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A Study on the Behavior of Debris around a Sump of a Safety Cooling System

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Abstract

The Regulatory Guide 1.82 recommends an analysis of hydraulic performance of safety cooling System sump when LOCA(Loss of Coolant Accident) occurs in a nuclear power plant. The present study deals with 3-dimensional, unsteady, turbulent and two phase flow simulation to examine the behavior of mixture of reactor coolant and debris in the floor of containment building in conjunction with appropriate assumptions. The dispersed solid model has been adjusted to the interfacial momentum transfer between reactor coolant and debris. According to the results, the counterclockwise recirculation zone had been formed in the region between sump and connection aisle about 376s after LOCA occurs. The debris thickness accumulated on a sump screen periodically increases or decreases up to 2000s, afterwards its peak decreases.

1. Introduction

An Emergency Core Cooling System(ECCS) is designed to prevent a reactor core from melting and overheating after Loss Of Coolant Accident(LOCA). When LOCA occurs, the ECCS initially draws a coolant from a refueling water tank(RWT) and subsequently recirculation actuation signal(RAS) realigns the ECCS pumps to draw a coolant from a containment sump. Since the NSSS is highly pressured, a break during LOCA is expected to result in generating an significant insulation fragments demolishing adjacent insulation materials by an extraordinary momentum force due to an jet impingement[1]. The debris screen is installed in the front of sump to hinder insulation fragments from flowing in the ECCS pumps such as high pressure safety injection(HPSI) pump and low pressure safety injection pump(LPSI). The ECCS pumps could not meet an effective net positive suction head(NPSH) in case that the insulation fragments are accumulated on the sump screen over a design criterion. When their effective NPSH do not meet the required NPSH, the ECCS pumps could be in a critical condition due to a cavity phoenomena.

Regulatory Guide(RG) 1.82[2] recommends that the influence of insulation fragments on the sump hydraulic christeristics be reflected in the design process of the ECCS of a nuclear power plant. This is able to be done from examining the behavior of a mixture of coolant and debris according to the time history after LOCA. The objective of present study is to deal with 3-dimensional, unsteady, turbulent and two phase flow simulation to examine the behavior of mixture of reactor coolant and debris in the floor of containment building in conjunction with appropriate assumptions.

2. Preliminary Assumptions

Since the LOCA mechanism is physically very complicated one, several assumptions have been introduced to predict the unsteady behavior of debris in the present study. The assumption that the location where LOCA occurs is a welding section of the largest pipe in the reactor coolant sytem has been conservatively introduced. The debris was assumed as a nukon which is a kind of insulation substance of steam generator and the containment floor and sump are filled with safety injection water after LOCA. In addition, the coolant source was assummed to originate from RWT during SI mode. However, a portion of this water was supposed to be vaporized due to an ambiant condition within the containment building. Also, a portion of total SI volume is postulated to be unavailable for a long term recirculation mode and collected within some region, such as in-core instrument cavity, cavity sump, containment recirculation sumps, containment normal sumps and suction line of ECCS pumps. In this section, the water level on a containment floor and rate of debris generation are predicted from the several assumptions described above.

2.1 Modelling of containment building floor

The geometry of containment floor and sump were a little simplified to facility a numerical calculation as shown in Fig. 1. The secondary shelter which envelopes the steam generator and reactor core has a geometry of 1.22m in thichness and 14.6m in radius. The sump is isolated by the secondary shelter from the reactor core. The steam generator pedestal, reactor coolant pump pedestal, lube oil tank and sump pumps were included in the calculation domain, except an tri-sodium phosphate baskets. Only a 90^{o}~270^{o} region was selected as an computational domain because of a mirror image of the containment floor. Also, the four sides of sump are named as F1, F2, S1 and S2 for convenience, respectively. A diagram of sump was shown in Fig. 2. The sump was designed to have a trapezoid shape with 4.0m in base, 3.5m in upper and 2.75m in height. Also, the debris screen has a geometry of a rectangle with 4.58m in width and 3.36m in height. In the present study, an upper section of debris screen was considered as a rectangle with 4.58m in width and 3.36m in height. The region under the containment floor was excluded from a computational doamin. Accordingly, the computational domain of sump was considered as the four surfaces including deris screen.

