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Original Article

Evaluation of jet breakup length with a CFD code under steam generation condition in a pre-flooded cavity

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ABSTRACT

When the reactor vessel is penetrated in a severe accident of light water reactor, the molten fuel-coolant interaction including the jet breakup occurs and the jet breakup length becomes one of the important parameters. Most numerical studies on jet breakup process have been carried out using dedicated computer codes. Some researchers are trying to apply commercial CFD codes to their investigations on comprehensive jet breakup process. However, the complexity of the phenomena limits the CFD application only to hydrodynamic aspects. In the present study, numerical analysis of jet breakup under vapor generation is pursued using the STAR-CCM + code. The obtained CFD prediction of the MATE09 experiment shows jet breakup progression patterns consistent to the images taken in the experiment. Further, the predicted positions of leading head, which determine the jet breakup length, are in good agreement with the MATE 09 data. The investigation of hydrodynamic effects on the jet breakup with higher jet velocity results in a stronger shear force and earlier jet breakup process even though there exists the vapor pocket around the corium jet. In future studies, the effect of vapor intensity on the jet breakup length would be investigated further by changing other parameters.

1. Introduction

Jet breakup mechanism-related researches have been carried out over the last several decades due to the importance in various engineering applications including jet cutting, ink-jet printing, liquid fuel injectors, metallurgy, aerospace propulsion systems, and nuclear industries [1–3]. Regarding a core melt accident, a hypothetical nuclear severe accident in light water reactors, jet breakup process is deeply involved in the safety, which is associated with the containment integrity, of nuclear power plants. According to whether the molten corium, which is mixture of the reactor core and other internal structure materials having low melt temperature, locates inside or outside the reactor vessel, such an accident accompanying fuel-coolant interactions (FCIs) is largely categorized into two different Cases (in-vessel and ex-vessel).

In the Case of an in-vessel, as the accident progresses, the molten corium flows downward, settles, and contacts with water at the lower plenum of the reactor vessel. In the ex-vessel Case of nuclear power plants (NPPs) adopting the wet or pre-flooded cavity strategy, if the failure of the overall emergency cooling system in-vessel accident sustains and worsens, the accumulated thermal loads, the chemical reactions, and the built-up pressurization inside the reactor vessel may lead the bottom head of the reactor vessel to be breached. As a result, through the breach the molten corium is rapidly discharged into the containment cavity filled with water, and sequentially interacts with water. During the transient period of the ex-vessel severe accident, FCI phenomena mainly create not only vigorous multi-physics environments, such as jet breakup and fragmentation, and energetic multi-phase flows including massive steam bubbles due to extreme heat conversion, but also may potentially result in a steam explosion or a molten corium concrete interaction (MCCI). Consequently, the incidents may render the integrity of the reactor containment to be encountered with an imminent threat, afflicting physical damage to the reactor containment boundaries causing the leakage of radioactive fission product to the environment.

In the early stage of the ex-vessel accident, the jet penetrating into the cavity pool surface starts experiencing coarse breakup and fragmentation under the influence of the thermal-hydraulic effects. Through the breakup process, the degree of droplet sizes and breakup length are developed. The sizes of droplets play a crucial role in determining melt-coolant contract area for heat transfer rate

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by which the intensity of rapid steam generation is strongly governed. In the circumstance of no-steam explosion occurrence, the droplet sizes are still act as an influential parameter on the debris bed coolability along with other resultants, such as size distribution [4]; S. [5] and jet breakup length which are determined from the subsequent thermal-hydraulic processes. Practically, in order to minimize the possibility of MCCI occurrence, debris bed porous media through which the coolant naturally circulates to remove the decay heat need to be formed in the debris bed.

It has been known through numerical and experimental analyses that the effective porosity highly depends on droplet sizes as well as the size distribution. Also, it has been known that the jet breakup length is a critical parameter related to determining undesirable conditions, such as debris agglomeration or cake formation [6], for the debris bed coolability [7]. Therefore, over the last serval decades the efforts of many researchers have been dedicated to investigating the comprehensive process of melt jet breakup for nuclear safety. Along with extensive experiment works, numerical analyses on melt jet breakup behavior to aid better understanding fundamentally on the key aspects have been developed using computer codes such as TEXAS, MC3D, and TRACER-II [8].

