Development of the VESUVIUS Code for Steam Explosion Analysis

Part 2 : Verification of Jet Breakup Modeling *

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Abstract In the companion Part 1 paper, the jet breakup model incorporated into the VESUVIUS code was described. Herein, initial verification of the VESUVIUS jet breakup modeling by comparison of calculation results against the PREMIX PM10 and FARO L-14 experimental data is discussed. Predictions of the main experimental parameters, which include steam outlet flow rate and "interaction region" development for the PREMIX test and test vessel pressure and level swell for the FARO test, are shown to be in good agreement with the test data. In addition, the change with time of the jet axial profile and two-dimensional spacial distributions of the jet and coolant, which are not available as experimental data, are discussed in an attempt to further clarify molten jet behavior.

Keywords : Jet Breakup, Interaction Region, Level Swell

1. INTRODUCTION

A continuation of the Part 1 jet breakup modeling description (Vierow, 1998), this paper discusses initial verification of the VESUVIUS modeling. The two experiments which are analyzed involve release of a high-temperature jet into a coolant pool and the subsequent breakup and mixing with the coolant.

The philosophy of the verification process is to show that the VESUVIUS modeling can accurately predict the details of jet breakup scenarios over a wide range of conditions and jet characteristics. The importance of this prediction flexibility

becomes evident when the conditions for actual nuclear reactor scenarios are considered. Since these scenarios are difficult to reproduce experimentally due to large scales of space and time, etc., calculation tools must have the capability to analyze beyond the range of conditions which experiments are conducted under. Further, uncertainties exist, such as in the material properties of molten nuclear fuel mixtures, and the calculation tools must be able to perform parametric studies to cover all possible conditions. In line with this philosophy, the two verification tests were chosen to challenge various aspects of the VESUVIUS modeling under

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different conditions.

2. PREMIX PM10 SIMULATION

2.1 Analysis Description

The first verification calculations of the VESUVIUS jet breakup model have been performed against FZK experimental data from the PREMIX PM10 test (Kaiser, 1997). The PREMIX test is a particularly good verification test for the VESUVIUS code because the primary jet breakup mode was surface stripping from Kelvin-Helmholtz instabilities, which is the jet breakup mode VESUVIUS models.

In the PREMIX test series, the molten jet (Al_2O_3) is released through a nozzle at the bottom of the melt generator into a test vessel with a water pool. As the molten material mixes with the coolant and water evaporates, steam leaves the vessel through four vent pipes. The system is initially saturated at atmospheric pressure.

The test pressure vessel was modeled as shown in Fig. 1. The jet was released in the central radial cell with an inlet velocity of 6.0m/s for most of the injection duration. The total mass, initial temperature, average speed and duration of the melt release were reported to be 20kg, 2600K, 6.0m/s and 0.8 seconds, respectively. The molten jet and particles were treated by the code as the third and fourth components respectively. Since scattered droplets preceded the jet in PREMIX experiments,

Fig. 1 PM10 Analysis Mesh

a small concentration of particles was included in the top 6cm of the coolant pool, just below the jet nozzle.

2.2 Results of PREMIX PM10 Simulations

Fig. 2 shows the comparison of steam flow rates out of the test vessel as calculated by VESUVIUS and measured in PM10. The calculated flow rate fluctuated in good agreement around the experimental data. These results indicate that the jet breakup modeling, increase in heat transfer area between molten material and coolant, and coolant vaporization rates were in order with the experimental phenomena.

For the base case, the diameter of particles breaking off from the jet surface was set at a constant 3mm. The VESUVIUS model includes a mechanistic method for estimating the breakoff particle diameter based on a force balance at the jet surface (Part 1 paper, Vierow, 1998), however the sizes obtained were larger than could be expected. Consequently, within the calculation, the jet disintegrated into particles near the water pool surface. These results will be discussed in conjunction with the parametric study on particle diameters.

The jet profile as a function of time is shown in Fig. 3. At the water surface, the jet diameter was equal to the release diameter during the injection period of 0.6 seconds. With time, the jet penetrated deeper into the water pool and the profile extended towards the vessel floor. Thinning of the jet with depth was a result of breakup and transfer of the resulting particles to the fourth component.

Fig. 2 PM10 Outlet Steam Flow Rate

Fig. 3 PM10 Jet Profile

At later times, the jet also became thinner due to the increasing void fraction in the center region of the vessel. The higher void fraction presented less flow resistance to the jet, allowing it to accelerate freely by gravitational forces. The apparent drop off of the diameter in the bottom 0.04m was due to the jet arriving in the lowest calculation cell, upon which jet behavior is no longer calculated. In this lowest row of cells, molten material was simply assumed to spread outward and further breakup and mixing with coolant was not considered.

