megapixels. The laser system incorporates an infrared beam of wavelength 805 nm and is capable of pulsing at frequencies up to 1000 Hz. The laser can also pulse twice during a single camera frame to produce a double image used in determining velocity information. The beam of the laser is scattered with an opaque sheet of plastic to produce uniform background lighting for imaging. The system captures high-resolution images of the injection streams and analyzes the images at a rate of about 7 frames per second, identifying droplets as dark images in front of the laser-illuminated scattering sheet. The diameter of each droplet is determined automatically by referencing the number of dark pixels in the droplet image to the pixel area of a calibration circle.

A variety of user-defined parameters control the counting of the droplets, including focus rejection and spherocity criteria. Focus rejection is determined by considering the sharpness of a droplet image, done by quantifying the intensity gradient at the outer edge of the droplet, described in [4]. In addition to this, the droplet analysis duration can be controlled by elapsed time, number of frames, or number of droplets counted. The software also calculates real-time statistics such as mean and sauter-mean diameters as well as displays the diameter distribution and, if applicable, the velocity distribution. Velocity is determined by double-pulsing the laser to capture the motion of a droplet. Analysis of the velocity is done automatically using criteria such as direction of motion, velocity range, and size matching.

Test Procedure

The test setup for this analysis involves positioning the camera such that the view is through the quartz windows on the sides of the facility housing. The laser is placed opposite the housing such that it provides a backlighting through the rod bundle. The size of the area imaged is large enough for only two subchannels to be analyzed for each position of the camera. A general schematic of the camera setup is shown in Fig. 3.

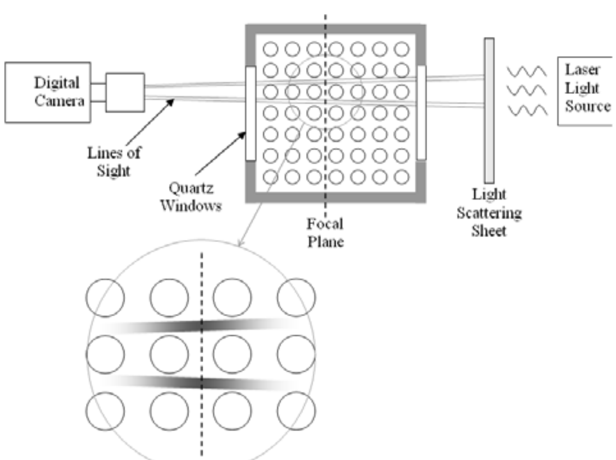

Figure 3. General Schematic of the Imaging System.

It can also be seen in Fig. 3 that the size of the probe volume will not be bounded by the edges of the rods at the focal plane. The width of the focal plane will be smaller than the gap size due to the parallax of viewing through the depth of the rod bundle. Fig. 4 is an example of the image produced when viewing through the bundle. The center of the image is the row of rods directly in front of the camera and the white regions are the row of gaps on either side of the rod. The width of the probe volume will be a function of the distance of the camera from the rod bundle. It is also important to note that fuzzy borders produced by out-of-focus rods in the image decrease the width of the probe volume even more. The variation of the gap size in the image is due to the difficulty in aligning the camera to a high degree of precision. For the experiments presented here, the width of the focal plane is approximately 2.16 mm (0.085 in), which is about 70% of the overall gap width.

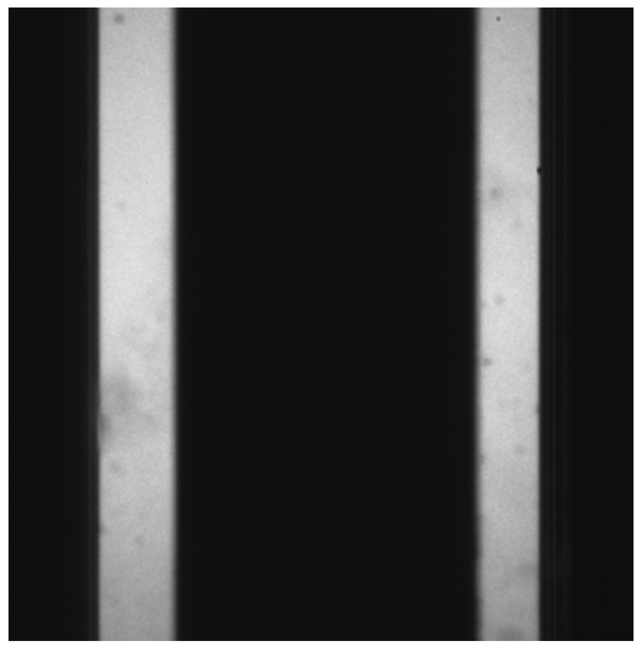

Figure 4. Typical VisiSizer Image through the Rod Bundle (no droplets present).