Generally speaking, investigators [9–12] [22–23] have provided insights into jet breakup phenomenon based on the effect of three combined hydrodynamic erosion mechanisms, which are two interfacial fluid instabilities and boundary layer: Kelvin-Helmholtz instability (KHI), Rayleigh-Taylor instability (RTI), and Boundary Layer Stripping (BLS). According to the location of jet surface, K–H instability is generally applied to the surfaces of jet column falling through the coolant in the reactor cavity pool. Under Kelvin-Helmholtz (K–H) instability, any perturbation renders the interface between two immiscible parallel fluid streams of different velocities to be unstable, creating waves and its growth.

In the meantime, when two flows encounter vertically, R-T instability is basically applied to two vertical flows, and it is taken into account to be a dominant mechanism at the front-leading edge (facing-down edge of mushroom-like jet head) at which wavy flows occur due to the deceleration and density discontinuity. During the R-T and K–H instabilities proceed, the jet undergoes wave creation, wave growth, and wave crest stripping. When the growth of the waves goes over a certain limit, i.e. shear forces overcome the surface tension, a portion of the crests of the waves are broken off the jet surface [10]. Moreover, RTI contributes to further breakup. In another word, the initial drops of large sizes which are generated by both KHI and RTI are deformed and fragmentized into several smaller droplets [12]. At both lateral sides of the jet head, which is called vortex ball or leading edge ball, BLS may be operative as a dominant mechanism until the jet reaches steady-state after the jet enters the water pool [10]. In the process of BLS, the boundary layer of the leading edge is stripped off the jet due to the formation of a jet stagnation flow induced by the dynamic pressure and shear forces [13]).

The complex and rapid thermal-dynamic processes of high-temperature (2300 ~ 2700 ^{o}C) melt jet and water make it challenging to simultaneously analyze and to quantitatively evaluate jet behavior. Hence, focusing on hydrodynamics under adiabatic(non-boiling) condition, numerical and experimental studies to understand the mechanisms and physical processes have been widely carried out. The isothermal simplification may facilitate the quantitative as well as qualitative assessments on the jet breakup, i.e. more accurate measurements on breakup length, fragmentized particle size, etc. are possible, and better visual results are obtainable as not taking thermal effects (e.g., massive vapor generation, phase change) into account.

However, the great importance of thermal aspects on molten corium jet breakup has been never overlooked, and it has been always addressed. Wang et al. [9] stated the strong dependency of jet breakup on steam generation through a numerical modelling approach. A few of well-known experimental works (CCM: [14]; PREMIX: [15]; GPM: [16] dedicated to thermal-hydraulic FCI phenomena have been carried out by using melt jet stream higher than a temperature of 2200^{o}C. To investigate water-melt jet interaction under the influence of massive steam generation, extreme temperatures which are close to actual molten corium jet temperature have been applied to the tests with various parameters such as water temperature, melt mass, nozzle diameter, etc. The obtained data from the test results (e.g., jet breakup length, droplet size distribution, steam flow intensity, etc.) were commonly used to validate their related codes as well as to develop models. Regarding the examination of the jet breakup length, Moriyama et al. [16] assessed GPM tests by comparing the data with Taylor and Saito correlations according to three nondimensional numbers (We, Fr, Bo).

Recently, some researchers are trying to apply commercial CFD codes to the investigation on the jet breakup phenomena. However, due the complexity of the multi-phase, numerical analysis on the jet breakup using CFD codes are carried out mostly under isothermal conditions excluding thermal effects. In the present study, three-dimensional simulations on jet breakup and fragmentation considering thermal effects are conducted using a commercial CFD code, STAR-CCM +. To deal with the numerical work, detached eddy simulation (DES) turbulence model coupled with volume of fluid (VOF) method, which is one of multiphase models for tracking the interfaces between immiscible fluids, is applied to the computation.

2. Numerical methodology establishment of CFD model

As mentioned above, among turbulence models which are embedded in STAR-CCM + code, the DES modelling approach in the Eulerian multiphase framework has been employed in the current analysis. As a hybrid modelling, the DES model applies the features of RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) to boundary layers and unsteady separated regions, respectively; the details are available in the code manual (Simcenter STAR-CCM+, 2020)[24].

