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An Experimental Investigation on the Droplet Behavior Impacting a Hot Surface above the Leidenfrost Temperature

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***Abstract*—**An appropriate model to predict the size of the droplets resulting from the break-up with the structures will help in a better understanding and modeling of the two-phase flow calculations in the simulation of a reactor core loss-of-coolant accident (LOCA). A droplet behavior impacting on a hot surface above the Leidenfrost temperature was investigated. Droplets of known size and velocity were impacted to an inclined plate of hot temperature, and the behavior of the droplets was observed by a high-speed camera. It was found that for droplets of Weber number higher than a certain value, the higher the Weber number of the droplet the smaller the secondary droplets. The COBRA-TF model over-predicted the measured secondary droplet sizes obtained by the present experiment. A simple model for the secondary droplet size was proposed using the mass conservation equation. The maximum spreading diameter of the droplets was also compared to previous correlations and a fairly good agreement was found. A better prediction of the heat transfer in the case of LOCA can be obtained with the presented model.

***Keywords*—**Break-up, droplet, impact, inclined hot plate, Leidenfrost temperature, LOCA.

I. Introduction

THE phenomena of droplets impacting on a hot surface are found in many applications such as turbines, mist spraying and in the case of a large break loss-of-coolant accident (LOCA) in nuclear reactors.

In a large break LOCA, emergency systems initiate and start reflooding the reactor core with water. The fuel rods in this case have a very high temperature exceeding the Leidenfrost temperature for water. As the quench front propagates at the quenching surface, water splatters and many droplets of different size and velocity are generated and carried with the steam in the cooling channel. Fig. 1 shows a typical two-phase flow in a reflooding scenario [1].

The droplet heat transfer is of importance in the dispersed flow region. Guo et al. [2] conducted a non-equilibrium heat transfer simulation for post-dryout in a dispersed flow. They found that in the case of low pressure and low mass velocity, ignoring such heat transfer mechanisms will result in unacceptable error. According to Bajorek and Young [3], the direct droplet-wall heat transfers are relatively large at low flow rates up to about 30% of the total heat transfer rates.

During a large break LOCA, the fuel rod experiences an increase in temperature. This increase causes a deformation and sometimes relocation of the fuel pellets inside the fuel rod cladding. In this deformed and ballooned section of the fuel rods, the flow areas are narrowed down and either completely or partially blocked. As the steam and entrained droplets flow to the blocked region, the droplets will collide with the ballooned surface. Depending on how much the rod is deformed, the more the rod is ballooned the higher the impact angle of the droplet to the ballooned surface. This represents a droplet impacting on an inclined hot surface.

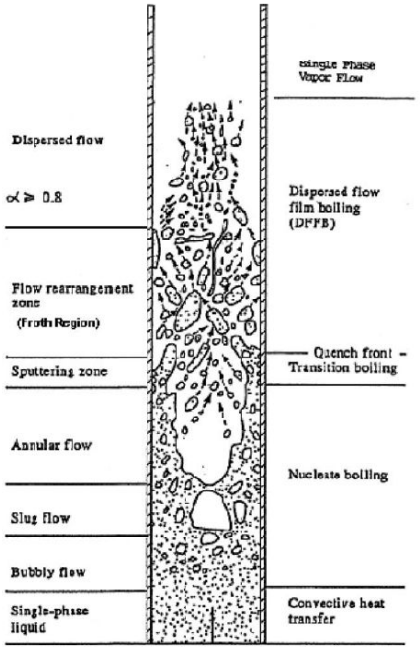

Fig. 1 Two Phase Flow Regime in flooding Scenario

Droplets in such flows surrounded by superheated steam act like heat sinks aiding the cooling of the superheated steam. Also, heat transfer is improved by the direct heat transfer from the wall to the droplet by the droplet and wall contact. Ireland et al. [4] investigated the behavior of the droplets passing through the spacer grid during reflooding, and found a 29% decrease in the mean size of the droplets. They also measured the velocity

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of the secondary droplets. They concluded that due to the turbulence made by the mixing vanes and the shattered droplets on the spacer grids, no correlation can be found for the secondary droplet velocity and the behavior is random.

