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The Effect of Coriolis Force on the Formation of Dip on the Free Surface of Water Draining from a Tank

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1. Introduction

When the water level in a tank is below the critical height, a dip starts to develop, thus causing air ingression into the drain line before the water drains fully, as shown in Fig. 1.

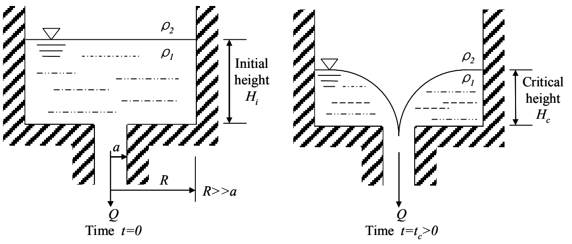

Fig. 1 Schematic of dip formation on the free surface of a draining liquid.

For the case of RWT (refueling water tank) connecting to the ECC (emergency core cooling) line, it can be surmised that there is a possibility of ECC pump failure due to air ingression into the ECC supply line even before the RWT is drained away. Therefore, it is important to check if the operational limit of the RWT water level is set at a value higher than the critical height that causes a dip formation on the free surface of a draining liquid.

In the previous work [1], such complex unsteady flow fields both in a simple water tank as shown in Fig. 1 and in the RWT at the Korean standard nuclear power plant have been simulated using the CFX5.10 code [2] which is well-known as one of the well-validated commercial CFD (Computational Fluid Dynamics) codes. However, for the simplicity of those calculations the Coriolis force has not been taken into account.

Thus, in the present paper, the effect of Coriolis force-induced vortex flow on the dip formation of dip has been investigated for the simple water tank (see Fig. 1) to confirm validity of the previous work [1]. To do this the unsteady flow fields accompanied by vortex in the simple water tank as shown in Fig. 1 has been simulated using the CFX5.10 code

2. Mathematical Formulation

2.1 Governing Equations

To closely simulate the flow behavior during the entire discharging phase, the transition of laminar flow to turbulent flow is considered with the standard k-ε turbulent model. Additionally, the inhomogeneous two-fluid model is used for the simulation of the air-water two-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 can be expressed as follows [2],

<u>Mass conservation equation of phase α</u>

$$\frac{\partial (r_\alpha \rho_\alpha)}{\partial t} + \nabla \bullet (r_\alpha \rho_\alpha U_\alpha) = S_{MS\alpha} + \sum_{\beta=1}^{N_p} \Gamma_{\alpha\beta} \tag{1}$$

where $S_{MS\alpha}$ is the mass source, r_α, ρ_α, U_α are the volume fraction, density, and velocity of α phase, respectively. N_p is the total phase number. $\Gamma_{\alpha\beta}$ is the mass flow rate per unit volume phase β to phase α. The summation of volume fractions is unity.

<u>Momentum conservation equation of phase α</u>

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha U_\alpha) + \nabla \bullet (r_\alpha \rho_\alpha U_\alpha \otimes U_\alpha) - \nabla \bullet \left(r_\alpha \mu_{\alpha eff}\left(\nabla U_\alpha + (\nabla U_\alpha)^T\right)\right) \tag{2}$$
$$= -r_\alpha \nabla p_\alpha^{'} + r_\alpha(\rho_\alpha - \rho_{ref})g - 2 r_\alpha \rho_\alpha \omega_\alpha U_\alpha + M_\alpha$$

$$p_\alpha^{'} = p_\alpha + \frac{2}{3}\rho_\alpha k_\alpha, \quad \mu_{\alpha eff} = \mu_\alpha + \mu_{t\alpha}, \quad \mu_{t\alpha} = C_\mu \rho_\alpha \left(\frac{k_\alpha^2}{\varepsilon_\alpha}\right) \tag{3}$$

where μ_α, p_α, k_α, ε_α, C_μ are the viscosity, pressure, turbulence kinetic energy, turbulence dissipation rate of phase-α and the constant value (=0.09), respectively. The 3rd term on the right side of Eq. (2) is the Coriolis force. The 4th term M_α denotes the sum of interfacial forces acting on phase-α due to the presence of other phases. The operator $\otimes$ is a tensor product and $(\nabla U_\alpha)^T$ is the transpose of a matrix ∇U_α.