Since the interaction of immiscible fluids (melt and water) due to jet breakup in the domain is highly concerned, the interface capture or tracking is of great importance. In the current analysis, among several techniques available to handle the non-penetrating interfaces between fluids, the VOF method has been selected to solve problems involving free surfaces as well as immiscible fluid mixtures. The distribution of phases and the position of the interface are described by the fields of phase volume fraction. The successful applicability of VOF method to simulations related to hydrodynamic jet breakup as well as droplet deformation has been presented by other adopters [17–19].

Since it is a major concern to predict possibly accurate interface phenomena in two phase flows, fine and dense meshes are favored ideally. However, an effort to apply such meshes to the whole simulation domain could practically require an excessive computational cost. Such a circumstance may be mitigated utilizing adaptive mesh technique. Once the mesh refinement is applied to the computation domain, the mesh size and density of critical regions become automatically changeable (increase or decrease) within selected cell size as shown in Fig. 1. In the current simulation, the adaptive mesh technique intensively operates along the jet surface as well as on the periphery of its fragmentized particles. The meshes are constructed using hexahedral cells and the cell size variable; the finest and the coarsest grid have 2.2 mm and 40 mm edge long, respectively.

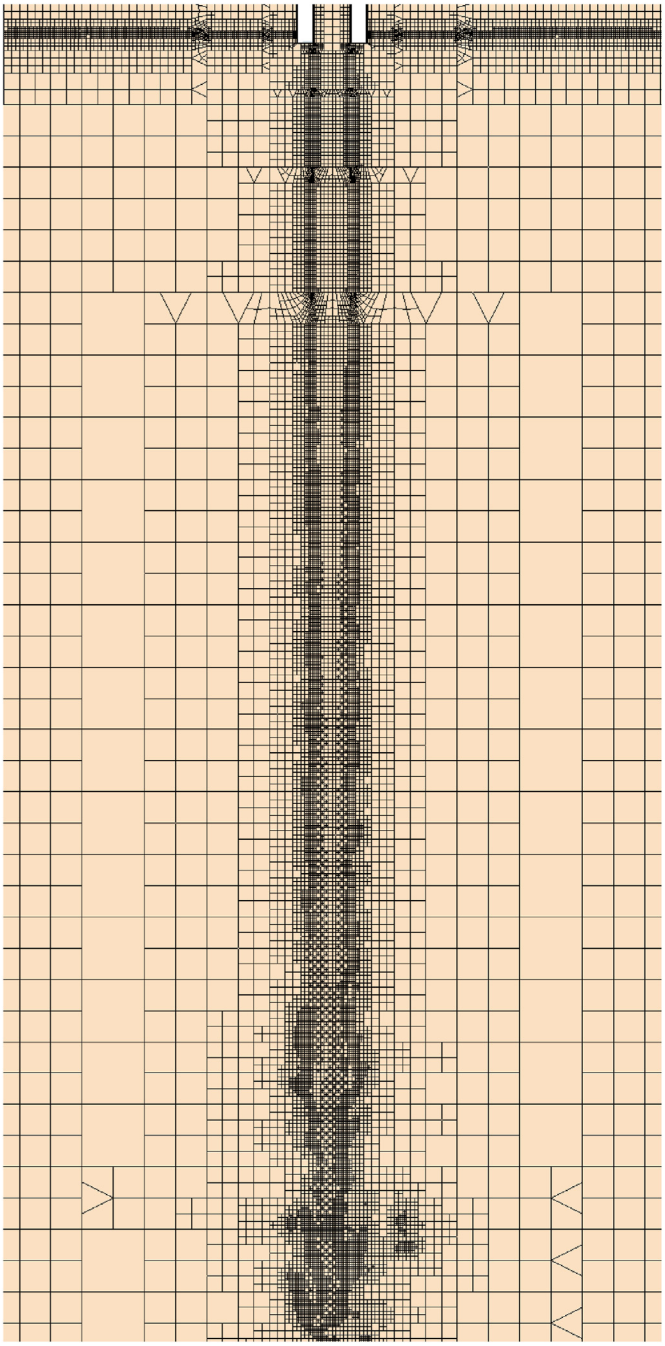


Fig. 1. Adaptive mesh scheme applied to the computational domain.

