EX175

Nucleate Boiling

FLUENT 6.0 is used in this example to simulate the process of forced convection nucleate boiling, a condition that occurs in nuclear Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs) during normal and non-nominal modes of operation. To simulate this complex phenomenon, customized functions are incorporated into the mixture multiphase model in the code. The results for vertical pipe flow are found to be in good agreement with experimental measurements.

In nuclear power plants, heat exchangers are used to extract the continually generated heat from the fuel. If the wall temperature in the heat exchanger pipes rises above the saturation temperature while the bulk of the heat exchanger liquid is subcooled, nucleate boiling will take place. In this regime bubbles are formed in microcavities adjacent to the wall. They then grow until they reach some critical size, at which point they separate from the wall and enter the fluid stream. This phenomenon is modeled in FLUENT through temperature-driven boiling heat and mass transfer, implemented by a user-defined function (UDF). The UDF includes the effects of boiling at two locations: the liquid-wall inter-face, and the bubble-liquid interface. The predictions of the model are shown to be in reasonably good agreement with experiment.[1]

The nucleate boiling model is based on work carried out at Rensselaer Polytechnic Institute.[2] The RPI model is implemented in FLUENT 6.0 as a modification to the mixture model, which is popular for its economic treatment of multiphase flows, such as the gas-liquid mixture in the heat exchanger pipes. In the RPI model, heat and mass transfer are split into two major components: interfacial boiling/condensation taking place at the bubble interface, and wall boiling occurring at the wall/liquid surface.

The bubble interface mass transfer depends on several system variables, such as the temperature, saturation temperature, interfacial heat transfer coefficient, bubble diameter, latent heat, and vapor void fraction. Boiling at the wall depends on the evaporation heat flux and the wall heat transfer coefficient, which combines single phase heat transfer and the quenching effect of liquid filling the voids near the wall after the bubbles depart.

The heat exchanger pipe studied in this example is described in Reference 1. It has an inner diameter of 15.4 mm, a length of 2 m, and is pressurized at 4.5MPa. Subcooled water is introduced through an inlet at one end of the pipe, and a constant heat flux is applied to the wall. The pipe is oriented vertically, and the effect of gravity is included in predicting the flow of water and vapor through it. The

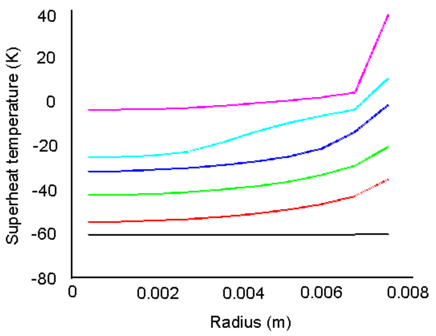

Figure 1: Radial profiles of superheat temperature (K) at five axial locations, measured from the inlet: 0m (black); 0.4m (red); 0.8m (green); 1.2m (blue); 1.6m (cyan); and 2.0m (magenta)

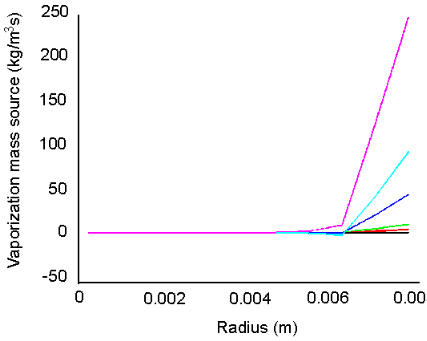

Figure 2: Radial profiles of vaporization mass source for the six axial locations described in Figure 1

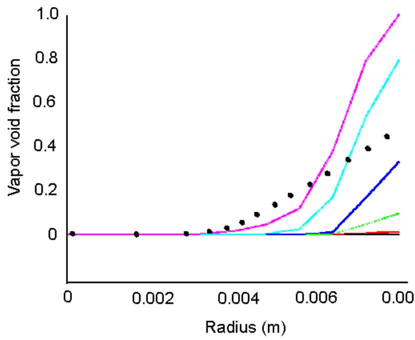

Figure 3: Radial vapor void fraction profiles at the six axial locations described in Figure 1, along with Eulerian multiphase predictions, 1.6m from the inlet [Ref. 2]

standard k-ε model is used for the turbulent conditions. A 2D axisymmetric computational domain consisting of 20,000 cells is used, with 10 cells used to span the pipe radius. Subcooled boiling is observed in the pipe and its main characteristics are computed. These are compared to measurements reported in Reference 1.

