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A Study on the Free Surface Vortex in the Pipe System

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배관내 자유수면에서 와류현상에 대한 연구

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Abstract

During mid–loop operation of Nuclear Power Plant, to prevent the Decay Heat Removal System (DHRS) from failure due to air entrainment of free surface vortex in the piping system, a set of simulating experiments was performed. Through these experiments, a relation between the non–dimensionalized numbers, such as H/d, Froude number, Reynolds number, was found. It was also found that the perturbation of the system by the disturbance such as pump start, valve operation, etc., has a strong effect on the free surface vortex. Furthermore, from viewpoint of reactor safety, a modified inlet device which is reducer type is strongly recommended for the prevention of air entrainment into DHRS.

요 약

원자력 발전소에서 Mid-loop 운전시 배관내에서 발생하는 자유수면 와동으로 인해 잔열 제거계통 배관내 공기가 흡입될 가능성이 있으며 이로 인한 계통상실 방지를 위하여 수위와 흡입유량과의 관계를 실험을 통해서 H/d, 프라우드수, 레이놀즈 수 등과 같은 무차원 수로 구하였다. 실험결과 레이놀즈수는 크게 영향을 미치지 않았으며 주로 프라우드수가 자유수면 와동을 지배하는 것으로 판명되었다. 한편 운전시 펌프나 밸브의 개폐로 인한 수면의 섭동이 와동에 많은 영향을 미치는 것이 밝혀졌다. 원자력 발전소의 안전과 관련하여 배관내에서 와동으로 인한 공기흡입 방지책으로 Reducer형의 흡입구 개선방안을 제시하였다.

1. Introduction

Through the life time of a reactor, there are many times mid–loop operations in which the reactor coolant system (RCS) is partially filled with the coolant. During this operation mode, the power from fission is negligible, while power from decay heat of fission product is dominant. Until recent year the significance of the Decay Heat Removal System (DHRS) failure has not sincerely been recognized from the viewpoint that the power is a small fraction of full power and even if that failure occurs, various kind of cooling devices and enough time necessary for correction actions could be available. However, since Diablo Canyon accident (1987), PRA results and operational experience of utilities show that during the mid--loop operation, the probability of loss of DHRS is very high and if any, it can threaten the reactor safety without detection. Also it can damage the core within 1 hour rather than 4 hours.[1]

The important phenomena associated with the mid-loop operation are

i) air entrainment due to the free surface vortex in the suction line of DHRS,

ii) malfunction of instruments in the system,

iii) the RCS pressure increase.

The most important one is the air entrainment due to free surface vortex. Everyday we experience this phenomenon. When this occurs in the RCS during mid-loop operation, the air can be sucked into DHRS and cause the instrument malfunction and if the void fraction is more than about 15%[2,3], finally it leads to total failure of the DHRS. Acknowledging the significant effect of this failure on nuclear reactor safety, U.S.NRC issued a letter and recommendation saying that utilities and vendors take actions to prevent the air entrainment fundamentally.[4] Accordingly an experiential apparatus which was scaled down Yonggwang Nuclear Power Plant (YGNPP) to 1/6 was designed and installed. Also to improve the existing design of the inlet of DHRS, a reducer type inlet was tested.

2. Governing Equations and Non-Dimensionalized Variables

2.1. Nondimensionalized Governing Equations.

Governing equations and boundary conditions for the free surface vortex are follows. Here flow is assumed incompressible and steady.

Continuity equation : $\Delta \cdot \vec{V} = 0$

Momentum equation : $\rho(\vec{V} \cdot \Delta)\vec{V} = -\Delta P + \mu \Delta^2 \vec{V} + \rho \vec{g}$

Boundary conditions :

i) $\Delta P = P - P_0 = -\frac{2\sigma}{r_c} (r \to 0)$,

at the interface of the air core.

ii) $\Delta P = P - P_0 = \rho g H (r \to \infty)$,

at the interface far from the air core.