The depth of the probe volume is also dependent on the distance of the camera from the bundle, but more directly on the focus rejection setting. The focus rejection setting is used to reject droplets that appear out-of-focus due to their distance from the focal plane. In the experiments presented in this paper this depth is approximately 5 mm.

The imaging system is calibrated using a small calibration reticule. The system is trained and focused on the reticule which is attached to a quartz window on the housing. Using the known size of the calibration circles on the reticule, the distance can be determined between the camera and the quartz window using a calibration curve that was developed. The camera can then be focused on the center of the desired subchannel in the bundle by adjusting the focus setting to the desired new distance from the camera.

In the experiments presented here, the camera was moved over two elevations for similar test conditions and droplet diameter information only was taken. The elevations within the bundle were approximately 2.74 m (108 in) and 2.90 m (114 in), with a grid located at about 2.79 m (110 in). The bundle was pressurized to 1.38 bar (25 psia) and the reflooding rate was set to 25.4 mm/sec (1 in/sec). The injected water was 65.6 °C (150 °F) subcooled.

Results

The diameter distributions obtained from the two locations can be seen in Fig. 5. It can be seen that the droplet distribution changes shape from upstream to downstream of the grid, and that the mean size decreases. As had been done in the FLECHT-SEASET series of tests [6,7] a log-normal distribution was assumed for the distributions. Fig. 6 shows the log-normal fit for the distributions upstream and downstream of the grid as per the method outlined in [6]. These probability curves show more dramatically the effect of spacer grid droplet breakup.

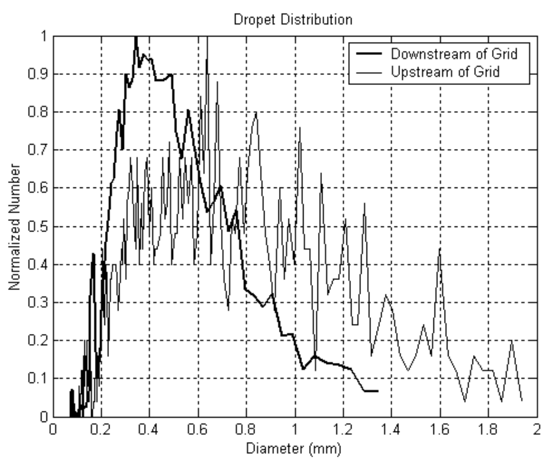

Figure 5. Normalized Droplet Distributions Upsteam and Downstream of the Spacer Grid

The arithmetic mean diameters for the droplets upstream and downstream of the spacer grid are 0.64 and 0.45 mm (0.025 and 0.018 in) respectively, which represents a 29% decrease in the mean size of the droplets.

In the FLECHT-SEASET series of tests, analysis was done of droplets impinging in heated grid straps in order to improve the drop breakup model used in COBRA-TF [7]. The analysis involved the observation of high-speed movies taken for droplets shattering on grid straps of thickness 0.3 mm (0.012 in). Fig. 7 shows a plot of drop breakup data for different drop size to grid strap thickness ratios as a function of drop impact Weber number. Figure 7 also shows the curve fit correlated to the data in the FLECHT-SEASET experiments.

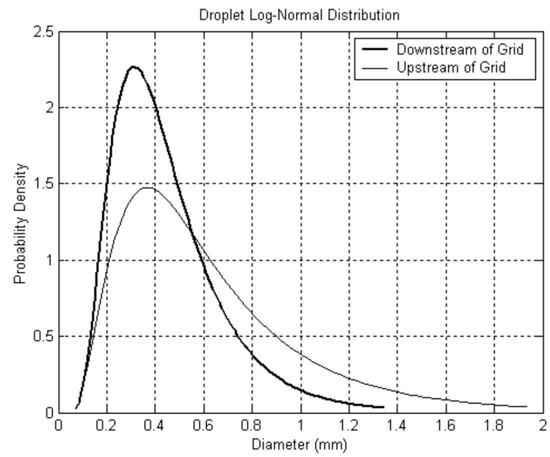

Figure 6. Probability Distribution Log-Normal Curve Fits Upstream and Downstream of the Spacer Grid

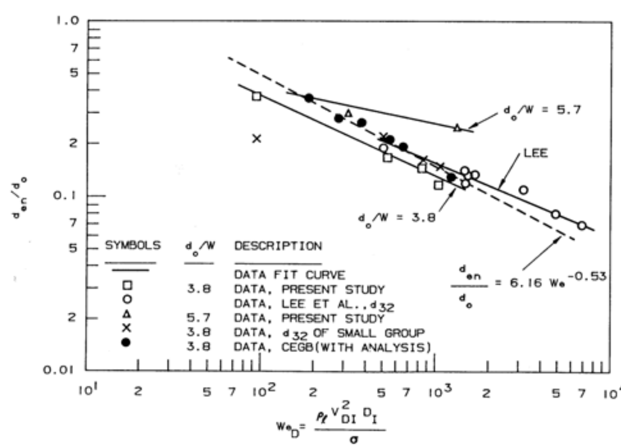

Figure 7. Drop Breakup Data as a Function of Droplet Impact Weber Number.

