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Prediction of Water Droplet Size Generating from a Wet Spacer Grid in a Rod Bundle

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1. Introduction

The behavior of the entrained droplets generated above the quench front has crucial effect on heat transfer by decreasing the superheated steam temperature and interacting with a rod bundle and spacer grids during the reflood phase of LOCA (Ergun, 2006). The reflood test data from the rod bundle heat transfer test facility showed that the grids in the upper portion of the rod bundle could become wet well before the arrival of the quench front and that the sizes of the liquid droplets downstream of a wet grid could not be predicted by the former droplet breakup models for a dry grid (Srinivasan, 2010). To investigate water droplet generation from a wet grid spacer, a viscous linear temporal instability model of the water sheet issuing from the trailing edge of the grid with the surrounding steam up-flow is developed in this study. The Orr–Sommerfeld equations along with appropriate boundary conditions for the flow are solved using Chebyshev series expansions and the Tau–Galerkin projection method.

2. Theoretical Model

The droplet generation process through the wet grid can be divided into several steps. First, liquid droplets contacting the grid form a water film on it, and a water sheet then issues from the trailing edge of a wet spacer grid. It is broken up into ligaments due to an interaction with the surrounding steam flow and each ligament is further disintegrated into droplets due to capillary force.

2.1 Water sheet interaction with surrounding steam flow

A model for water sheet interaction with the surrounding steam flow is based on perturbing a steady-state solution of the flow with a small-amplitude wave in normal modes, and analyzing its growth rate with the linearized Navier-Stokes equations. Consider a thin water sheet sheared by a steam flow downstream of the trailing edge of a spacer grid as sketched in Fig. 1. The linear stability analysis model for a two-dimensional sheet of constant thickness, 2*h*, of viscous water sandwiched between two identical viscous steam streams can be developed from two-dimensional continuity and momentum equations for the water sheets and the surrounding steam flow. The basic velocity profiles for the water sheet and the steam boundary layer were approximated by quadratic function of y coordinate, independent of the downstream coordinate.

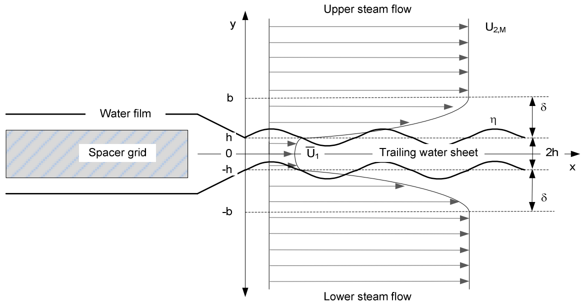

Fig. 1. Schematic diagram for co-flowing water sheet and steam

The linear stability of the basic state with respect to the normal mode two-dimensional perturbations is governed by following two coupled Orr-Sommerfeld equations.

$$\phi_\alpha^{iv}(y) - \frac{ik}{\nu_\alpha}\left[\frac{\omega}{ik} + U_\alpha(y) + \frac{2\nu_\alpha k^2}{ik}\right]\phi_\alpha''(y)$$
$$+\frac{ik}{\nu_\alpha}\left\{k^2\left[\frac{\omega}{ik} + U_\alpha(y) + \frac{\nu_\alpha k^2}{ik}\right] + U_\alpha''(y)\right\}\phi_\alpha(y) = 0 \quad (1)$$

The appropriate boundary conditions are velocity continuity and stress balance across the interface plus the kinematic condition. For the application of Tau spectral method, the occurrences of spurious eigenvalues has been discussed by several authors (Gardner et al., 1989; McFadden et al, 1990). A new function $\psi=\phi''$ is introduced into the above equation for the removal of spurious solutions and for better convergence.

2.2 Equilibrium water film thickness and droplet diameter

The equilibrium thickness value is obtained through a combined mass and force balance on the liquid film by invoking suitable simplifying assumptions. Since the thickness of the water film is expected to be much smaller than the dimensions of the spacer grid structure, the velocity of the water film can also be approximated into a fully-developed flow. The governing equation can be integrated twice to yield the velocity of the water film. The integration constants can be determined using the no slip and interfacial shear boundary conditions.

The water sheet is separated into several ligaments and their sizes can be obtained on the basis of the specific wave number corresponding to the maximum growth rate. The ligament further disintegrates into individual droplets according to Rayleigh's theory for the instability of cylindrical liquid columns. The mean diameter of the newly generated droplets can be obtained from the conservation of mass.

2.3 Numerical Method

To solve the system of coupled Orr–Sommerfeld equations with the boundary conditions, the Chebyshev series expansions and Tau–Galerkin projection method are employed. Since the governing system of equations is linear and homogeneous, the solution can be separated into even and odd functions for the water sheet. Special attention is given to the sinuous mode since the sinuous mode has been found to be a dominant instability mode for the air-assistant water sheet breakup. The computation of the generalized eigenvalue problem with complex variables is solved with the DGVLCG routine, the generalized complex eigenvalue problem solver based on the QZ algorithm.

3. Results and Discussion

To test the possible syntax and computer program errors, the results for the special cases were checked against the known results of a plane Poiseulle flow (Orszag 1971). Orszag found that the critical Reynolds number was 5772.22 for the Poiseulle flow. The numerical scheme developed in this study regenerated the same critical Reynolds number for the instability of a plane Poiseuille flow. Sensitivity calculations for the size of Chebyshev polynomial were carried out. The results showed that the convergence of the eigenvalues could be achieved with a reasonable size of polynomial.

Fig. 2 shows the non-dimensionless temporal growth rates as a function of non-dimensional wavenumber for several steam velocity, respectively; maintaining all the remaining fluid properties and thicknesses constant. It can be observed in the figure that all the curves have a range for which the growth rate is positive, i.e., for which unstable waves can propagate, and all of them present a maximum for a determinate wavenumber, corresponding to the most unstable mode. As the steam velocity increases in Fig. 2, the unstable region broadens, and the maximum growth rates notably increase and are displaced toward larger wave numbers. This result evidently shows the strong destabilizing effect of the steam velocity on the water sheet. On the contrary to the case of a steam velocity variation, the maximum growth rate decreases as the water velocity increases. Its location slightly shifts toward smaller wave numbers. The increment of water velocity induces the reduction of the relative velocity between the steam and water velocities, resulting in a smaller kinetic energy ratio and momentum ratio, which have a stabilizing effect on the water sheet.

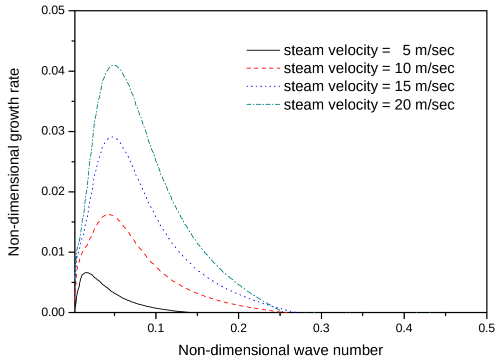

Fig. 2. Non-dimensionless temporal growth rate as a function of non-dimensional wavenumber for P=0.15 MPa, T=400^{o}C, U_1=1m/sec, H=0.05mm, δ=0.5mm, and different steam velocities

4. Conclusions

A physical model for predicting water droplet size generating from a wet spacer grid in a rod bundle has been developed in this study. It is found that a larger relative steam velocity to water velocity has a tendency to destabilize the water sheet with increased dynamic pressure. The latter is directly responsible for the size distribution of water droplets downstream of a wet grid.

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