SIMPLE (Semi-Implicit Method for Pressure Linked Equations) numerical algorithm has been adopted to resolve the pressure-velocity linkage in the momentum equation. Related to control unsteady time-stepping, implicit unsteady solver has been employed. For time-interest transient simulation, the jet breakup analysis has been carried out by maintaining Courant number less than 0.1 for all calculations. Also, upwind scheme has been used to solve the discretized system of equations that the code (STAR-CCM+) constructs from the chosen models and their boundary conditions.

Various heat transfer regimes during the interactions between the discharged melt jet and the coolant take place. In order to reflect thermal phenomena in the simulation, the simulation model has utilized an embedded heat transfer model in STAR-CCM+, which is able to deal with the regimes from natural convection to film boiling.

3. Simulation results and discussion

The capability of a commercial CFD code, STAR-CCM+, has been explored in terms of three-dimensional modeling of jet breakup by taking into accounts heat transfer and phase change, as well as accompanying thermal-hydraulic phenomena in multiphase systems. The validity of the simulation model has been assessed by comparing it with one of the MATE (Melt jet breakup Analysis with Thermal Effect) tests, which is MATE 09 [20] shown as Case 1 in Table 1, has been adopted as a reference experiment for the validity of the simulation model. The MATE facility comprises a rectangular water pool vessel and a crucible for generating and injecting melt jet. The geometry of the water pool is 0.55_{width} m x 0.55_{length} m x 2_{height} m, and at ambient pressure the water pool can be heated up to the saturation temperature. The composition and properties of the melt jet are presented in Table 2. The MATE tests were carried out at POSTECH using a Bi–Sn alloy with the weight percentage of 58/42 as a simulant of corium melt jet. The purposes of the MATE tests were to investigate the changes in jet breakup length according to two non-dimensional numbers, Bond number and Froude number, and to observe the influence of steam generation intensity on jet breakup length.

The geometry of the jet breakup simulation corresponding to MATE 09 test is presented in Fig. 2. The first simulation was implemented based on the conditions of Case 1 shown in Table 1. A solidification of corium jet is not included in the simulation because the temperature of most corium jet is maintained above the melting temperature of the Bi–Sn alloy during the short simulation time and the main concern of the present study is the prediction of the jet breakup length. Fig. 3 (a) shows the simulation results of the melt jet breakup process using the volume fraction of contours of the corium. As the melt jet (250 ^{o}C) penetrates into the water pool, steam is generated due to the heat transfer between the melt jet and the subcooled coolant (60 ^{o}C). Fig. 3 (b), which presents the volume fraction of steam in the calculation, shows that the melt jet is surrounded by vapor film as the jet breakup proceeds. It is observed that the mushroom-like leading edge is fully developed at 0.1 s. Subsequently, the leading edge is deformed, and its surface is stripped, generating some ligaments. Also, based on the color indicating the volume fraction of the corium, it is recognizable for the leading-edge neck to get thinner. This leading-edge deformation and fragmentation can be clearly recognized by comparing Fig. 4 with Fig. 1. As described by Cheng et al. (2020), neck-thinning may be caused by the shear forces from vortex flows which are formed between the jet column and the leading edge, and the lateral surface of the leading edge is stripped by BLS [13]).

The three-dimensional results, presented in Fig. 5, more clearly and qualitatively show the jet breakup and fragmentation process. In the legend of Fig. 5, both blue and red represent the part where the volume fraction of the corium is 0.5. The figure illustrates that as the melt jet descends deeper, irregular waves develop more

Table 1
Simulation conditions of the jet breakup simulation.

	Case 1(MATE 09)	Case 2
Jet injection velocity [m/s].	4	8
Jet free fall distance [m].	0.5	0.5
Jet diameter [mm].	22	22
Coolant temperature [^{o}C].	60	60
Jet temperature [^{o}C].	250	250

Table 2
Properties of the melt jet.

Properties	Bi–Sn alloy
Composition [%]	58 : 42
Density [kg/m^3]	8750[a]
Melting temperature [°C]	138
Specific heat [J/kgK]	159[a]
Surface tension [N/m]	0.4[a]
Latent heat [kJ/kg]	54.9[a]
Kinematic viscosity [m^2/s]	2.88×10^{-7}[a]

[a] The properties are calculated based on the alloy composition ratio.