For the current analysis, the un-shattered droplet diameter to grid strap thickness ratio (d_o/W) is 2.1. Simulating the reflood experiment with the COBRA-TF computer code [7], a prediction was made for the velocity of the droplets upstream of the spacer grid. This velocity calculated is 1.78 m/s (5.85 ft/s) and the corresponding Weber number (using properties at saturation) is 55.24. Using the correlation from FLECHT-SEASET, the resulting droplet diameter ratio (d_{en}/d_o) should be about 0.74. For the current experiments, the ratio is 0.71.

The change in droplet diameter due to evaporation was another factor considered in the FLECHT-SEASET tests. For droplet evaporation over a 76 mm (3 in.) length, the droplet diameter was calculated to reduce by less than 1%. Although the current experiment is conducted over about twice that length, the RBHT test was performed at a lower temperature. Therefore, it can be assumed that the overall change in droplet diameter due to evaporation would be less than 2%, which would not account for much of the 29% reduction in diameter over the grid span.

The uncertainty in the diameter measurements is also quite small. Using the technique for determining 95% confidence based on droplet diameter used by Todd [5], the uncertainty for the range of droplet sizes was calculated. For the smallest droplets (0.1 mm), where the confidence in the diameter is the lowest, the uncertainty is about 3.2%, and for the largest droplets (2 mm), the uncertainty is only about 0.03%. For the droplets of about the mean size (0.5 mm), the uncertainty is about 0.30%.

Finally, it should also be noted that some velocity information had been collected with the VisiSizer system for experiments with similar conditions. For the current experiment, only the diameter information was recorded, but for completeness it is prudent to include this additional measurement from earlier experiments on the same rod bundle for similar reflood test conditions. Figure 8 shows a plot representing the diameter and velocity distribution for an experiment where the camera was in position at about 2.74 m (108 in) and shows the resulting velocity and size distribution downstream of the grid.

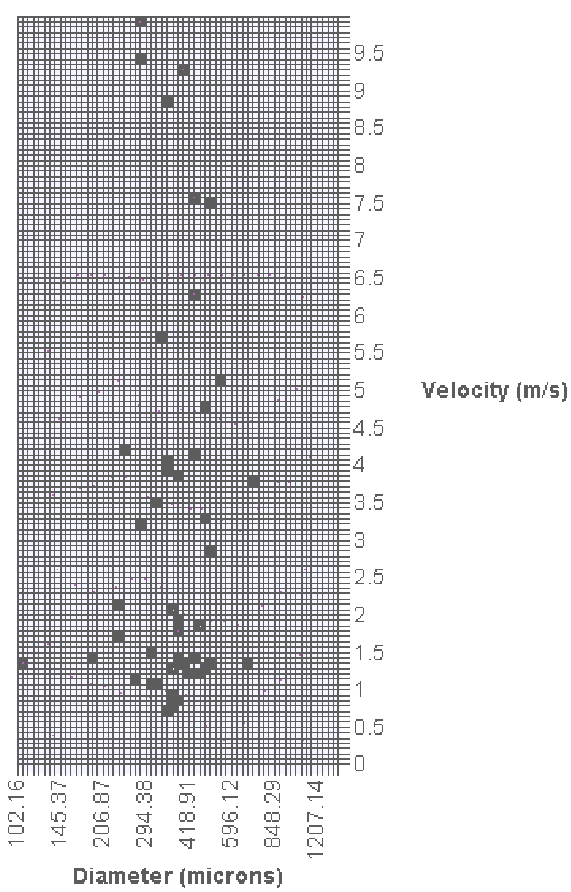

Figure 8. Size and Velocity Distribution Downstream of the Spacer Grid.

This distribution shows that there is very little correlation between size and velocity for droplets immediately downstream of a spacer grid. This is due to the turbulence created by the mixing vanes and the shattering of the droplets on the grid straps.

Discussion

Although the current experiment considered all droplets that passed through the spacer grid (both those that impacted the grid and those that did not), the agreement between the mean diameter ratio and the correlated experimental data is quite good, differing by only about 4%. This may indicate that the vast majority of the droplets that pass though the grid experience the grid breakup effect. It can also be concluded that the information collected with the VisiSizer digital imaging system indicates that there is little relationship between the size and velocity of droplets that are immediately downstream of a spacer grid.

Acknowledgements

This work was done under the Pennsylvania State University Rod Bundle Heat Transfer Project supported by the US Nuclear Regulatory Commission under Contract # NRC-04-98-041.

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