Here P_0 is the atmospheric pressure, r_c is the radius of the core, σ is the surface tension, r is the distance from center of air core, and H is water level.

Substituting

$$V^* = \frac{V}{U},\ r^* = \frac{r}{L},\ P^* = \frac{P}{\rho U^2},\ r_c = \frac{U^2}{g}$$

into momentum equation and boundary conditions, the following non-dimensionalized equation and boundary conditions can be obtained.

$$V^* \cdot \Delta V^* = -\Delta P^* + \frac{1}{Fr^2}$$

$$\Delta P^* = -\frac{1}{We\ Fr^2} (r^* \to 0)$$

Here, U, L, σ, g, μ, ρ are defined as average velocity, representative length(d=diameter of suction pipe), surface tension, gravity, viscosity, density and Re, Fr, We are Reynolds number($\frac{U}{\sqrt{gd}}$), Froude number($\frac{\rho dU}{\mu}$), Weber number($\frac{\rho U d}{\sigma}$), respectively. Therefore, from the above equations, a relation between the non-dimensionalized variables can be obtained as follows.

$$H/L = f(Fr, Re, We)$$

2.2. Non-Dimensionalized Variables (Similitude)

Among the non-dimensionalized variables governing the free surface vortex, in particular, at the condition of mid-loop operation of Nuclear Power Plant, Froude number is the only dominant variable.[5,6] The rationale is as follows.

i) When Re is greater than 10^5, the effect of Re is negligible (Re of the NPP is about 10^6, the number of the experiment is $3\times10^4 \sim 3\times10^5$).[7,8]

ii) When We is ranged between 1.2×10^2 and 3.4×10^4, the effect of We is negligible (We of the NPP is about 3.3×10^4, and the number of the experiments ranged between 5.7×10^2 and 3.5×10^3).[9,10]

3. Experimental Apparatus and Method

3.1. Experimental Apparatus

The experimental rig was designed with 1/6 scale of Yonggwang Nuclear Power Plant #3 (YGNPP #3). It consists of a water resovior, a hot leg (transparent acryl tube), a suction piping, a circulating pump, a flow meter, and two scales for water level mesurement (see Fig. 1).
More detailed are as follows.

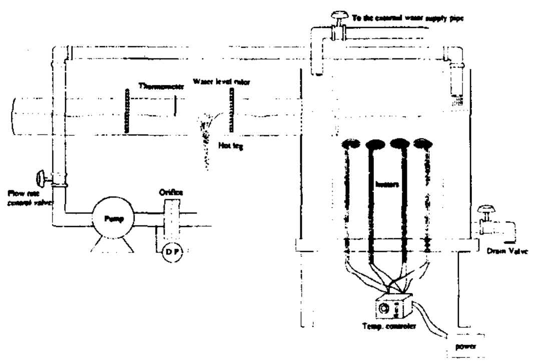
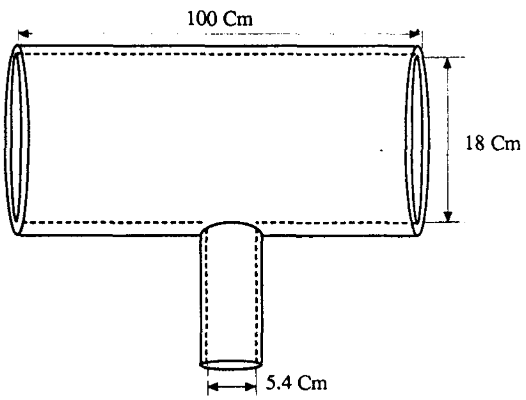


Fig. 1. Schematic Diagram of Test Loop

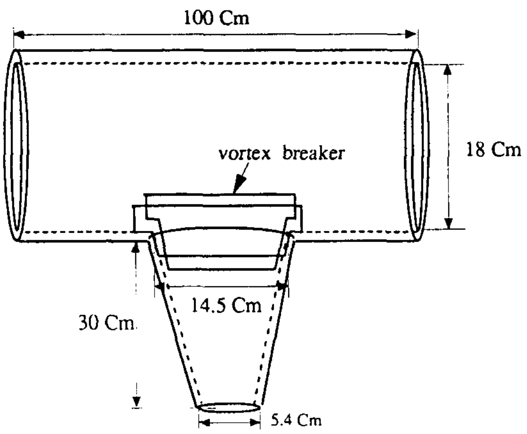
① Water resovior
The resovior was cylindrical (60cm×90cm), steel tank, open to atmosphere. Porous membrane was installed inside of the tank, to damp surface perturbation of incoming water from the circulating pump.

