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Numerical simulation of vortex in residual heat removal system during mid-loop operation

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ABSTRACT

Free surface vortex, especially in a pattern of full air core vortex, causes serious security problems in the residual heat removal system. Vortex in a T-junction pipe system was numerically investigated under the premise that the simulation results are in agreement with the experimental results. First, four typical states were obtained in the formation and evolution process of vortex, namely, surface dimple, critical submergence state, air entrainment vortex state, and large air entrainment state. With increasing Froude (*Fr*) number, the time from an initiate flow field to the critical submergence state decreased, and the time interval between critical submergence state and large air entrainment state increased. Finally, the variation law of vortex intensity was analyzed during the evolution process. The vortex intensity initially increased with time and reached its maximum value and then decreased until it reached a minimum value before the large air entrainment state. With the increase of *Fr*, the maximum values of vortex intensity gradually increased.

1. Introduction

Free surface vortex easily forms in outlets and causes harmful hydraulic and mechanical problems. Air entrainment, especially that induced by vortex, often occurs in nuclear power systems (Ezure et al., 2011; Moudjed et al., 2016; Tenchine et al., 2014; Yamaguchi et al., 2011). One potential scenario is vortex-induced air entrainment in residual heat removal system (RHRS), which play a vital role in the safe operation of nuclear power units (Tong et al., 2009). During a mid-loop operation, vortex-induced air entrainment greatly influences the RHRS of nuclear power units (Chang and Lee, 1995) and the normal operation of downstream pump systems, thereby directly affecting the safety of nuclear power systems. Therefore, investigating air entrainment and the variation law of free surface vortex is necessary.

The formation and evolution mechanism of vortex is relatively complex. As shown in Fig. 1, the patterns of vortex are generally classified into surface dimple, air entrainment vortex, and full air core vortex (Knauss, 1987). Surface dimple usually evolves into air entrainment vortex and full air core vortex. Pressure in a vortex core gradually reduces with the decrease of water level, which would entrained more air. As shown in Fig. 2, a critical submergence state exists in the evolution of vortex (Odgaard, 1986). At this state, the bottom of the vortex reaches the outlet. The rapid formation of air entrainment vortex and full air core vortex at water levels lower than the critical submergence often results in serious engineering issues.

For the prevention of these issues, analyzing the vortex and studying its formation and evolution mechanism comprehensively are vital. A number of studies were performed for the study of free surface vortex by theoretical analysis, numerical simulation, and experiments. Theoretical formulas expressed in terms of dimensionless number are significantly beneficial to the prediction of the critical submergence state. Odgaard (1986) proposed an empirical formula about critical submergence after disregarding the role of surface tension to predict the vortex formation process. Hite and Mih (1994) derived the velocity expressions of the free surface vortex. Saleh et al. (2011) developed a theoretical analysis to predict critical submergence at a branch-off pipe system. Bowden and Hassan (2011) performed gas entrainment experiments in a reduced T-junction pipe, and they compared the critical submergence results to publish models. Their study has poor agreement with studies conducted in stratified gas–liquid reservoirs. Experimental flow visualization methods were used for the measurement of the velocity distribution of the flow field, velocity circulation and shape of vortices. Constrained by the experimental structure, cylinder and rectangle tank were mostly used as test section for the acquisition of the flow field information of vortices. Monji et al. (2008) used PIV measurements to obtain the velocity field and circulation of intake vortices

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Nomenclature

D	diameter of main pipe
L	length of transition section
d	diameter of vertical pipe
Re	Reynolds number
We	Weber number
Fr	Froude number
h	free surface level
h_{cr}	critical submergence
z	vertical distance
k	turbulent kinetic energy
V_{θ}	tangential velocity
g	gravitational constant
t	time
P	pressure
S	Swirling Strength
I_S	vortex intensity
U	velocity
A	circular slice

Greek symbols

ν_{air}	air content
ε	turbulent rate of dissipation
ρ	density of the liquid
μ	turbulence viscosity
ω	specific dissipation rate
λ	dynamic viscosity

Acronyms

CFD	computational fluid dynamics
RHRS	Residual Heat Removal System
SST	Shear Stress Transport
RNG	Re- normalization group
PIV	Particle Image Velocimetry

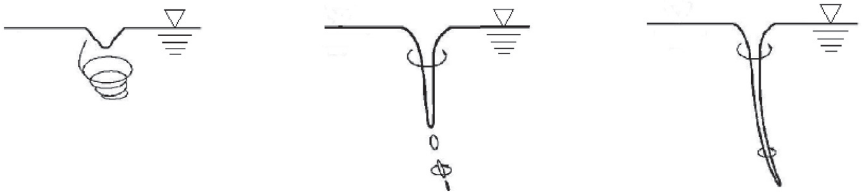
(a) Surface dimple (b) Air entrainment vortex (c) Full air-core vortex

Fig. 1. Classification of free surface vortex (Knauss, 1987).

in a cylindrical vessel. Amiri et al. (2011) performed acoustic Doppler velocity measurements to obtain the velocity field. An experiment concentrated on intake vortex at the bottom outlet was carried out by Wang et al. (2011). Time-averaged velocity fields of a vortex at pump-intakes were studied by Rajendran and Patel (2000). PIV measurements were conducted in a large-scale hydraulic intake model by Keller et al. (2014), and the surrounding velocity field of air core intake vortex with air entrainment was obtained. With the development of computational fluid dynamics, numerical simulation has become a common method of researching the intake vortex problem owing to its low cost and direct visualization results. Ahn et al. (2017) successfully simulated vortex flow and obtained the effect of surface vortices on operating conditions in tidal power units. Sakai et al. (2008) proposed an air entrainment design criteria based on a computational fluid dynamics method for two types of air entrainment phenomena from a vortex dimple. Constantinescu and Patel (1998) calculated the flow in the pool by using the k-ω turbulence model and the k-ε turbulence models, respectively. The results of the two turbulence models were analyzed and compared, and the numerical simulation results accurately showed the location, strength, and size of the swirl inside the pool. Škerlavaj et al. (2014) proposed a single phase simulation for free surface vortex with different turbulence models. They concluded that the simulation results obtained by SST k-ω model with curvature correction were in good agreement with the experimental results.

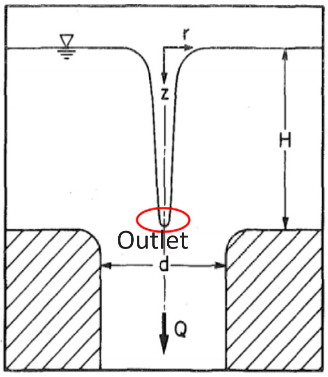

Fig. 2. Sketch of critical submergence (Odgaard, 1986).

The study of vortex in residual heat removal systems should not focus only on the judgment of critical submergence. Effective ways for preventing air entrainment problems can be determined by the thorough investigation of vortex-induced air entrainment and exploration of the formation and evolution mechanism of vortex. Few studies concentrated on the characteristics of vortices in T-junction pipes, especially during numerical simulation. Numerical simulation method can be used for extensively investigating vortex movement. Numerical simulations can give more information about flow field, such as velocity distribution, vortex intensity distribution and air content at a certain location.

In this paper, the RHRS was simplified as a T-junction pipe system, and free surface vortices under different operating conditions were investigated through numerical simulation. The formation and evolution process of a vortex was obtained, and variations in flow field characteristics were analyzed. Time intervals between the critical submergence state and large air entrainment state were obtained under different conditions. Variation in vortex intensity during the formation and evolution process of vortex were analyzed. This study can provide theoretical support for the nuclear power units under mid-loop operation.