2.2 Determination of water level

The containment floor and sump are filled with safety injection water after LOCA. Then, the following assumptions were adjusted to determine the water lever above the containment floor. During SI mode, the water source is RWT with a capacity of 2928m^3. The total useful water volume is 73.7% of RWT[3] and its instrumental channel has a reading error of 9.4% in the present model. In addition, a portion of water source is supposed to be vaporized in an ambient of containment building during SI mode. Under these assumptions, the water volume filled in the containment floor, V_t was calculated as follows;

$$V_t = (0.737 - 0.094) \cdot V_{RWT} = 1878 m^3 \tag{1}$$

The evaporation rate of coolant was estimated by 2 HPSI pumps, 2 LPSI pumps and 2 CSS with a capacity of 4656lpm, 19302lpm and16956lpm, respectively. The time for pumping the volume of SI water, V_t into the containment was calculated as follows;

$$t = \frac{1878 m^3}{(4656\text{lpm} + 19302\text{lpm} + 16565\text{lpm}) \times 2} = 1371 s \tag{2}$$

The evaporated coolant volume, V_e was estimated based on pressure-temperature profiles of the general design guide of nuclear power plant[4]. The average saturation temperature at 1371s was shown as 130°C from that guide. At a given saturation temperature and pressure, V_e can be claculated from the specific volume of saturated water and vapor as follows;

$$V_e = V_{cont} \times (1/n_g) \times n_\ell = 128m^3 \qquad (3)$$

where ν_g and ν_l represent the specific volume of saturated water and vapor, respectively. The available volume, V_r which could be filled with SI water was deduced by subtracting the evaporated water volume and an unavailable volume from total water volume, V_t. The unavailable volume from V_{un} was resonablely assumed to be 539.1m^3 from the design diagram[5,6,7] in the present study. Therefore, the minimun water depth above the containment floor, D_{min}, by the available volume of SI water for a long-term recircualtion is equal to;

$$D_{min} = V_r \ / A_r = 1.12m \qquad (4)$$

2.3 Debris generation

Debris generation from pipe failures within the containment due to pipe whip, pipe impact and jet impingement is considered. The jet impingement generates an jet forces that will cause a fine insualtion debris. An assumption has been conservatively made in this calculation that the largest pipe in the Reactor Coolant System(RCS) is postulated to break. The break is postulated to occur at the welding connection between steam generator nozzle and RCS hot leg. This is expected to result in a significant damages to the insulation material from the jet impingement forces, and generate a significant insulation debris. Under the above assumption, the volume of debris generation, V_{INS} is assumed to be 6.1m^3 according to the reference[9].

3. Numerical Analysis

3.1 Governing equations

The coolant as a continum phase and solid debris as a dispersed phase were assumed to coexist after LOCA. The Euler-Euler model was incorpolated to calculate the two-phase flow for a mixture of coolant and debris. The 3-dimensional unsteady mass conservation equation, momentum equation, turbulent kinetic equation and turbulent kinetic energy dissipation equation were simultaneously solved for an continum phase and dispersed phase, respectively.

<u>Mass conservation eq.</u>

$$\frac{dr_i r_i}{dt} + \nabla(r_i r_i \vec{v}) - D_{r,i}\nabla(r_i) = 0; \quad i = 1 \sim 2 \qquad (5)$$

$$r_i = \frac{V_i}{V_c} \qquad (6)$$

Where r_i, V_c and V_i represent the volume fraction of i-th phase, the volume of continum phase and the occupied volume by the i-th phase. The subscript, i represents the coolant (i=1) and debris(i=2). ρ, $\vec{v}$ and t represent density, velocity vector and time, respectively. The third term of LHS of eq.(8) represents the turbulant diffusion due to an irregualr movement of dispersed pahse. D_r is the function of the density of each phase, turbulent kinematic viscosity, ν_t and laminar kinematic viscosity, ν as follows;

$$\begin{cases} D_{r,1} = r_1(n + n_t) & ;\ \text{for continum phase} \\ D_{r,2} = r_2(n + n_t) & ;\ \text{for dispersed phase} \end{cases} \qquad (7)$$