② Hot leg
The tube was made of four transparent acryl tube of 1m in length (inside diameter is 18cm). Its one side was connected to the water resovior and the other side was closed to simulate hot leg condition during mid-loop operation. The suction line is located 260cm from the water resovior.

③ Suction line.
Two types of suction inlet device were used, one was T type and the other Reducer types (with and without vortex breaker). The former was intended to find out the physical insight of vortex phenomena and the critical water level, while the latter to improve the inlet suction piping (to prevent the air entrainment). The dimension of the T type inlet piping is 5.4cm ID and 100cm long and the reducer type has a 15.4cm ID and tapered 5.4cm with length of 30cm as seen Fig. 2.



(A) T-Type Suction Pipe



(B) Reducer Type Suction Pipe

Fig. 2. Types of Suction Pipe

④ Circulating pump
The driving force of the flow in the experimental rig is provided with a vertical single stage centrifugal pump of which inlet and outlet diameter is 7.5cm. The head, maximum flow rate, power, and RPM of the pump are about 3m, $0.0055m^3/sec$,

0.74 HP, and 1750 RPM, respectively.

⑤ Flow meter

This instrument consists of a U-tube filled with mercury, and one pair of orifice flange and a brass orifice plate manufactured to comply with ASME code.

The instrument was calibrated as installed by the mesurement of the water mass in 10 seconds.

⑥ The other devices

There are installed a thermometer and two scales whose purposes are to measure water heights at the just outlet of reactor vessel and the just upstream of the DHR inlet. The purpose of the water level measurement at two point is to find out the level difference can be utilized to optimize the location of level instrument.

3.2. Experimental Method.

After filling the system with water supplied from external source to a predetermined level (choose a certain water level according to water flow rate), then start the pump and control the flow rate with a regulating valve. The water level is just enough not to induce air entrainment. If the system reaches a steady state, then open the drain valve or external water source valve to control water level just enough to entrain the air. This level is defined critical water level in the present experiment.

The experiment are divided into two parts. One is to find out the critical water level of the existing system, and the other is to modify the inlet of DHRS.

The followings are the experimental condition performed.

Table. 1. Experiment Conditions.

Item	Test range
Froude No.	1.20, 1.51, 1.92, 2.28, 2.67, 3.00
Temp.	Room temp.(8~11℃)
Type	T-type, Reducer type, Reducer type with vortex breaker

4. Results and Discussions

The experiments were performed to find out a relation between the critical water level and the flow rate in DHRS line for the T type, and reducer types (with and without vortex breaker). The results of these experiments are follows.

4.1. Results

1) Characteristics of vortex in piping system (T type)

Experiment was focused on the T types inlet device which is the same as the case of YGNPP #3,4. The summary of the physical phenomena of vortex in the piping system is summerized as follows.