<u>Interfacial forces acting on phase α</u>

$$M_\alpha = \sum_{\beta \neq \alpha} M_{\alpha\beta} = \sum_{\beta=1}^{N} c_{\alpha\beta}^{(d)}(U_\beta - U_\alpha) + \sum_{\beta=1}^{N}\left(\Gamma_{\alpha\beta}^{+} U_\beta - \Gamma_{\beta\alpha}^{+} U_\alpha\right) + \ldots \tag{4}$$

$$p_\alpha = p, \quad \alpha = 1,2,\ldots\ldots, N \tag{5}$$

2.2 Boundary and Initial Conditions

The no-slip boundary conditions for wall surfaces, constant velocity conditions for outlets of drain pipes, and opening conditions for top surfaces of air spaces above water free surfaces have been specified as in reference [1].

Initial conditions are necessary to perform the present transient analysis. The initial water level $z_{w_i} = 4.0\ ft = 1.22\ m$, and the initial velocity $U_i = 0.0\ ft/\sec = 0.0\ m/s$ are specified. In addition, the volumes of air and water are set to occupy each space. In other words, the volume fraction of water VF_w with z_w of water level can be defined as,

$$VF_w = 1, \text{ if } z < z_w, \quad VF_w = 0, \text{ if } z \geq z_w \tag{6}$$

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

$$p_i = \rho_w \cdot g \cdot (z_w - z) \cdot VF_w \tag{7}$$

3. CFD Analysis

Previous research related to the present problem was performed for a very simple problem by B. T. Lubin and G. S. Springer [3]. When the two fluids with the different densities are initially stationary forming the layers in the tank, the dip can be generated due to the drop of fluid level with high density through the discharging cylindrical pipe located at the bottom of the tank.

When the upper part of the reservoir occupied by water has a free surface and is exposed to the atmosphere, the numerical simulation of the dip formation accompanied with vortex flow due to Coriolis force and its behavior inside the reservoir during the forced discharging through the bottom port is presented in this work. In the previous work [1], the CFX-5.10 code [2] utilized in this simulation has been demonstrated to have the applicability to the simulation of the complicate air-water two-phase flow field considered herein.

Thus, the same problem as in references [1,3] is chosen to investigate the effect of Coriolis force-induced vortex flow on the dip formation of dip and the acceleration of draining using the finite volume method built in the CFX-5.10 [3]. To simulate and analyze the flow behaviors 3-dimensionally during the entire phase of discharge, the transition of laminar flow to turbulent flow is considered with the standard k-ε turbulent model. In addition, to calculate the air-water two-phase flow, the inhomogeneous two-fluid model is applied, and for the structure of the tank and inner wall, the wall function method is applied.

4. Results and Discussion

The radii of reservoir and discharging pipe, initial water level, discharging flowrate, water and air densities for the benchmarking problem are R = 0.114 m, a = 0.013 m, Hi = 0.051 m, Q = 0.25 $kg/\sec$ kg/s, ρ_w = 1,000 kg_m/m^3, and ρ_a = 1.39 kg_m/m^3, respectively. The time step for the transient computation is 0.01 sec.

Calculations have been performed for the following 6 cases. ① The case where the Coriolis force is neglected. ② The real situation of earth rotation. The imaginary cases where the earth is assumed to rotate ③10 times per day, ④ 100 times per day, ⑤ 1000 times per day. ⑥ The case where the flow field in the tank is subjected to a specified initial rotational velocity of 0.1 $m/\sec$ which is equivalent to about 250,000 revolutions per day.

Figure 3 shows the water volume fractions at the elapsed times of 5.0 sec, 5.5 sec, and 6.0 sec after starting of draining from the tank of which the initial water level is 0.053 m for the 3 cases ①, ②, ③, and ⑥. The figure displays the time history of the free surface movement and dip formation for a second.