The droplet break-up behaviors due to the impact on a ballooned surface might be much different with the break-up by spacer grids. The droplet break-up is due to the cutting and splashing by the thin spacer grids. On the while, the droplet break-up is mainly from the splashing on the ballooned surface. The spacer grids do not have a heat source while the ballooned rods have nuclear heat. Thus, the droplet break-up phenomena will be influenced by the temperature of the ballooned rods.

In order to correctly predict the heat transfer associated with the direct droplet contact with the wall, one must correctly understand the nature of the interaction. One of the earliest studies on droplet behavior was done by Wachters and Westerling [5]. They found that droplets incoming to a hot surface over the Leidenfrost temperature with a Weber number of less than 30 will experience a deformation without any disintegration. On the while, droplets with a Weber number higher than 80 will disintegrate in the initial part of the impact. For a Weber number between these two values, the droplet will disintegrate as it begins to rise from the hot surface.

The value of this Leidenfrost temperature was found to be affected by the incoming Weber number and the impinging angle of the droplet along with other surface properties. Yao made an empirical correlation for the Leidenfrost temperature with the incoming vertical Weber number [6].

$$T_q - T_s = 135.6\, We_V^{0.09} \tag{1}$$

where T_q is the Leidenfrost temperature, T_s is the saturation temperature and We_v is the vertical Weber number. He found the effect of the impinging angle and correlated it with a non-dimensional Leidenfrost temperature as follows

$$\frac{T_q - T_s}{T_{qv} - T_s} = 0.28\,\theta - 0.00019\,\theta^2 \tag{2}$$

where T_q is the Leidenfrost temperature with an incoming angle, T_{qv} is the vertical Leidenfrost temperature and θ is the incoming angle.

Karl [7] investigated the interaction of the droplets and hot walls, and correlated the normal momentum loss and the maximum spreading diameter of the droplets on the surface. He also found a minimum impinging angle for disintegration. Comparing different liquids together, he found the minimum angle to be almost the same.

When a droplet impinges on a hot plate above the Leidenfrost temperature; a vapor cushion forms between the droplet and wall. During the interaction, the droplet expands radially. The spreading motion is stopped by the surface tension and the droplet reaches the maximum droplet diameter [7]. Udea also proposed an empirical correlation for the maximum droplet diameter and found that [8].

$$\frac{D_{max}}{d} = 0.87\sqrt{\frac{We}{6} + 2} \tag{3}$$

where D_{max} is the maximum diameter of deformation the droplet reaches, d is the initial diameter of the droplet and We is the droplets Weber number.

The range of initial droplet size in this study is around two millimeters, which is a typical value in a large-break LOCA. Spray applications have been widely studied. Many experiments of droplet behavior for spray applications have been conducted for small particles of microns in size. Studies for droplets of millimeters in size have been rarely studied. Most of these studies made on the reflooding in a large-break LOCA observe the droplets upstream and downstream the spacer grid. The droplet break-up process associated with ballooned and deformed fuel rods is different. For this reason, droplets of millimeters in size impacting on an inclined hot surface are investigated in this study.

II. Experimental Apparatus and Analysis

A. Experimental Facility

A schematic of the experimental apparatus is shown in Fig. 2. Droplets are directed to a hot copper plate whose temperature is above the Leidenfrost temperature from a nozzle. Droplet behavior and secondary droplets are observed and filmed using a high speed camera with a lamp for enough light for a clear and focused image. The images are then stored on a computer for analysis.

The velocity of the droplets is controlled by applying pressure to the closed water tank shown in Fig. 2. Power is supplied to the pressure regulator, which pressurizes the tank forcing water to flow to the nozzle and then to the copper plate.

Water droplets with a uniform size are generated by applying vibration to the nozzle from a vibrator. Vibrations are generated by an amplifier and a function generator. Vibrating the nozzle creates longitudinal oscillations on the water jet breaking it into droplets [9]. Imposing the correct wavelength will give uniform droplets.

