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De-entrainment of Droplets on a Staggered Array of Vertical Rods in the Upper Plenum

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1. Introduction

During the reflood phase of a large-break loss-of-coolant accident, a portion of emergency core cooling water is entrained into the upper plenum by the upward steam flow from the reactor core. The droplets entrained into the upper plenum can be carried over by the steam flow to the hot-legs and steam generator. The vaporization of droplets in the SG U-tubes contributes to the steam binding problem and degrades core cooling.

However, the upper plenum contains a large number of internal structures, such as control rod guide tubes and support columns, and these structures act as a steam-water separator. As a result, a large amount of droplets are de-entrained by inertial impaction on the upper plenum structures: these droplets subsequently accumulate in the upper plenum and consequently fall back to the core.

The main purpose of this study is to evaluate the de-entrainment efficiency of a staggered array of vertical rods that simulate the control rod guide tubes.

2. Experiments

The detailed schematic of the experimental apparatus is shown in Ref. 1. Figure 1 shows two test sections for a multi-row with staggered array of vertical rods. One array is composed of five rows with 18 rods (Array A), and the other is composed of five rows with 13 rods (Array B). The gaps between the rows in each array are zero. There is no gap between the half rods and the side wall. The diameter-to-pitch ratios in each array are 0.5 and 0.33.

In the experiments, we increased the number of rows from one to five. At every step, we measured the flow rates of water de-entrained on each row. The de-entrained water that flowed down along each rod was measured directly.

The total de-entrainment efficiency for an N-row of rods, $\eta_{T,N}$, is defined as

$$\eta_{T,N} = \frac{\Sigma \dot{m}_{D,N}}{\dot{m}_T}, \qquad (1)$$

where $\dot{m}_{D,N}$ is the droplet mass flow rate de-entrained by the rods in the Nth row; and $\dot{m}_T$ is the total droplet mass flow rate that reached the array of rods.

3. Results and Discussion

Figure 2 shows the measured total de-entrainment efficiencies for array A and array B, respectively. We obtained 30 items of data for each array for various combinations of the droplet mass flux and air velocity with an increase in the number of rows. The ranges of the average droplet mass flux (G) were 1.0 kg/m2s to 3.2 kg/m2s, and the upstream velocities of air (V_a) were 3 m/s and 6 m/s.

The results indicate that about 90 percent of the droplets are de-entrained in array A, while about 50 percent of the droplets are de-entrained in array B. For each rod array, the total de-entrainment efficiencies for the multi-row of rods show insignificant dependence on the experimental conditions.

The total de-entrainment efficiency for an N-row of

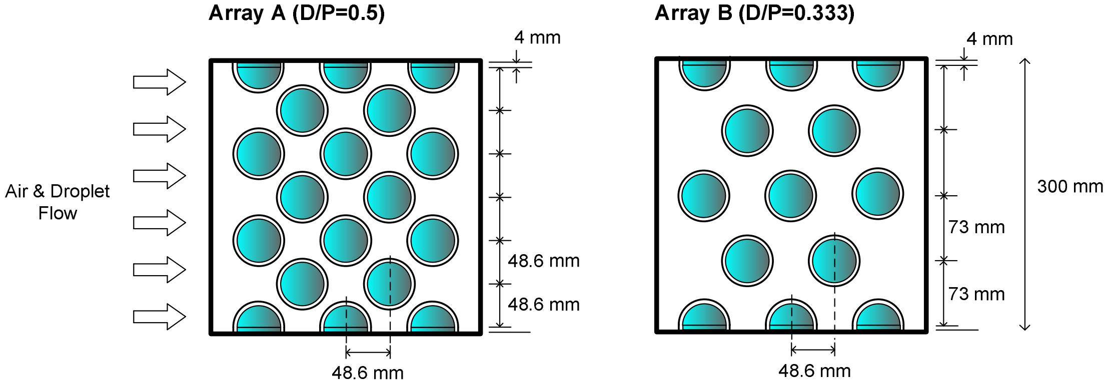

Figure 1. Test sections for a multi-row of rods.

rods can also be predicted on the basis of the de-entrainment efficiencies of each row of rods, $\eta_{R,N}$. Assuming that the droplet flow in each row is formed only in the gaps between the rods, the total de-entrainment efficiency for an N-row of rods is as follows (Ref. 2):

$$\eta_{T,N} = 1-\left(1-\frac{A_R}{A_T}\eta_{R,1}\right)(1-F\eta_{R,2})\cdots(1-F\eta_{R,N})\,. \quad (2)$$

where A_R is the total projected area of rods in the first row, A_T is the total flow area of the wind tunnel, and F is the proportion of the projected area of rods of the Nth row to the gaps of the N-1th row. For a staggered array of rods, as shown in Fig. 11, the values of F are 1.0 for array A and 0.5 for array B.