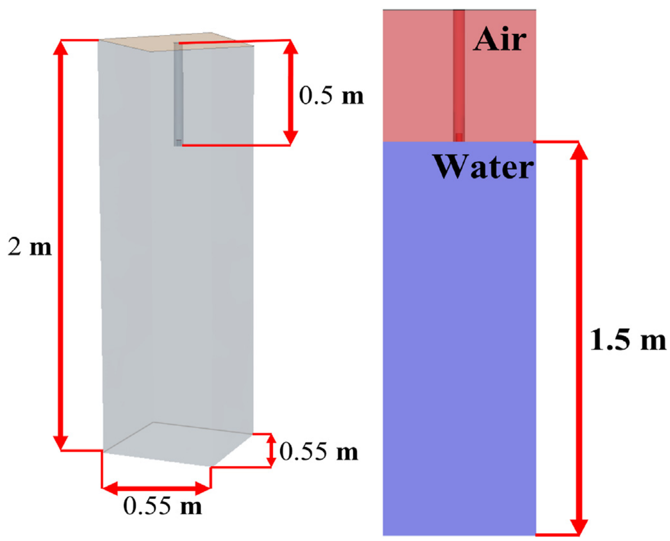


Fig. 2. Domain geometry of 3D jet breakup simulation model.

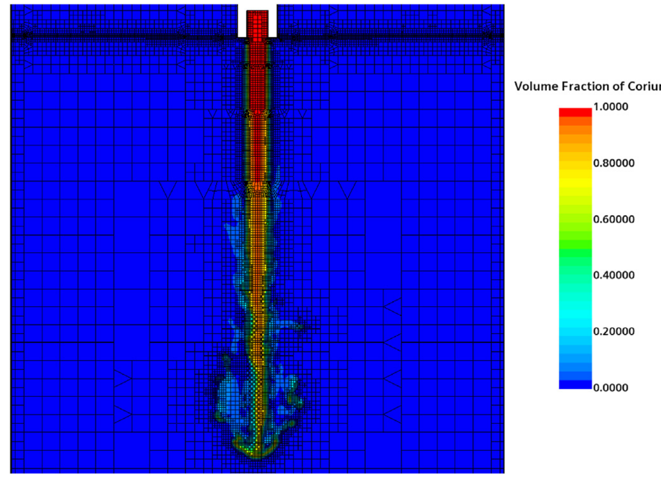
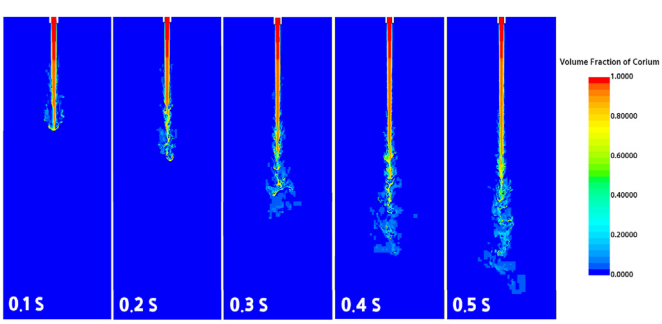


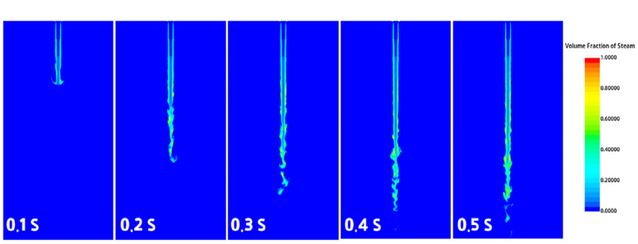
Fig. 4. The corium volume fraction of jet breakup process of case 1at 0.15 s.

intensely on the jet column surface. The stripping of a portion of the wave crests intensifies, which occurs due to the shear stress caused by the relative velocity between the jet and the coolant. As mentioned earlier, this phenomenon may be explained based on K–H instability.