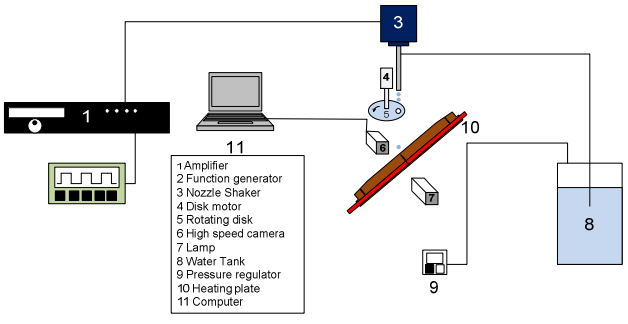


Fig. 2 Experimental Apparatus

In order to study the behavior clearly a single droplet should be isolated so that its behavior would not be interrupted by preceding or upcoming droplets. Therefore, a disk with a hole

in it was rotated in front of the jet stream. With the correct rotating speed related to the droplet velocity, only one droplet is allowed to pass from the disk to the hot plate.

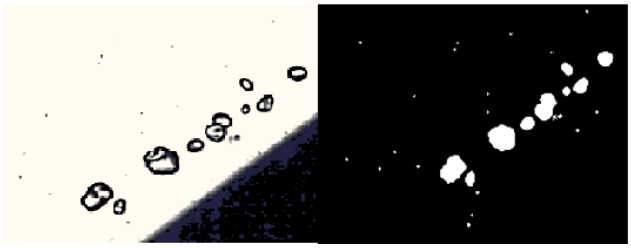
B. Analysis

VisiSizer (Oxford Lasers) and MATLAB (Math Works) were used for the analysis of the droplet behavior. VisiSizer uses a technique called a Particle/Droplet Image Analysis. It is used to calculate the velocity and size of the droplets.

VisiSizer measures both the diameter and the velocity of the droplets. The diameter given by the VisiSizer is the diameter of the equivalent circular area of the droplet shape. For velocity measurements, two consecutive images are taken and the distance between the centroid of the droplets is calculated. The droplet velocity is calculated with the droplets moving distance and the time interval between the two images (frame rate).

An image processing program was developed using MATLAB's image processing toolbox. Fig. 1 (a) below shows an image before being processed, and Fig. 1 (b) shows the same image after being processed using the MATLAB program.

The MATLAB program detects the droplets and calculates their diameter. The MATLAB program was also used to measure the maximum spreading diameter of the droplets by processing the image when the droplet is in its maximum deformation.



(a) Original image (b) processed image

Fig. 1 Original and processed Image for a shattered droplet

III. Results

Many droplet behaviors were observed during the experiments. Fig. 2 shows two pictures of different droplets impacting on a hot surface.

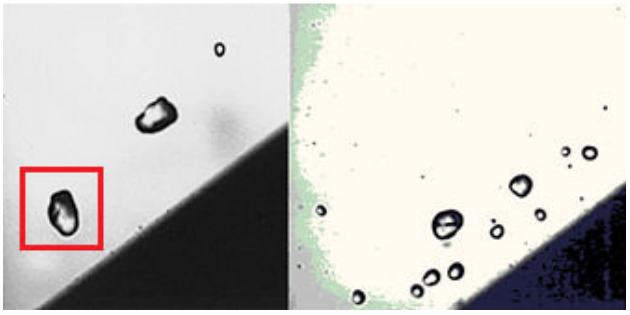


Fig. 2 Droplet Behavior, low Weber number (left), High Weber number (right)

The droplet on the left has a very low Weber number of around 20, and the droplet on the right has a much higher Weber number of around 88. Clearly, the droplet on the right is shattered into smaller droplets, while the droplet on the left did not break up and only deformed on the plate and then rose from it. This shows the logical assumption that the higher the Weber number of the droplet, the smaller the resulting secondary droplets become. A droplet with even smaller than a threshold Weber number will not break-up at all. Wachters determined this threshold value to be 30 [5].

