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Evaluation of the Safety Issue Concerning the Potential for Loss of Decay Heat Removal Function due to Crude Oil Spill in the Ultimate Heat Sink of Nuclear Reactors

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1. Introduction

A barge crashed into a moored oil tanker at about 7:15 a.m., Dec. 12, 2007, dumping around 10,500 tons of crude oil into the sea in Korea. The incident took place about 15 kilometers northwest of Manripo beach in South Chungcheong where is Korea's west coast in the Yellow Sea. In a few days, the oil slicks spread to the northern and southern tips of the Taean Peninsula by strong winds and tides. As time went the spilled oil floating on the surface of sea water was volatilized to become tar-balls and lumps and drifted far away in the southern direction. 13 days after the incident, some of oil slicks and tar lumps were observed to flow in the service water intake at the Younggwang nuclear power plants (NPPs) operating 6 reactors, which are over 150 km away from the incident spot in the southeastern direction. According to the report by the Younggwang NPPs [1], a total weight 83 kg of tar lumps was removed for about 3 days.

Oil spills in the sea can happen in any country or anytime due to human errors or mistakes, wars, terrors, intentional dumping of waste oils, and natural disasters like typhoon and tsunami. In fact, there have been 7 major oil spills over 10,000 tons that have occurred around the world since 1983. As such serious oil spill incidents may happen near the operating power plants using the sea water as ultimate heat sink. To ensure the safe operation of nuclear reactors it is required to evaluate the potential for loss of decay heat removal function of nuclear reactors due to the spilled oils flowing in the service water intake, from which the service water is pumped. Thus, Korea Institute of Nuclear Safety identified this problem as one of the important safety.

When an incident of crude oil spill from an oil carrier occurs in the sea near the nuclear power plants, the spilled oil can be transported to the intake pit, where all service water pumps locate, by sea current and wind drift (induced) current. The essential service water pumps take the service water from the sea and supply to the component cooling water heat exchangers to remove the decay heat. The service water system shall provide sufficient cooling capacity during the reactor normal operation, transients, and loss-of coolant accidents (LOCAs). Specially, the ultimate heat sink is required to have a capacity of supplying the cooling service water over 30 days following a LOCA occurrence and the temperatures of cooling service water supplied to the safety-related components shall not exceed the design-basis values [2]. In this regard, first of all it is very important to confirm if the cooling function of the service water system can be threaten due to the ingression of the spilled oil floating on the surface of sea water in the intake area.

Thus, in this work, when an incident of crude oil spill occurs in the sea near a nuclear power plant using the sea water as the ultimate heat sink, the possibility of crude oil ingression into the component cooling water heat exchangers through the essential service water pumps has been evaluated in a conservative manner. In addition, the critical sea water level below which the oil begins to be sucked in the pump inlet nozzle has also been calculated. To do this, the unsteady flow field surrounding a service water pump in an intake pit initially filled with a limited volume of sea water of which the surface is covered with thick layer of spilled crude oil has been simulated numerically using a CFD (Computational Fluid Dynamics) code called CFX-5.11 [3].

2. Analysis

2.1 Definition of problem

Figure 1 shows the geometry of the analysis model of an intake pit including an essential service water pump. For simplicity and efficiency in numerical simulations, the unsteady flow field surrounding a service water pump in an intake pit initially filled with a limited volume of sea water, of which the surface is covered with a thick layer of spilled crude oil, has been modeled.

In this work, the CFD analysis is performed to predict the possibility of crude oil ingression into the component cooling water heat exchangers through the essential service water pumps and the critical sea water level below which the oil begins to be sucked in the pump inlet nozzle. The upper side of the thick oil layer is at atmospheric conditions. The pump flowrate $\dot{Q}$ is assumed to be 2.0 $m^3/\sec$ or 4.0 $m^3/\sec$. To consider the effect of the amount of oil drifting in the sea water surface on the critical sea water level conservatively, the initial thickness of spilled oil layer is set to be 0.5 m for the present analysis as shown in Fig. 2.

2.2 Governing equations

To closely simulate the flow behavior during the entire pumping out, the transition of laminar flow to turbulent flow is considered with the standard $\kappa - \varepsilon$ turbulent model. Additionally, the inhomogeneous three-fluid model is used for the simulation of the air-oil-water three-phase flow. The Reynolds-Averaged Navier-Stokes equations for conservation of mass, momentum, and turbulent quantities for the present problem in a Cartesian coordinate system are given as in reference [4].