In Fig. 5 (a), only amorphous and irregularly fragmented ligaments are observable around the front surface of the leading edge, making it difficult to determine whether its deformation is associated with R–H instability based on the results of Case 1. However, Case 2 results in Fig. 5 (b), which shows more intermediate snapshots of the evolution of the jet breakup after the fully developed mushroom head, show the exertion of jet breakup mechanism related to the R–H instability. For the qualitative validity of the simulation, MATE 09 jet breakup process images taken by using two high speed cameras are presented in Fig. 6, which displays the

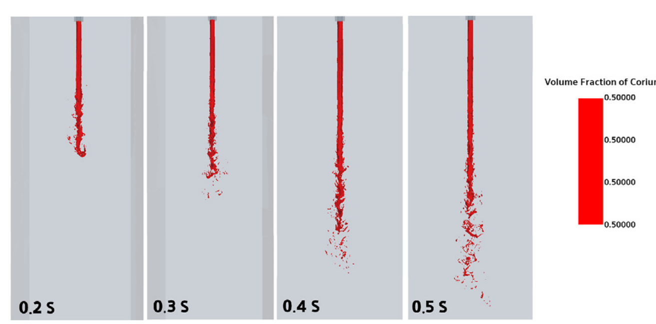


(a) Jet breakup process of case 1 simualtion based on corium volume fraction

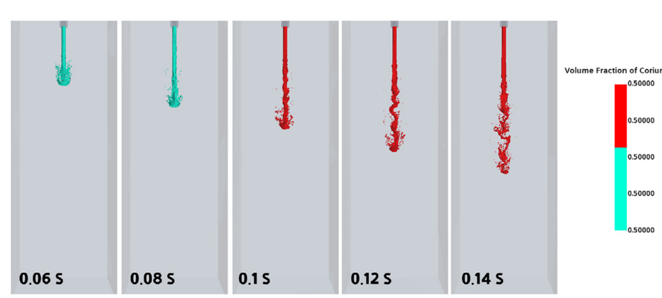


(b) Jet breakup process of case 1 simualtion based on steam volume fraction

Fig. 3. Jet breakup process of case 1.



(a) 3D jet breakup process of case 1(V_{jet} = 4 m/s)



(b) 3D jet breakup process of case 2 (V_{jet} = 8 m/s)

Fig. 5. 3D Jet breakup process.

complexity of all components, including corium jet, debris particles, and steam. However, the simulation result presented in Fig. 5 (a) only shows a three-dimensional domain where the volume fraction of corium is 0.5. This is a way to trace the interface of the corium region having the volume fraction of 0.5, which is used as a reference value for a fine adaptive mesh generation in the simulation. In addition, Fig. 3 shows the changes of volume fraction of corium and steam at a two-dimensional vertical cross-section of the middle part of the calculation domain. As a result, an overall visualization of the jet breakup process is limited in Figs. 3 and 5, which show a narrower jet breakup shape compared to the MATE09 experimental result in Fig. 6. The corium fraction shown in Fig. 3(a) most resembles the overall jet breakup process obtained in the experiment.

The quantitative evaluation of simulation accuracy is carried out through comparing the jet leading positions as illustrated in Fig. 7. The solid circle is the result of the MATE 09 experiment. The red diamond and the red dotted line represent the CFD simulation results and its trend line, respectively. As an approximate expression, the trend line has been created based on the simulation data and is added to express the consistency in the change of the leading-edge position after 0.2 seconds. The simulation shows that the movement of the jet column is consistent with the experiment up to 0.2 seconds, and according to the trend line, the change in the leading-edge position after 0.2 seconds in the simulation well agree with the experiment. Based on the data, the initial jet breakup seems to occur about 0.2 s. After the initial jet breakup, the fluctuation of leading-edge positions takes place around the trend line. This is caused by non-periodic repetitions of the detachment and reattachment of some of the fragmented segments to the jet column. This phenomenon is also addressed by other researchers [18,21].

Additionally, a non-dimensional jet breakup length $(L_b/D_j)/N_\rho^{0.5}$ is computed in terms of a non-dimensional number, Fr (V_j^2/gD_j), using the leading-edge position data mentioned above. N_ρ indicates the density ratio of jet versus coolant ($jet_\rho/coolant_\rho$). As one of important parameters in jet breakup behavior, the jet break length is normally defined as the distance between the free surface of the coolant and the jet neck when the initial separation of the jet head from the neck occurs. Table 3 presents the results of the MATE09 experiment as well as Cases 1 and 2 of the simulation, indicating the time and length of the jet break, along with non-dimensional jet breakup length. The results show that the jet breakup length in Case 1 is similar to the measured data in the MATE 09 experiment. In Case 2, a higher initial injection velocity leads to an earlier occurrence of the jet breakup length compared to Case 1 and the experiment.