Figure 1 displays radial profiles of liquid superheat (in degrees Kelvin) at five axial locations measured from the inlet: 0 (black), 0.4 (red), 0.8 (green), 1.2 (blue), 1.6 (cyan) and 2.0 (magenta) meters. As shown, the bulk liquid becomes superheated at about 1.5 - 1.6 m from the inlet. Figure 2 displays radial profiles of the total vaporization mass source for the wall and bulk components at the same axial positions used in Figure 1. As is evident in the figure, the wall boiling starts about 0.4 m from the inlet, prior to the onset of bulk boiling.

Figure 3 displays radial profiles of the vapor void fraction in the pipe, at the same axial positions used above. The radial profile at the exit (2 m, magenta) shows that the vapor content is almost 100% near the wall, indicating that wall dryout is taking place. This kind of observation is very important in the nuclear industry for the prediction of the so-called Critical Heat Flux, or point beyond which the cooling capacity of the heat exchangers severely degrades. The integrity of the fuel is directly tied to this parameter, since it cannot function properly if the heat generated by it cannot be removed. The figure also shows predictions from an Eulerian multiphase model[2] for the radial profile 1.6 m from the inlet.

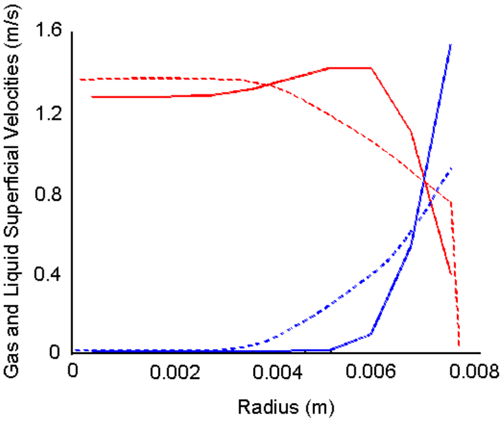

Figure 4 : Radial profiles of gas (blue) and liquid (red) superficial velocities, predicted by the mixture model (solid lines) and the Eulerian multiphase model (dotted lines) [Ref. 2], 1.6m from the inlet

In Figure 4, radial profiles of the vapor (blue) and liquid (red) superficial velocities are shown as predicted by the mixture model (solid lines) and the Eulerian multiphase model (dotted lines).[2] The results in Figures 3 and 4 suggest that boiling is more concentrated near the wall when the mixture model is used than when the Eulerian formulation is used. This is most likely due to the fact that the Eulerian model includes a turbulent dispersion force that causes vapor bubbles to carried by turbulent eddies, thereby increasing the diffusion of vapor into the stream.

Figure 5 displays an axial comparison between the FLUENT predictions and experimental measurements of the area averaged vapor void fraction.[1] A similar comparison of the area averaged temperature superheat is shown in Figure 6. Good agreement is in evidence in both figures. In both cases, the poorest agreement occurs near the pipe outlet, 2.0 m from the inlet. As was suggested in Figure 3, wall dryout happens in this region, and the current model is not capable of handling this condition.

In summary, the RPI subcooled boiling model, implemented within the FLUENT 6.0 mixture model framework, was able to adequately capture subcooled convective boiling in a vertical pipe. Predictions of the area averaged void fraction and liquid temperature superheat were found to be in acceptable agreement with experiment. This suggests that the methodology used can also be used with confidence to study other boiling applications, and implement other boiling models taken from the literature.

References:

1. G. G. Bartolomei, V. M. Chanturiya, Teploenergetika, **14** (2), pp 123-128, 1967.

2. N. Kurul and M. Z. Podowski, 9th Int. Heat Trans Conf., Jerusalem, p, 21-26, 1990.

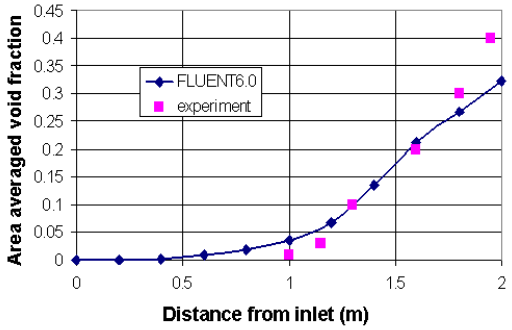

Figure 5: Comparison of FLUENT predictions and experimental measurement for the area averaged void fraction as a function of axial position

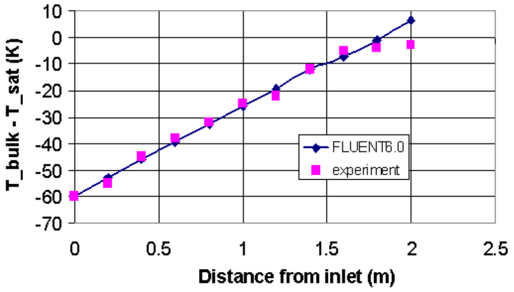

Figure 6 : Comparison of FLUENT predictions and experimental measurement for the area averaged liquid superheat as a function of axial position