<u>Momentum equation for i-th phase;</u>

$$\frac{dr_i\, r_i \vec{v}_{i,i}}{dt} + \vec{v}_{i,j} \bullet \nabla r_i\, r_i \vec{v}_{i,i} = -r_i \frac{dp_i}{dx_i} + r_i D_{f,i} \nabla^2 \vec{v}_{i,i} + D_{r,i} v_{i,i} \nabla^2 r_i + S_{ip} \tag{8}$$

$$\begin{cases} D_{f,1} = r_1 (n + n_t) & \text{; for continum phase} \\ D_{f,2} = r_2 (n + n_t) & \text{; for dispersed phase} \end{cases} \tag{9}$$

Turbulent kinetic energy equation;

$$\frac{dr_1\, r_1 k}{dt} + \nabla r_1\, r_1 \vec{v}_1 k = r_1 (m_1 + \frac{m_t}{s_k}) \nabla^2 k + (m_1 + \frac{m_t}{s_k}) k \nabla^2 r_1 + r_1 (G - re) \tag{10}$$

Turbulent kinetic energy dissiapption equation;

$$\frac{dr_1\, r_i e}{dt} + \nabla r_1\, r_1 \vec{v}_1 e = r_1 (m_1 + \frac{m_t}{s_k}) \nabla^2 e + (m_1 + \frac{m_t}{s_k}) e \nabla^2 r_1 + r_1 \frac{e}{k} [C_1 G - C_2\, re] \tag{11}$$

S_{ip} and $D_{\phi,i}$ represent the source term due to momentum transfer between phases and diffusion coefficient, respectively. Turbulent viscosity, m_t, generation term, G and turbulent constants, C_1, C_2, C_m, s_k, s_e are as follows;

$$m_t = C_m r \frac{k^2}{e}, \quad G = 2 m_t \frac{\partial v_i}{\partial x_j} \tag{12}$$

$$\begin{aligned} &C_1 = 1.44, C_2 = 1.92, \ C_m = 0.09, \\ &s_k = 1.0, \ \ s_e = 1.3 \end{aligned} \tag{13}$$

3.2 Momentum transfer

The mechanism of momentum transfer between each phase in two phase flow is generally classified into the drag force, lift force and pressure indifference. In the present study, the drag force which is the most important mechanism for the present two-phase model is only considered and is expressed as follows;

$$S_c = \frac{3}{4} \cdot \frac{C_d}{D_p} \cdot r_c \cdot r_c \cdot r_d \cdot |v_{slip}| \cdot (v_d - v_c) \tag{14}$$

$$S_d = \frac{3}{4} \cdot \frac{C_d}{D_p} \cdot r_c \cdot r_c \cdot r_d \cdot |v_{slip}| \cdot (v_c - v_d) \tag{15}$$

Where, S_c, S_d, C_d, D_p, r_c,, r_c , r_d , v_{slip}, v_c and v_d represent the momentum source of continum phase, monentum source of dispersed phase, drag coefficient, particle diameter, density of continum phase, volume fraction of continum phase, relative velocity, velocity of continum phase and velocity of dispersed phase. The drag coefficient, C_d was obtained from the correlation of Clift et al.[10] which was defined according to Reynolds number based on debris diameter and relative velocity.

3.3 Modelling of debris

The material of debris during LOCA was assumed as nukon and its density and void fraction are 30 ~ 140kg/m^3 and 0.9~0.93, respectively[11]. The nukon was assumed to break as ideal sphere with 1cm in diameter. In addition, the nukon is supposed to be completely wetted by coolant due to a forceful jet momentum. The density of an ideal debris, r_{nw} was obtained from coolant density, r_w, nukon density in air, r_{nd}, pure density of nukon, r_s and air density, r_a as follows;

$$r_{nw} = a r_w + (1-a) r_s = a r_w + (1-a) \times \frac{r_{nd} - e r_a}{1-e} = 1049 kg/m^3 \qquad (16)$$

3.4 Initial and boundary conditions

At an initial stage, the debris was assumed to be uniformly distributed in the inner region (R<14.6m) and the initial volume fraction was deduced from the rate of generated debris, V_{INS}. The coolant was postulated to be stagnanted and no debris exsit between outer region of the secondary shield(15.8m<R<22m). An appropriate boundary conditions had been given as follows. The inlet was assumed to an upper section of inner region of the secondary shield and the minium water level remained unchanged during LOCA. The outlet is the four surafces(F1, F2, S1 and S2) of sump and the debris can not pass through the sump screen.