To simplify Eq. (2), we assumed that the de-entrainment efficiency of each interior row (η_{IR}) was the same. Accordingly, Eq. (2) becomes

$$\eta_{T,N} = 1-\left(1-\frac{A_R}{A_T}\eta_{R,1}\right)(1-F\eta_{IR})\,. \quad (3)$$

When evaluating the de-entrainment efficiency for the first row ($\eta_{R,1}$), we used our experimental results for the de-entrainment efficiency of the single row expressed as Eq. (4):

$$\eta_{R,1} = \eta_I(1+3.34\beta^{3.7})\,. \quad (4)$$

Equation (4) is derived by comparing the results for a single rod with those of single row of rods. Based on the experimental data of Ref. 1, the de-entrainment efficiency of a single rod, η_I, can be fitted linearly as a function of the droplet mass flux as follows:

$$\eta_I = 0.24-0.016\,G \quad (5)$$

To predict the de-entrainment efficiencies of the interior rows, we used the average values of the de-entrainment efficiencies except for the fifth row, where the de-entrainment efficiency can include a large error due to the small quantity of de-entrained water. The calculated values of η_{IR} are 0.416 for array A and 0.336 for array B.

Considering that the value of η_{IR} approximates to the value of η_I as the rod diameter-to-pitch decreases, the value of η_{IR} can be correlated as follows by linear fitting as a function of the diameter-to-pitch ratio:

$$\eta_{IR} = 0.19+0.45\beta\,, \quad (6)$$

where the value of 0.19 in Eq. (6) represents the averaged value of the de-entrainment efficiency for a single rod (Ref. 1).

In Fig. 2, the solid lines represent the total de-entrainment efficiencies predicted by Eq. (3). We determined all the parameters in Eq. (3) from the configurations of the arrays of rods, Eq. (4) and Eq. (6), as follows:

$A_R/A_T \cong 0.50$, $F=1.0$, $\eta_{R,1}=0.24$, and $\eta_{IR}=0.42$ for array A ($\beta=0.5$);
$A_R/A_T \cong 0.33$, $F=0.5$, $\eta_{R,1}=0.20$, and $\eta_{IR}=0.34$ for array B ($\beta=0.33$).

The results show that the use of Eqs. (3), (4), (5), and (6) satisfactorily describes our experimental results, except for the second row of array A. The RMS errors of the correlations from the de-entrainment efficiencies experimentally obtained were 13.5 percent for array A and 11.6 percent for array B.

4. Conclusions

On the basis of the experimental data for the de-entrainment efficiency, we propose a new correlation to predict the total de-entrainment efficiency using the results of the single rod and those of the single row of rods. The RMS errors of the correlation from the de-entrainment efficiencies experimentally obtained are within 13.5 percent.

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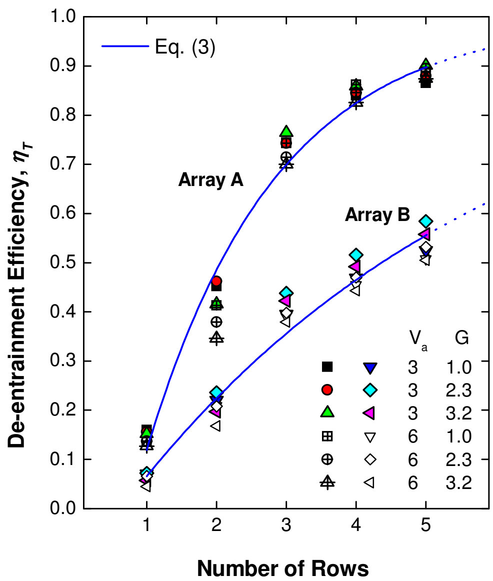

Figure 2. Comparison of measured de-entrainment efficiencies of multi-row with predicted values for array A and array B