2.3 Boundary and initial conditions

The boundary conditions specified for the present problem are the no-slip boundary conditions for wall surfaces, constant flowrate condition for the pump inlet, and opening condition for the top surface of air space above the liquid (water or oil) free surface. Initial conditions are necessary to perform the present transient analysis. The initial water level $z_{w_i} = 3.5\ m$, and the initial velocity $U_i = 0.0\,m/\sec$ are specified. In addition, the volumes of air, oil and water are set to occupy each space. In other words, the volume fractions of water VF_w and oil VF_o with water level z_w and oil level z_o can be defined as,

$$VF_o = 0\,,\ VF_w = 0\,,\ \text{ if } z_o \le z \qquad (1)$$

$$VF_o = 1\,,\ VF_w = 0\,,\ \text{ if } z_w \le z < z_o \qquad (2)$$

$$VF_o = 0\,,\ VF_w = 1\,,\ \text{ if } z < z_w \qquad (3)$$

Also, the volume fraction of air VF_a is defined as $1-(VF_o + VF_w)$. The initial pressure condition is applied to the region occupied with water to consider the static pressure of water as follows,

$$p_i = \rho_o \cdot g \cdot (z_o - z) \cdot VF_o\,,\ \text{ if } z_w \le z < z_o \qquad (4)$$

$$p_i = \rho_o \cdot g \cdot (z_o - z_w) \cdot VF_o + \rho_w \cdot g \cdot (z_w - z) \cdot VF_w\,,\ \text{ if } z \le z_w \qquad (5)$$

3. CFD analysis

Air or oil ingression into the essential service water system can affect the reactor safety by deteriorating the decay heat removal function. The air or oil ingression into a pump taking water from a tank filled with water or sea water covered with an oil layer having a free surface contacting with atmospheric air can be prevented by accurately predicting the critical water or sea water level below which the oil or air starts to flow in the pump inlet. Previous works related to this problem were performed by J. C. Jo et al [4, 5] and B. T. Lubin and G. S. Springer [6]. However, their works address simple problems that the water initially filled in a tank is drained downward through the outlet hole located at the bottom of the tank by a pump. If the outlet drain port installed at the bottom of a water tank has a three dimensional and complicated shape with the horizontal connection pipe on the side wall of a cubic sump, the analytical approach may not be available as in the previous works [4, 5]. Furthermore, because the direction of discharging flow through the pump is vertically upward, it is more difficult to address analytically.

Therefore, in this work, the flow fields around a vertical centrifugal pump inside the intake pit which is filled with three stratified fluids of sea water, oil, and air are numerically simulated using the finite volume method built in the CFX-5.11 [3]. For simplicity and efficiency, the pump model has been simplified as a vertical cylinder. As the pump runs, the fluids enter the inlet nozzle of cylinder at a height of 0.5 m from the bottom of the pit and flow upward as depicted in Fig. 2.

To simulate and analyze the flow behaviors during the entire phase of discharge, the transition of laminar flow to turbulent flow is considered. In addition, to calculate the air-oil-water three-phase flow, the inhomogeneous three-fluid model is applied, and for the flow boundaries of the pit inner wall and the cylinder outer wall, the wall function method and no slip conditions are applied. The calculation was performed with the transient mode and the physical time step set to 0.01sec with 100 of the maximum number coefficient iterations per time step.

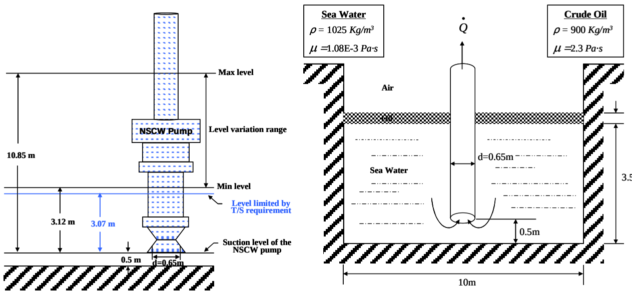

Fig. 1 Schematic and analysis model of a sea water intake pit with an essential service water pump at PWR nuclear power plant