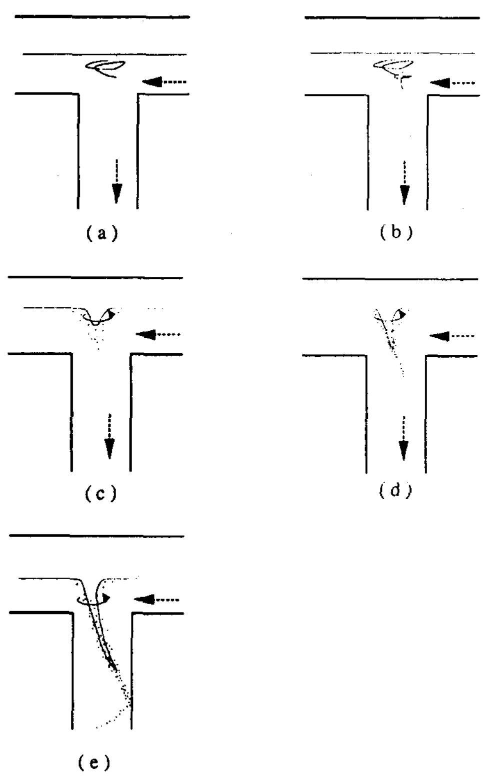


Fig. 3. Vortex Developing Stages in T-type Suction Pipe

①The vortex is very irrelegular, discontinuous, flickering (sometimes it appears and then it disappears, and inconsistent period of flickering).

②The location of the vortex core is drifted 1.5 d to the downstream of the flow. However, since the vortex is sucked to the inlet, the vortex is slanted to the downstream of the flow.

③The vortex intensity and critical water level is very sensitive to the disturbance such as pump and/or valve operation.

④The shape and period of the vortex (air entrainment) depend on the flow rate and water level. When the level is low, the period of the vortex (time interval between appearing and disappearing) is quite short (order of seconds). However if the level is high, the period of the vortex is long (order of minute), also high flow rate caused a big vortex core and large amount of air entrainment.

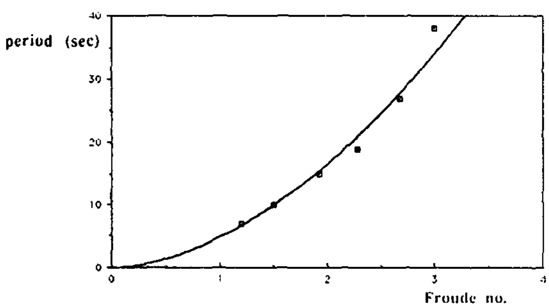


Fig. 4. A Relation Between Flow Rate and Air Entrainment Vortex Perod at Critical Water Level

2) Relation between the flow rate and critical water level.

For the experimental conditions shown Table 1, a relation between the flow rate (froude number) and critical water level (H/d) was found.

The error band was also determined from Student s t-distribution with 95% confidence level.

3) Reducer type inlet devices.

The reducer type inlet device is designed to prevent air entrainment by reducing flow velocity at the inlet. Some characteristics which is different from T type device are as follows.

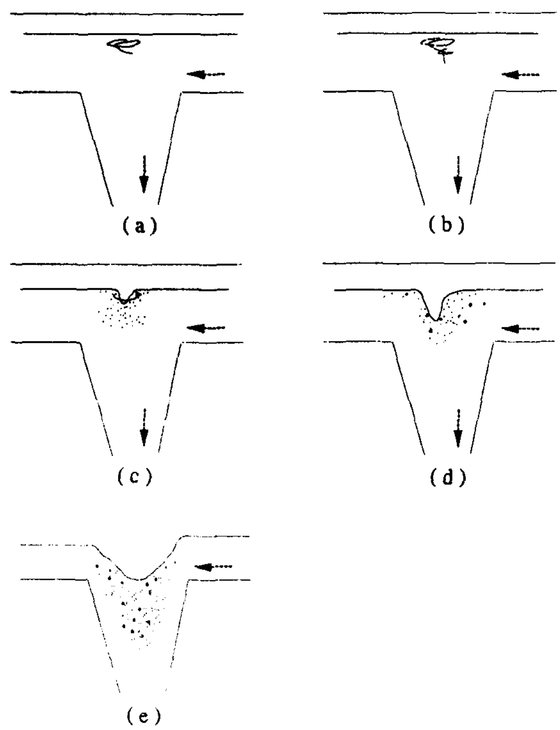


Fig. 5. Vortex Developing Stages in Reducer Type Suction Pipe

① The vortex intensity is subdued drastically, while the vortex diameter is enlarged. Also the suction force of the tube can be overcome by the buoyant force.