At constant elevation, the jet radius decreased at later times due to increasing voiding and steam

velocities in the region around the jet. For example, during the jet injection period of 0.6 seconds, the 0.3 second curve and the 0.6 second curve show the jet having the initial diameter at the pool surface and reaching the vessel bottom. However the 0.6 second curve shows a thinner profile. From equations 17 and 21 of the jet breakup model (Part 1 paper, Vierow, 1998), an increase in steam velocity caused a decrease in the time duration between breakoff events and therefore the jet was thinner at later times. Additionally, since the particle diameter was fixed at 3 mm, the melt-to-coolant heat transfer area and coolant evaporation rate increased. These results are consistent with the steam flow rates of Fig. 2, which increased significantly between 0.3 seconds and 0.6 seconds.

In the experiment, the jet was observed to have fallen through a conical-shaped, three-component "interaction region" which grew radially and axially with time. Similar growth of a highly voided region is also apparent in the Fig. 4 VESUVIUS results. After termination of jet injection, the conical region collapsed and the highly voided region shifted downward as melt spread across the vessel floor.

The growth rate of the interaction region in

Fig. 4 PM10 Water Distribution

the calculation was slightly slower than the experimentally estimated rate for two reasons. Firstly, the melt descent rate was slower in the calculation. The melt front (consisting of particles) reached the vessel bottom at 0.2 seconds in the experiment, and at 0.3 seconds in the calculation. Secondly, un-certainty as to an appropriate void value with which to define the edge of the interaction region and phenomena which are not modeled, such as droplet entrainment, also contributed towards discrepancies.

The effect of changing the diameter of particles breaking off from the jet is shown in Fig. 5. Results for the particle diameter estimated by the mechanistic approach (Equation 18 of Part 1 paper, Vierow, 1998) are shown by Curve 4. The particle diameter was set to $(a_1 - a_2)$ of Equation 18 which resulted in a diameter fluctuating between 4mm and 1cm. As the particle diameter was increased, the heat transfer area between melt and coolant decreased and so the steam generation rate also decreased. Fig. 5 shows this trend toward lower steam flow rates for larger particle diameter.

Without experimental data on the particle size, such a parametric calculation is useful for estimating the average diameter. For the PM10 test, a diameter of 3mm resulted in good agreement between measured and calculated steam flow rates. Local particle distributions should arise, however as discussed above, the mechanistic approach within VESUVIUS predicted particle sizes too large and resulted in underpredictions of the PREMIX flow

rates.

At later times, the curves crossed for two reasons. First, the two-phase water level reached the steam outlet and caused a sudden decrease in the steam velocities. Second, as mentioned above, a model for molten material spreading along the vessel floor and heat transfer correlations for this stratified geometry have not yet been incorporated. The steam velocities recovered from water level effects, however the steaming rate from the vessel bottom became the prime determinant of outlet flow rates and requires verification for long-term calculations.

Regarding breakup up rate, less of the jet reached the vessel bottom intact when larger particles broke off. This is a result of more jet mass being fragmented in a single breakoff event. For smaller particles, the evaporation rate and voiding increased and the interfacial area between the jet and water decreased. Since only water is assumed to exert friction forces on the jet, the jet experienced less flow resistance and descended intact to the vessel floor.

3. FARO L-14 SIMULATION

3.1 Analysis Description

In the FARO L-14 test conducted at the JRC/Ispra facilities, the primary jet breakup modes are considered to be surface stripping and vortex ball breakup. A vortex ball breakup model is not currently included in the VESUVIUS code. However FARO L-14 was chosen as a verification calculation because a continuous jet existed long enough to expect that a significant proportion of the breakup occurred by surface stripping. Further, the test conditions such as a higher pressure and an un-vented vessel challenge the VESUVIUS modeling under conditions different than those of the PREMIX PM10 test.

In the FARO test series, a molten jet (80% $\text{UO}_2 + 20\% \text{ZrO}_2$) is released through a nozzle at the bottom of the release vessel into the test vessel. The jet falls through a gas space and into a water pool, followed by jet breakup and melt quenching. The vessel then pressurizes due to coolant va-

Fig. 5 PM10 Steam Outlet Flow Rate-Particle breakoff diameter as parameter

porization and hydrogen generation. Upon FARO L-14 test initiation, the system pressure was 5.1MPa and the atmosphere consisted of 77% steam and 23% argon.

The test vessel was modeled as shown in Fig. 6. The piping volume out to the closed vent valves was included in the VESUVIUS model as additional gas space at the top of the nodalization. In the VESUVIUS calculation, a 125kg jet at 3073K was released in the central radial cell with an inlet diameter of 0.092m and an inlet velocity of 3.0m/s for most of the injection duration. The molten jet and particles were treated by the code as the third and fourth components respectively.