In order to investigate the influence of jet velocity on the jet breakup length, the analysis for Case 2 in Table 2 is carried out. The simulation is implemented under identical conditions with Case 1, but an increased velocity, 8 m/s. In Fig. 5 (b), the qualitative results on the jet breakup, obtained for the early stage of jet breakup, are presented, and compared with the simulation result of Case 1. It is clearly recognized that the deformation of the mushroom-like head and the jet breakup initiate more than two times earlier in Case 2 than Case 1. It is seen that the jet breakup of Case 2 takes place between 0.12 s and 0.14 s while the jet breakup of Case 1 occurs between 0.2 s and 0.3 s. Therefore, it is true that the jet breakup length is shorter in Case 2 than Case 1 as summarized in Table 3. It is believed that the increased velocity, with other fixed conditions (jet diameter, density, etc.), may cause stronger shear forces due to the increased relative velocity between fluids. Unlike non-boiling conditions, in the present work, the jet is surrounded by a thin vapor layer, of which function may dampen the shear forces. Before the simulation of Case 2, it was not clear how velocity change affects the jet breakup behavior when taking thermal effects into account under boiling condition. The Case 2 results reveal that the vapor effect is overwhelmed by the velocity effect. In other words, the vapor layer may not be thick enough to neutralize the effect of the increased velocity in this case. The importance of vapor thickness or steam generation intensity in jet breakup process has been emphasized by several researchers.

Fig. 6. Jet breakup process of MATE 09 experimental test [20].

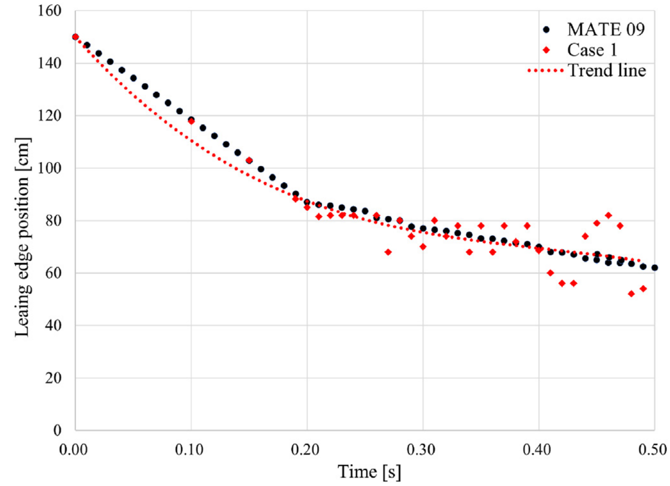


Fig. 7. Comparison of the leading edge positions (MATE 09 vs. Case 1 simulation).

Table 3
The comparison of the calculated jet breakup length.

Parameter	MATE 09	Case 1	Case 2
Time [s]	0.20	0.21	~0.13
Jet breakup length [cm]	63.0	68.5	56.0
Non-dimensional jet breakup length	9.52	10.52	8.06

4. Concluding remarks

In the present study, three-dimensional numerical simulations are performed to explore jet breakup behaviors under thermal effects using a commercial CFD code, STAR-CCM+. For the simulation, DES turbulence model, VOF method, and adaptive mesh scheme are adopted. The MATE09 experiment is analyzed using STAR-CCM+ and the simulation results are compared with the experimental data. The CFD prediction shows a good agreement quantitatively as well as qualitatively. It reveals that based on the corium volume fraction the overall breakup process qualitatively looks similar with the image of MATE 09. Also, it is found that the positions of leading head determining the jet breakup length are predicted to be in good agreement with the MATE 09 data points. Furthermore, it is shown that the applicability of major breakup mechanisms is successfully observed through the simulations.

The significance of the present work could be evaluated as a preliminary overall simulation for jet breakup accompanying phase change as well as vapor generation in subcooled temperature coolant. In the future studies, to get more insights of the thermal effects on jet breakup behavior, it is expected to conduct more simulations under various conditions in which steam is more intensively generated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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