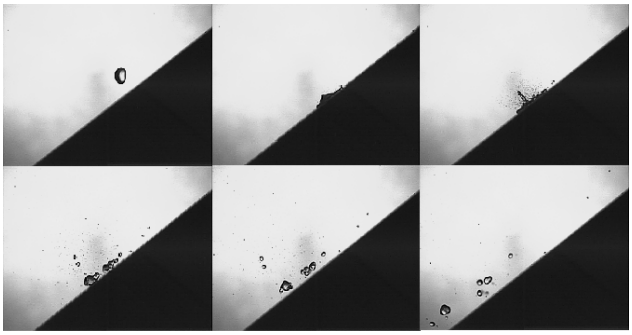


Fig. 3 Droplet Behavior (We_n=83.5)

Fig. 3 shows images taken on a different time for a single droplet with a Weber number normal to the wall of 83.5.As the droplets touches the surface, it starts to spread and a thin vapor film separates the droplet from the surface due to the Leidenfrost effect. Once the droplet reaches its maximum spreading diameter, it breaks into smaller droplets and leaves the surface.

The behavior of the droplets was observed, and the secondary droplets size, number and velocity were measured. It was found that over a certain value of Weber number normal to the wall the droplet breaks up into smaller droplets.

Fig. 4 shows the ratio of Sauter mean diameter of the secondary droplets to the initial diameter of the droplet and a COBRA-TF model derived from both Watchers and Takeuchi data [10] to predict this ratio.

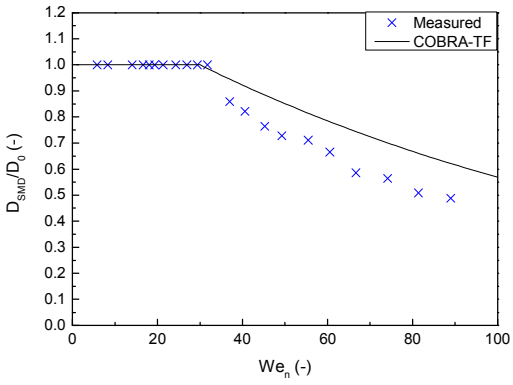


Fig. 4 Droplet Breakup

The model over-predicts the Sauter mean diameter of the secondary droplets but gives a similar trend.

To accurately predict the heat transfer associated with the direct droplet-wall interaction, the interfacial area between the two surfaces must be known. For this reason, the maximum spreading, or deformation, of the droplets was measured. The measurements were made at the point right before the droplet started to contract and lift off, or right before break-up for droplets with a higher Weber number.

Fig. 5 shows the experimental data of the maximum spreading diameter of the droplets to the initial diameter compared to Karl et al. [6] Udea et al. [7] and Kendell and Rohsenow [10], the data show very good agreement with Karl's model, which takes into consideration the normal momentum loss, surface area of the droplet, and normal Weber number as follows:

$$r_{dmax} = \left[\frac{We_n}{6}\left(\frac{1+r_n^2}{2}\right)\right]^{0.5} \quad (4)$$

where r_{dmax} is the ratio of the maximum radius of the droplet to the initial radius of the droplet, We_n is the Weber number normal to the surface, and r_n is v_2/v_1 being the ratio of the droplets velocity normal to the wall after and before impact.

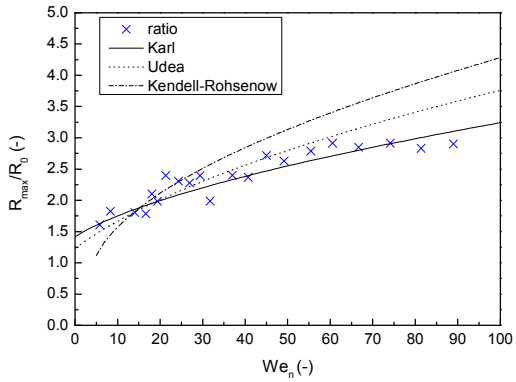


Fig. 5 R_{max}/R_0

The number of the droplets and their velocities are important parameters in a two-phase flow calculation. The droplets act as heat sinks to help sub-cool the water vapor surrounding the droplets.