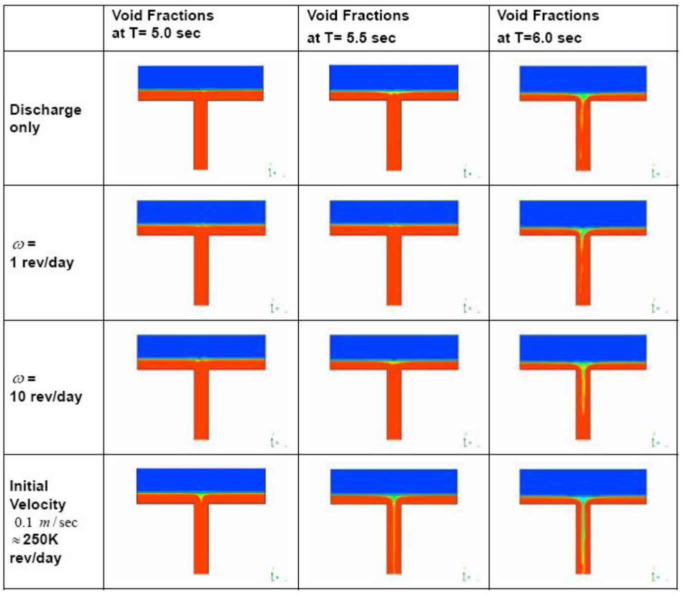

Fig. 3 Water Volume Fractions

As shown in the Fig. 3, for the cases ①, ②, and ③ the time at which the dip begins to form hardly differ from each other while for the case ⑥ where the initial velocity of 0.1 $m/\sec$ is specified the dip begins to form earlier than the former three cases. In the case of ⑥, the dip begins to form at about 5.0 second after the start of draining and air entrainment into the drain line occurs at 5.5 second.

Figure 4 shows the water velocity vectors and streamlines on the free surface at the elapsed time of 6.0 sec for the 6 cases. The free is defined as the iso-surface on which the void fraction is 0.5. As seen from the figures, the vortex flow hardly forms even if the Coriolis force increases up to 10 times i.e. $\omega = 100\, rev./day$. However, for the case ⑤ where the force is assumed to increase further the dominant vortex flow forms.

Thus, it is seen that the effect of Coriolis force caused by the earth rotation on the formation of dip is negligible because the force is so week compared to other forces. However, the vortex flow forming a dip earlier can be caused more likely by initial stirring of water in a tank, asymmetry of water tank structure, eccentric drain flow, etc as in the case ⑥ where the initial rotation velocity is specified.

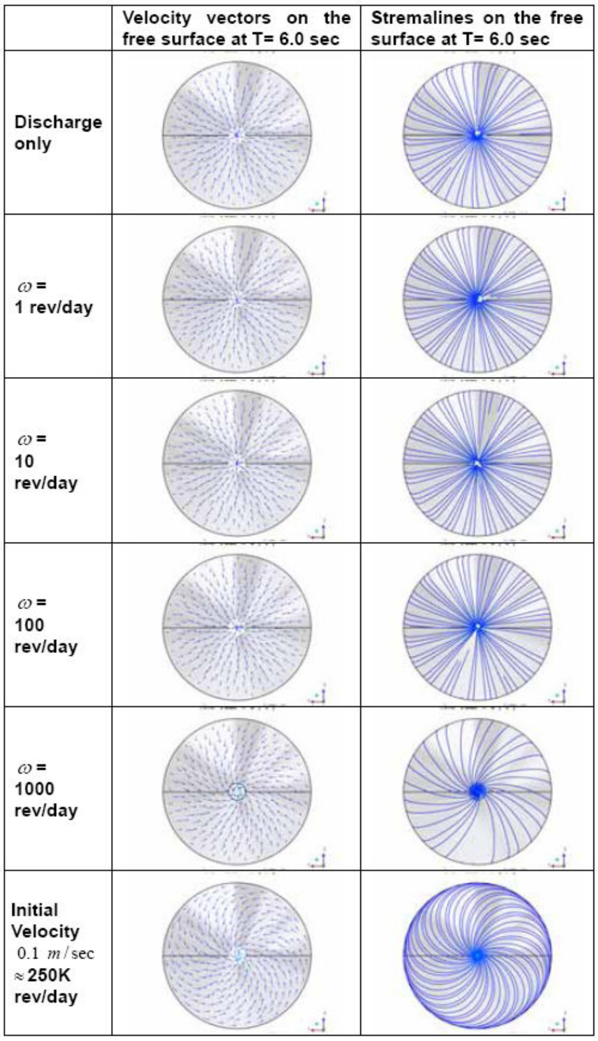

Fig. 4 Water velocity vectors and streamlines at the free surface

5. Conclusions

In this work, the effect of Coriolis force-induced vortex flow on the dip formation of dip has been investigated for the simple water tank to confirm validity of the previous work.

CFD calculations have been performed to simulate the unsteady flow fields in a simple water tank under draining for the 6 cases where the magnitude of angular velocity causing the Coriolis force is specified differently each other.

Based on the CFD calculation results, it is concluded that the effect of Coriolis force caused by the earth rotation on the formation of dip is negligible because the force is so week compared to other forces.

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