3.2 Results of FARO L-14 Simulations

For the base case calculation, the diameter of particles breaking off from the jet surface was set at a constant 5mm. Post-test investigation of L-14 debris revealed that 50% of the fragmented melt had a diameter of less than 4.8mm.

Fig. 7 shows a comparison of the test vessel pressure as calculated by VESUVIUS against the experimental data. The timing of initial rise and the trends after the pressure peak are in good agreement. These results are verification of the heat transfer analysis methods since in order to match the pressurization rate, the calculated steaming rate after 3.0 sec. had to be close to the experimental rate. The difference in the total pressure rise is

Fig. 6 FARO L-14 Analysis Mesh

Fig. 7 FARO L-14 Test Vessel Pressure

due to hydrogen generation, corresponding to about 0.4MPa in the experiment. The increase in the argon partial pressure is estimated at less than 0.05MPa and may be neglected for the pressure comparison. VESUVIUS does not model noncondensable gases due to the code limitation of four components (for premixing calculations, steam, water, jet and particles). When an adjustment is made for hydrogen generation, Fig. 7 shows that the VESUVIUS results are in excellent agreement with the measured pressure increase.

The jet profile as a function of time is shown in Fig. 8. General trends are the same as described for PREMIX PM10. Specific to FARO L-14, the jet profile was fairly similar from 0.4 seconds to 0.8 seconds. The jet injection terminated at 1.0 second and after this time, the diameter at the jet tail decreased. From 1.2 seconds on, the axial profile grew thinner than at previous times and a peak occurred below the release point, which is believed to be due to the injection boundary

Fig. 8 FARO L-14 Jet Profile

conditions. This peak does not affect the calculated event progression. By 2.0 seconds, the jet diameter decreased to 5mm and is considered to have completely disintegrated.

Fig. 9 shows the water volume fraction distribution in the test vessel. Since steam was not vented from the FARO vessel and the pool depth was much greater, the development of the voided region was largely different from that in PREMIX PM10. Rather than a conical region that grew radially with evaporating coolant flowing upward, the voided region existed only in the vicinity very near to the melt and vessel pressurization suppressed steam generation. Adopting the FARO L-14 definition of the water level at a 0.95 void fraction, Fig. 9 reveals a level swell of 1.2m from 2.0 seconds to the end of the calculation. This compares well with the experimental level swell of 1.1m at 2.1 seconds which remained nearly constant for the remainder of the 6 second period. The level swell calculation is a confirmation of the heat transfer and interfacial area calculation methods. Further, the melt was assumed to spread on the vessel floor with no further mixing and this simplified modeling is also seen to be reasonable.

As for jet descent rates, the jet arrival at the pool surface was recorded at 0.46 seconds, about 0.06 seconds later than in the VESUVIUS calculation. The jet in the experiment reached the vessel floor at 0.9 seconds and most of the melt arrived by 1.62 seconds. In the calculation, the amount of jet breakup was overestimated and the jet did not arrive at the vessel floor intact. However particles reached the vessel floor at 1.0 second and all of the melt accumulated in the bottom row of cells by 2.0 seconds. The calculated descent rate through the water pool was at most 25% slower than the rate in the experiment.

Post-test experimental data indicate that 105kg of the original 125kg fragmented into particles. In the VESUVIUS calculation, 97% of the jet fragmented. Discrepancy with calculation results is believed to be due to the jet leading edge modeling and the current lack of a vortex ball breakup model.

As for the PREMIX PM10 calculation, the mechanistic method for estimating the breakoff particle diameter predicted average diameters larger than could be expected and the jet was calculated to completely breakup near the water pool surface. Again, a parametric study of the effect of breakoff

Fig. 9 FARO L-14 Water Distribution

Fig. 10 FARO L-14 Test Vessel Pressure-Particle breakoff diameter as parameter

particle size was performed. Fig. 10 shows similar trends as for the PREMIX PM10 simulation. Namely, as the breakoff diameter increased, the steam generation rate decreased and the total pressure rise was less.

4. CONCLUSIONS

Herein, initial verification of the VESUVIUS jet breakup modeling by comparison of calculation results against the PREMIX PM10 and FARO L-14 experimental data has been shown. Predictions of the main experimental parameters, including steam outlet flow rate and "interaction region" development for the PREMIX test and test vessel pressure and

level swell for the FARO test, were shown to be in good agreement with the test data. The progression of other phenomenon not available as experimental data, such as jet and coolant spacial distributions, were also discussed. Two areas requiring model improvement were identified, namely the mechanistic formulation for breakup particle diameter and addition of a leading edge vortex breakup model. Finally, the potential of the VESUVIUS code to predict characteristics such as the average particle size in the PM10 test was discussed. This ability to characterize the debris will be particularly valuable for prediction of containment vessel scenarios and debris coolability.

5. ACKNOWLEDGMENTS

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