For each droplet, the secondary droplets were counted and for a small range of Weber number an average secondary droplet number was calculated. Fig. 8 shows the average droplet fragments with its fitting equation given as

$$N = We_n^{0.794}\, exp\left(\frac{-78.054}{We_n}\right) \quad (5)$$

For We_n>30, With N being the average number of droplet fragments.

Fig. 7 shows the velocity of individual secondary water droplets.

As can be seen from Fig. 9 as the secondary droplets are larger in size the velocity almost becomes equal, and the smaller the droplets the larger their velocity range.

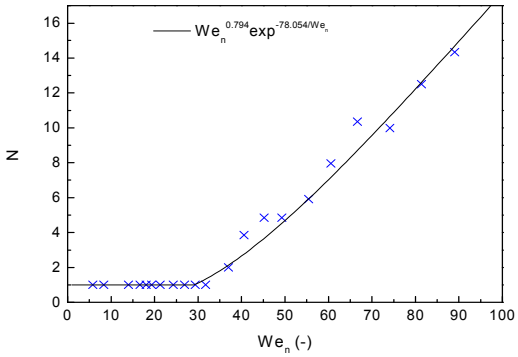


Fig. 6 Secondary Droplet Number

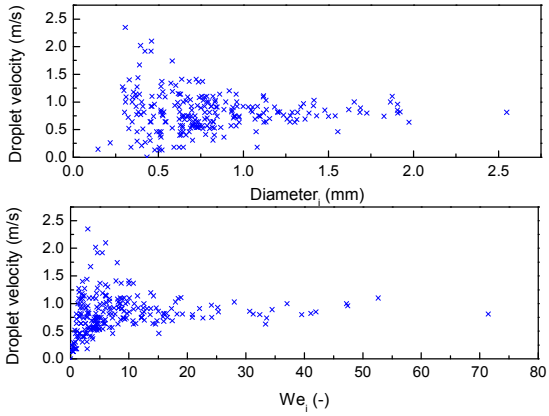


Fig. 7 Droplet Diameter to Velocity (Top) Droplet Weber Number to Velocity (Bottom)

IV. Suggested Model

The measured data shown in Fig. 4 are the ratio between the sauter mean diameter of the secondary droplets and the initial diameter for the incoming droplet. The sauter mean diameter is calculated as follows:

$$D_{sm} = D_{32} = \frac{\sum D_i^3}{\sum D_i^2} \quad (6)$$

with D_{32} as the sauter mean diameter, n_i as the number of secondary droplets, and D_i as the secondary droplet diameter. And the volume mean diameter given by

$$D_{30} = \left(\frac{\sum_i n_i D_i^3}{\sum n_i}\right)^{1/3} \quad (7)$$

Then, the mass conservation equation before and after impact will be

$$\frac{4}{3}\rho_0 D_0^3 = \sum_i \frac{4}{3}\rho_i n_i D_i^3 \quad (8)$$

Assuming no change in droplet density and substituting the volume mean diameter we get

$$D_0^3 = \sum_i n_i D_i^3 \tag{9}$$

From (7)

$$\left(\sum_i n_i D_i^3\right)^{1/3} = N^{1/3} D_{30} \tag{10}$$

Substituting (10) in (9) it can be concluded that

$$\frac{D_{30}}{D_0} = (N)^{-1/3} \tag{11}$$

Assuming that $D_{30} = c\, D_{sm}$ and knowing (5), we get

$$\frac{D_{sm}}{D_0} = c\left(We_n^{0.794}\, exp\left(\frac{-78.054}{We_n}\right)\right)^{-1/3} \tag{12}$$

Even if the change of density is taken into account due to the temperature increase in the droplets, the change in density between room temperature and saturation temperature is less than 5%.This would not give a significant affect and it can be safely said that the change in density can be ignored.