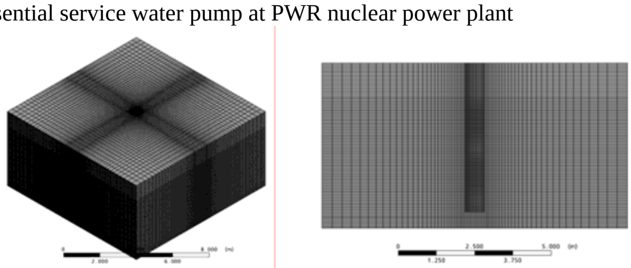

Fig. 2 Mesh of the CFD calculation model

4. Results and Discussion

The calculation domain is discretised into hexahedral meshes (see Fig. 2) with over 400,000 nodes for the cases of oil layer thickness 0.0 m or 0.5 m and with over 3,000,000 nodes for the case of oil layer thickness 0.05 m . Fine meshes are generated for the oil layer, the periphery of the vertical cylinder modeled as the pump, and the pump inlet nozzle region. When the sea water occupies the intake pit with a level of 3.5 m , the total initial sea water volume of the pit is 10.0 m × 10.0 m × 3.5 m = 350.0 m^3 . Hence, the water level is estimated to fall from the initial height of 3.5 m to the level of pump inlet nozzle (0.0 m) at about 175 sec after the start of draining.

As an illustration, the velocity vectors for the case of oil layer thickness 0.5 m and pump flowrate $\dot{Q} = 2.0\ m^3/\text{sec}$ are displayed in Fig. 3. Figure 4 shows the time histories of volume flowrates of oil and sea water in cases of $\dot{Q}_{out} = 2.0\,m^3/\text{sec}$ and $4.0\,m^3/\text{sec}$. Figure 5 shows comparison of oil layer dip formation between both cases of $\dot{Q}_{out} = 2.0\,m^3/\text{sec}$ and $4.0\,m^3/\text{sec}$.

The numerical simulation results show that in general, the oil covering the free surface of sea water in the intake can hardly flow into the pump inlet until the oil changes into tars which are heavier than the oil as long as the sea water level does not fall below the limit value specified in the Technical Specification of each nuclear plant. It is also shown that the critical sea water level increases as the pump flowrate increases. This is physically plausible considering the effect of gravitational force.

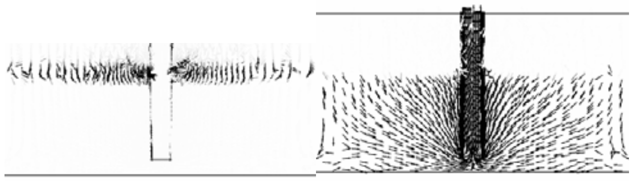

Fig. 3 Velocity vectors in case of $\dot{Q}_{out} = 2.0\,m^3/\text{sec}$

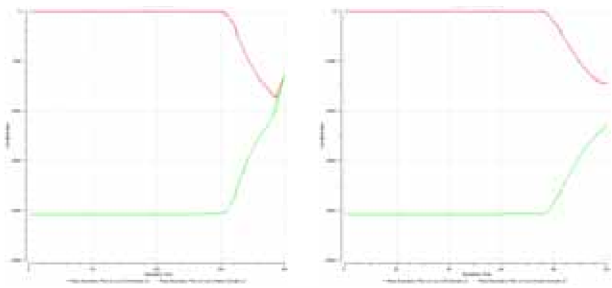

Fig. 4 Volume flowrates of oil (red line) and sea water (green line) in cases of $\dot{Q}_{out} = 2.0\,m^3/\text{sec}$ (left) and $4.0\,m^3/\text{sec}$ (right)

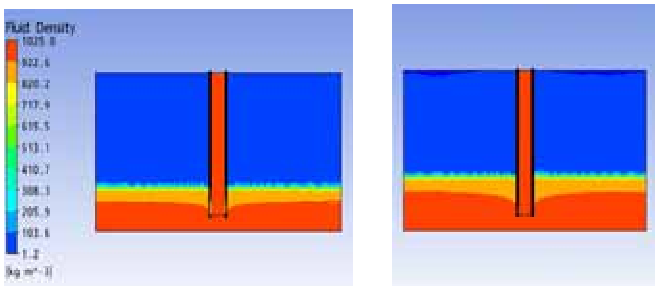

Fig. 5 Oil-dip formations for $\dot{Q}_{out} = 2.0\,m^3/\text{sec}$ (left) and $4.0\,m^3/\text{sec}$ (right)

5. Conclusions

In the case where a crude oil spill incident occurs in the sea near a nuclear power plant using the sea water as the ultimate heat sink, the possibility of crude oil ingression into a service water pump was evaluated successfully.

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