Table. 2. Results of the Experiment.(Temp≃11℃)

Type (cm^3/sec) Flow rate	Critical water level(cm)		
	T-type	Reducer type	Reducer type with vortex breaker
0.0020	7.3	*	*
0.0025	7.8	*	*
0.0032	8.5	*	*
0.0038	9.2	*	*
0.0044	9.9	8.2	*
0.0050	10.7	10.1	*

Table. 3. Critical Water Level Data in Terms of H/d for T-type, Reducer Types(With and Without).

Non-dim. No. (m^3/sec) Flow rate	Froude No.	H/d		
		T-type	Reducer type	Reducer type with vortex breaker
0.0020	1.2001	1.3586	*	*
0.0025	1.5029	1.4654	*	*
0.0032	1.9200	1.5900	*	*
0.0038	2.2800	1.7190	*	*
0.0044	2.6726	1.8353	1.5230	*
0.0050	3.0001	1.9987	1.8710	*

* : Air entrainment does not occur.

② Reducer inlet device with vortex breaker can prevent the air entrainment for all flow rate corresponding to operating condition of prototype.

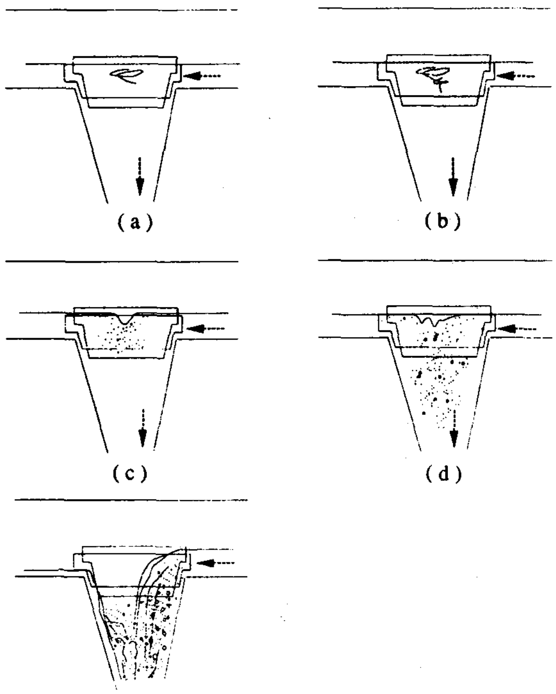


Fig. 6. Vortex Developing Stages in Reducer Type Suction Pipe With Vortex Breaker

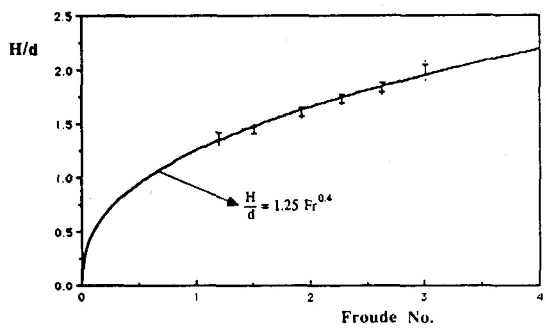


Fig. 7. Correlation Equation in T-type Suction Pipe with the Uncertainty Analysis

4.2. Discussions

1) The shape of vortex.

The location of vortex is shifted 1.5d to the downstream of the flow by the inertia of the flow. When the reducer type is used, the drifted location returns to the upstream of the flow (almost at the axis of the suction pipe). Also since the tail of the vortex is sucked into the inlet, the vortex shape is slanted to the downstream.

2) Characteristics of vortex (air entrainment)

The vortex is not continuous. It repeats generation and disappearance randomly and irregulaly. Its period is not constant. The depth of air core is not consistent. Sometimes the tail of the air core reaches the inlet of the suction pipe : Then the air is sucked in. This air entrainment can cause the system failure (pump stop, instrument malfunction).