Fig. 8 shows an under prediction from the new correlation without the experimental constant (c) in (12).

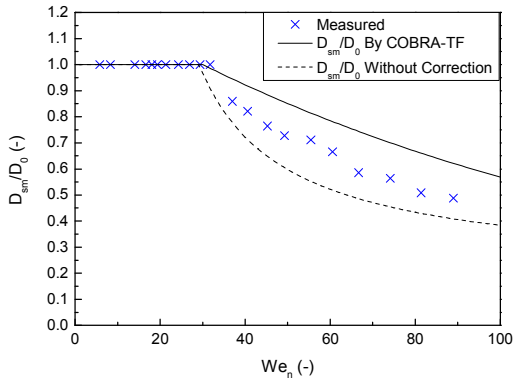


Fig. 8 Measured Data with New Model

Calculating the mean value of D_{32}/D_{30} it was found to be 1.245. Adding this correction factor to (12), we get the graph below.

As shown in Fig. 11 the correlation shows very good agreement with the measured data and the final resulting model is

$$\frac{D_{sm}}{D_0} = 1.245 \times \left(We_n^{0.794}\, exp\left(\frac{-78.054}{We_n}\right)\right)^{-1/3} \tag{13}$$

Due to the nature of the constant that is used in (13) there is an over prediction between 30-50 normal Weber number of the droplets. For this reason the experimental correction factor was smoothened exponentially.

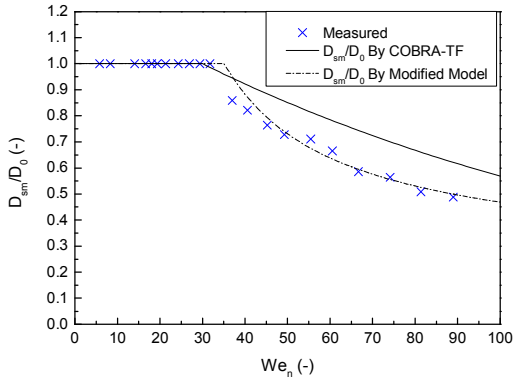


Fig. 9 Modified Model

It was found that when calculating D_{32}/D_{30} for the experimental data that there is a sharp increase in the value of the ratio. After this sharp increase, a mean value of 1.254 is reached. Adjusting the experimental correction factor to apply to this behavior the following correction factor was obtained:

$$c = 1.266 - 3.3exp(-0.084\, We_n) \tag{14}$$

Adding this experimental correction factor to the suggested model we find that the model agrees with the experimental data.

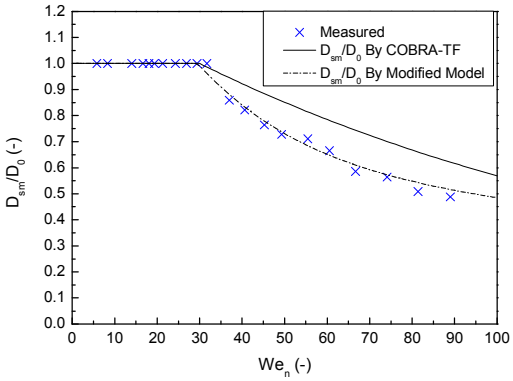


Fig. 10 Adjusted Correction Factor

V. Conclusion

Experimental investigations were made to study the behavior of a droplet impacting on a hot surface above the Leidenfrost temperature. The COBRA-TF model over-predicts the measured data of the secondary droplets. A simple correlation was suggested to predict more accurately the secondary droplet size. The new correlation under-predicts the size. A correction factor was added to the correlation to make-up the usage of the Sauter mean diameter for better prediction, and a fairly well prediction was obtained. The velocity of the secondary droplets was measured, and it was found that the larger the secondary droplet size, the narrower the droplet velocity range is. With this new model, a better two-phase flow heat transfer analysis could be obtained. More experiments are needed to determine the threshold value on which the droplets start to break up, and to extend the range of study onto a higher Weber number.

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