4. Method of Numerical Analysis

The commercial CFD code, PHOENICS, was utilized to analyze the unsteady behavior of deris in the present study. The covariant velocity component with the staggered grid system was selected as the dependent variable for the velocity. The grid system consists of 48 x 3 x 76 cells, along x, y and z direction, respectively. The hybrid scheme as a spatial scheme and IPSA(InterPhase Slip Algorithm) to obtain the pressure field were employed respectively. The computation was preformed until 3600s after LOCA and this total time was divided into 400 time step. Eighty iterations at each time step were required to secure convergence and this took about 6 days on IBM PC Pentium II with CPU 266MHz and RAM 128Mbyte. In order to achieve the convergence, two kinds of under relaxation devices, linear and false time relaxation, were employed during the iteration process. Linear relaxation(relaxation factor=0.2) was applied to the pressure and the temperature while a false time step type of relaxation was applied to the velocity components.

5. Results and Discussions

The debris volume accumulated in the sump screen, $V_{n,i}$ was obtained by integrating the debris volume as follows;

$$V_{n,i} = \sum_{cell} [cell\ volume \times r_2\ ] \qquad (17)$$

The velocity at each outlet, v_i was extracted from vloume flow rate at each outlet and the deris thickness, e_i was given from the debris volume divided by outlet area as follows;

$$v_i = \frac{Q_i}{A_i} \qquad (18)$$

$$e_i = \frac{V_{n,i}}{A_i} \qquad (19)$$

5.1 Distributions of velocity vector

Fig. 3 shows the vecocity vector of coolant at the vicinity of containment floor at the time of t=37s, 90s, 222s, 376s, 637s and 1513s, respectively. The coolant at inner region of the secondary shield is shown to pass through the connection aisle in Fig. 3(a) which represents the velocity vector at t=37 after LOCA. Two recirculation zone is formed after passing through the connection aisle. The recirculation zone is more developed at t=90 and the upper recirculation zone rotates counterclockwise, whereas the lower recirculation revolves clockwise.

It is seen in the Fig. 3(c) at t=222s that the flow field is more vigorously developed at the left side where the oulets locate than the right side of computation doamin. The coolant is initially approaching the sump and shows a little defection toward F1 surface. At 376s, the a big single recirculation region rotating counterclockwise is examined between the sump and the connection aisle. Since the velocity vectors after t=637s and t=1513s show a similar fashion, the flow field of coolant seems to be in a steady state after t=637s.

5.2 Debris behavior

Fig. 4 shows the debris volume fraction, r_2 at the same time step which represents the velocity vector. It is seen that the debris with an initial volume fraction of 0.014 gushes out the connection aisle in the inner region of secondary shield at t=37s. The debris region at t=90s is expanded 3~4 times than that of at t=37s. At 222s, the debris region with the shape of mushroom is examined and the debris is approaching at the screen for the first time.

It is observed at t=637s that the debris has finished one round trip between the sump and connection aisle. Therefore, one may estimate that the time for debris to round between the sump and connection aisle is required about 600s. Since the outlet is located in the left side of containment foor, a lower volume fraction of debris is examined in the right side of containment floor at most of the time. Since all the debrises initially staying in the inner region of the secondary shelter move into the outer region of the secondary shelter, no debrises are found in the inner region of the secondary shelter in Fig. 4(f) representing debris volume fraction at t=1513s.

5.3 Hydraulic performance of sump

Fig. 5 shows the mean veocity vector, v_i at the four surfaces according to the time after LOCA. The velocity vector varies vigorously during the time step of 200s ~ 400s. This may give the clue that the debris starts to approach to the debris screen at t=200 and the debris via sump leaves the sump at t=400s. The F1 and F2 show a higher mean velocity vector because they are normal to the main flow direction, whereas S1 and S2 show a lower velocity vector because of its parallel geometry to main flow direction. The mean velocity vector periodically increases or decrease with an interval of about 400s because of unsteady nature of LOCA.

Fig. 6 shows the debris thickness at the four surfaces according to the time after LOCA. The debris thickness grows linearly during the time of 200s~400s for all the surafaces, afterwards it repeatedly increases and decreases. The mutual analogy of sudden change of debris thickness and velocity vector during the time interval of 200s ~ 400 s provides a resonable validation of present calculation. The debris thickness increases every 600s, whereas it decreases at the other surfaces. This provides the fact that the time for debris to passing around connection aisle via sump is 600s and its periodic behavior is continuously repeated. Also, the debris thichkness, 0.52m shows its maximum at t=2200s.