Also the shape of vortex can be affected by the flow rate. When the flow rate is high (the critical water level is high, too), the vortex has large diameter but shallow depth and long period.

Therefore it is difficult to make air entrained. However, if it occurs, a lot of air can be entrained to stop pump. Therefore, it is difficult to set up a consistent criteria for the critical water level. For this study, from the conservatism of reactor safety, however, the criteria was set up at a water level of which the air entrainment just start at the suction pipe DHRS. 3) Effects of disturbance on vortex.

The vortex is quite sensitive to the external disturbances such as pump start, valve opening and closing. The surface wave generated from the external disturbances can change the water level instantaneously.

4) Uncertainty of the vortex.

In this experiment the uncertainty of the critical water level was 1.2cm (20% of inlet diameter).

5) Reducer type suction pipe (modified inlet).

Since the enlarged inlet area reduces the flow velocity at inlet (proportional to $\frac{1}{D^2}$), the intensity of the vortex was decreased drastically. Therefore there was almost no air entrainment except at 120% of rated flow rate.

In particular, when we gradually lower the water level, the water level of the downstream side is lower than that of upstream side. This level difference prevents the vortex generation at low water level. If the water level is lowered further, the downstream side becomes dry.Therefore the water directly falls into the suction pipe like a cascade.

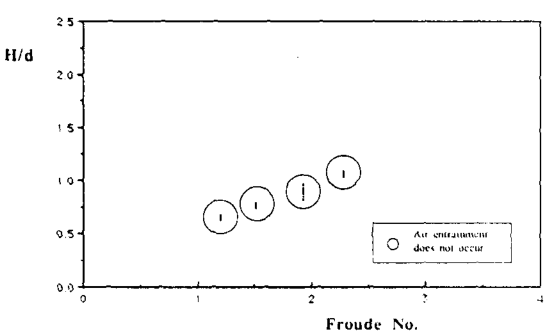


Fig. 8. A Relation Between H/d and Froude No. in Reducer Type Suction Pipe

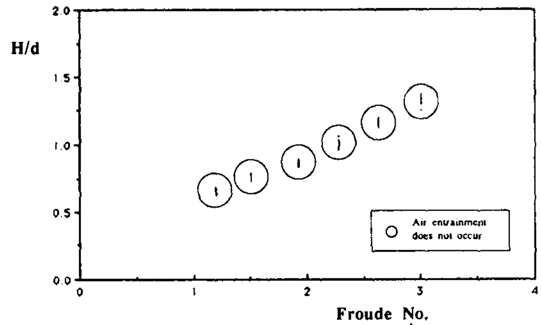


Fig. 9. A Relation Between H/d and Froude No. in Reducer Type Suction Pipe with Vortex Breaker

Even at the low flow rate, there is no vortex and no air entrainment.

5. Conclusions

5.1. Correlation

A relation between the critical water level (H/d) and Froude number ($\sqrt{\frac{U^2}{gD}}$) was obtained as follows.

$$H/d = C\ Fr_n$$

Here, constant C is 1.25 and power n is 0.4.

5.2. Characteristics of Free Surface Vortex.

The vortex (air entrainment, critical water level) can be affected by the disturbance such as pump start, valve opening. Also it has irregularity, randomness, discontinuity, and incosistent period.

5.3. Effects of Flow Rate(Water level)

When the water level is low, the flow rate corresponding to air entrainment is also low. Therefore the vortex intensity is weak so that the vortex is almost continuous and the corresponding to air entrainment is high so that the vortex is large and discontinuous, and if any, the air entrainment so large that it can stop the pump.

5.4. Effects of the Inlet Types

The change of the inlet suction pipe from T type to reducer type (with or without vortex breaker) reduces the vortex intensity significantly. Therefore the critical water level is decreased drastically. In particular, when the inlet is changed to the reducer type with vortex breaker, air entrainment does not occur over the whole range of the flow rate corresponding to YGNPP #3 operation conditions.

If the inlet diameter of the reducer type is enlarged, it is expected that air entrainment can be prevented completely.

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