6. Conclusion

The present study deals with 3-dimensional, unsteady, turbulent and two phase flow simulation to examine the behavior of mixture of reactor coolant and debris in the floor of containment building in conjunction with appropriate assumptions. The following results were obtained;

1. The counterclockwise recirculation zone had been formed in the region between sump and connection aisle about 376s after LOCA occurs. The debris thickness increases at the interval of 600s, whereas it decreases at the other surfaces.
2. The time for debris to passing around connection aisle via sump is 600s and its periodic behavior is continuously repeated.
3. The debris thichkness, 0.52m shows its maximum at t=2200s.

7. References

(1) NUREG 0897,1985, “Containment Emergency Sump Performance,” Rev. 1.

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(8) Korea Power Engineering Company, “Containment Building Concrete Outline Dimensional Control plan Drawing,” 9-311-C118-001, Rev.1.

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(10) Clift R., Grace J. R. and Weber M. E., 1978, Bubbles, Drops and Particles, Academic Press, pp. 111-114.

(11) Kaviany M., 1991, Principles of Heat Transfer inPorous Media, Springer-Verlag, New York, pp. 20~20.

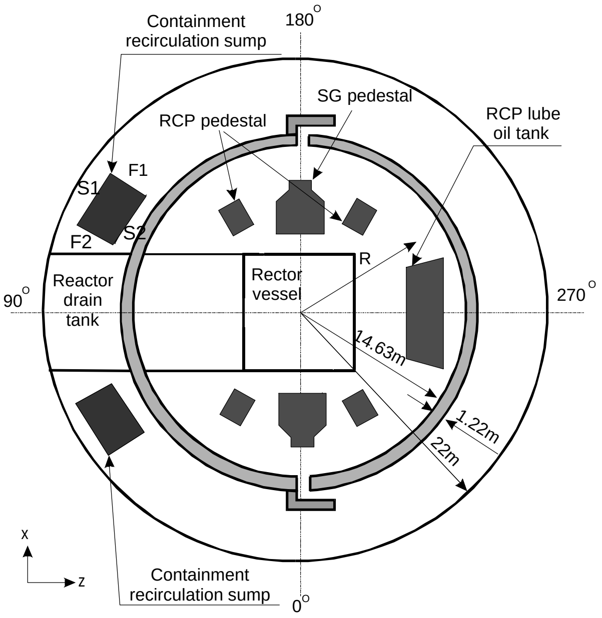


Fig. 1 Modelling of containment building at El. 26m

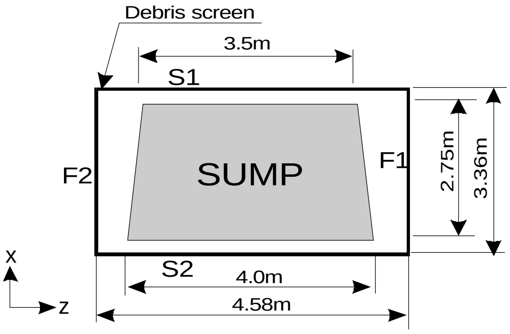


Fig.2 Schematic diagram of top surface of

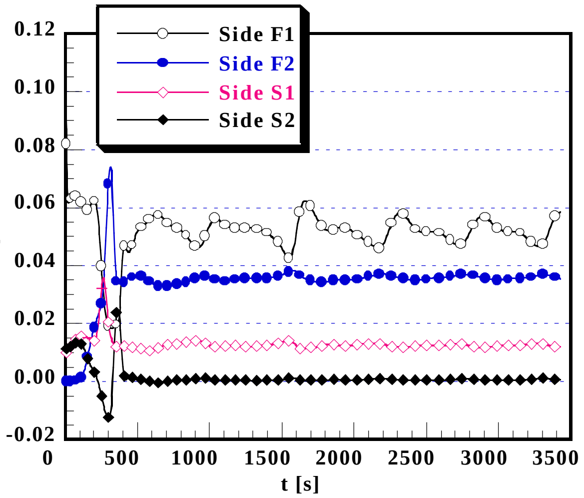


Fig. 5 Outlet velocity at the four surfaces of sump along time after LOCA

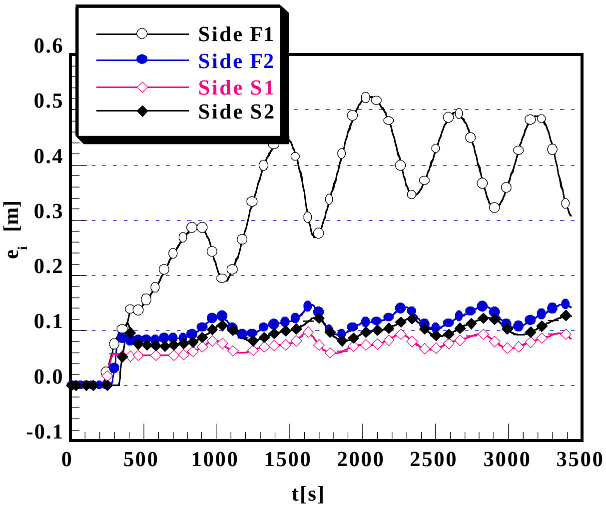
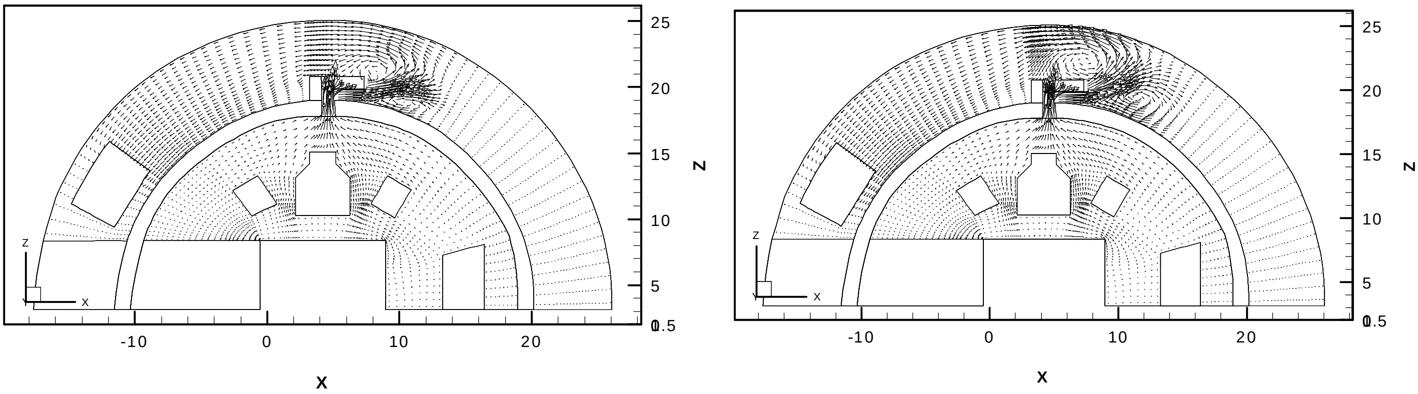
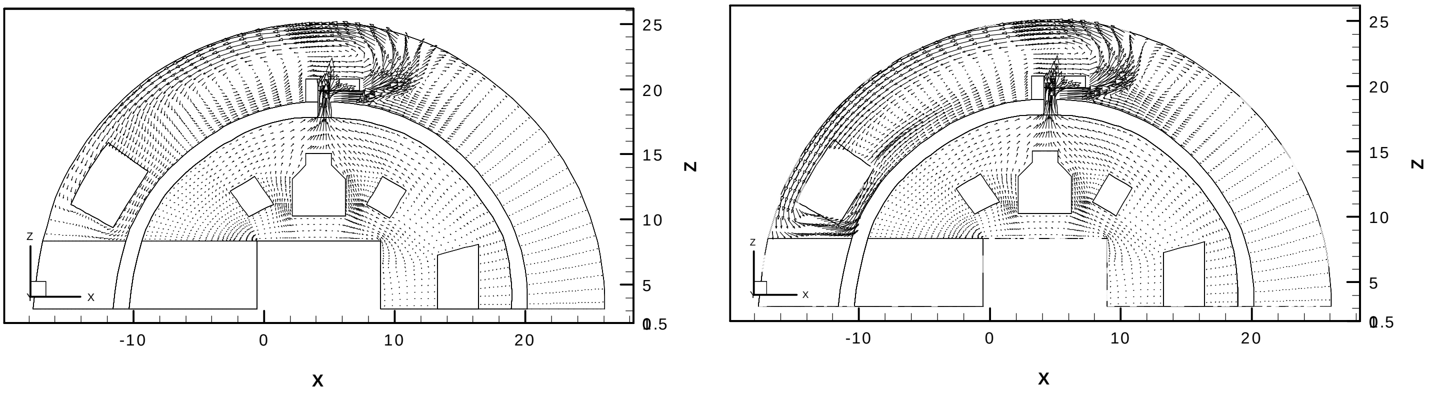


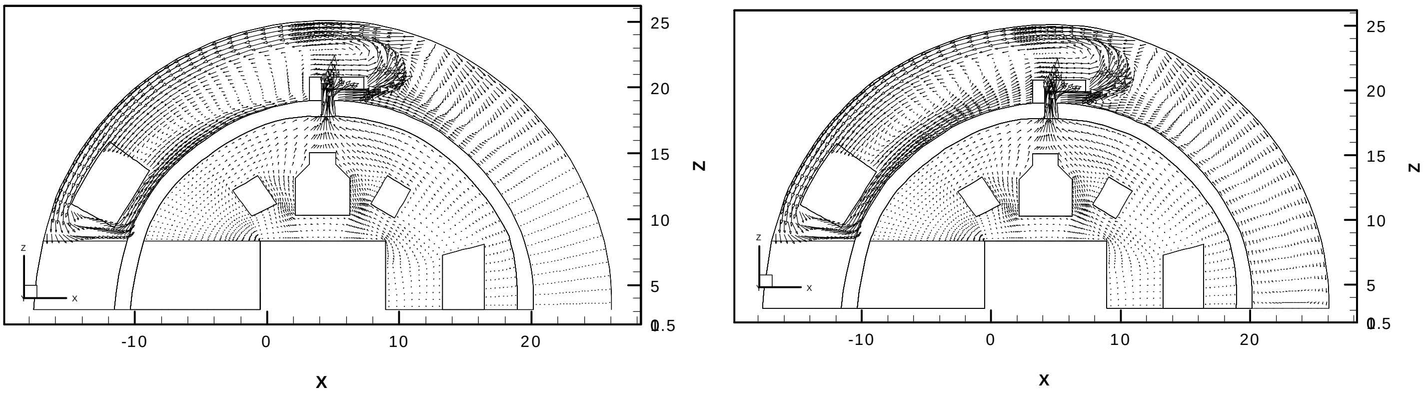
Fig. 6 Debris thickness at the four surfaces of sump along time after LOCA



(a) t=37 (b) t=90

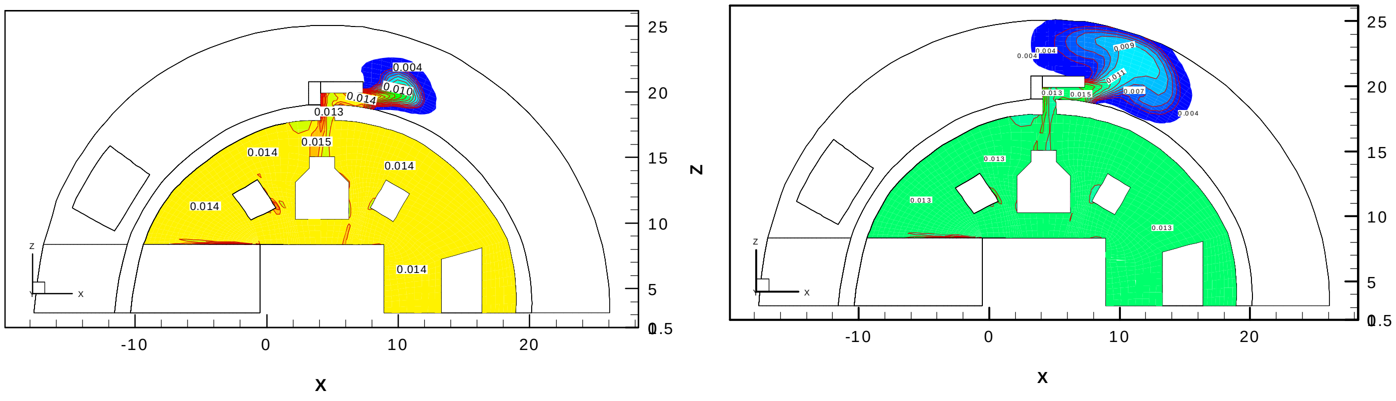


(c) t=222 (d) t=376

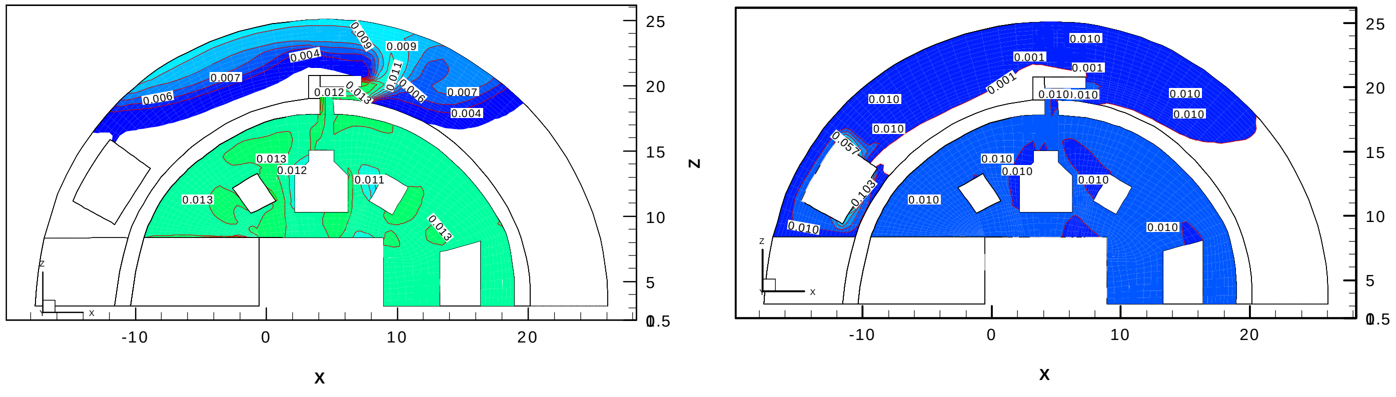


(e) t=637 (f) t=1513

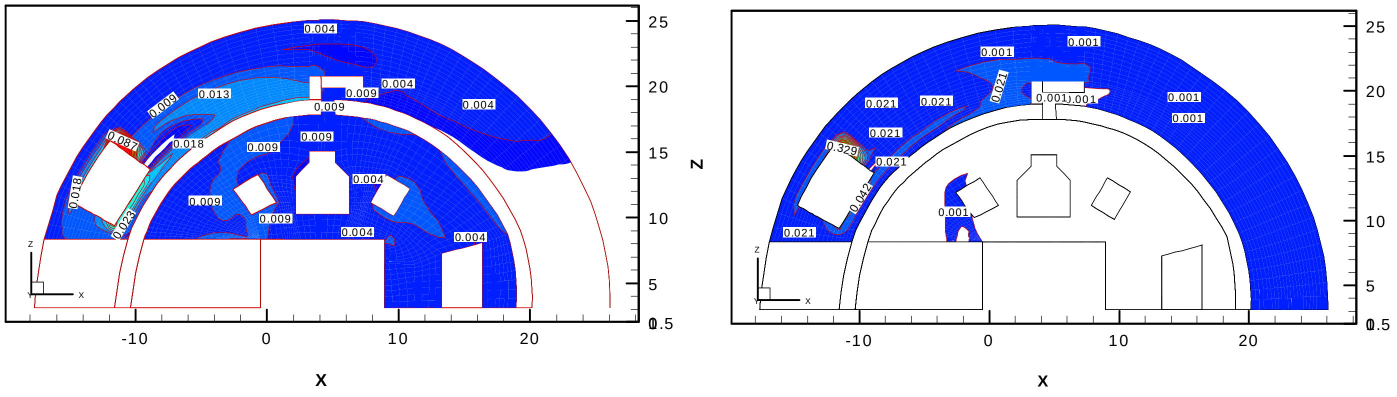
Fig. 3 Velocity vector around a floor of containment building after LOCA



(a) t=37 (b) t=90



(c) t=222 (d) t=376



(e) t=637 (f) t=1513

Fig. 4 Volume fraction of debris around containment building after LOCA