A Theoretical Model for the Prediction of Siphon Breaking Phenomenon

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1. Introduction

A siphon phenomenon or siphoning often refers to the movement of liquid from a higher elevation to a lower one through a tube in an inverted U shape (whose top is typically located above the liquid surface) under the action of gravity, and has been used in a variety of real-life applications such as a toilet bowl and a Greedy cup. However, liquid drainage due to siphoning sometimes needs to be prevented. For example, a siphon breaker, which is designed to limit the siphon effect by allowing the gas entrainment into a siphon line, is installed in order to maintain the pool water level above the reactor core when a loss of coolant accident (LOCA) occurs in an open-pool type research reactor [1,2]. In this paper, we develop a theoretical model to predict the siphon breaking phenomenon.

2. Methods and Results

2.1 One-dimensional Theory

Figure 1 illustrates the schematic of a simple siphon system consisting of a reservoir connected with a siphon line, and a siphon-breaking hole located at the top of the siphon line. Assuming that the siphon line diameter is much smaller than the tank diameter; single-phase flow of water exists between the points 1 and 2; single-phase flow of air exists between the points 0 and 2; two-phase flow of air-water mixtures exists between the points 2 and 3; air and water travel at the same velocity between the points 2 and 3 (homogeneous model), the extended Bernoulli equation between the points 1 and 2 can be written as [3]

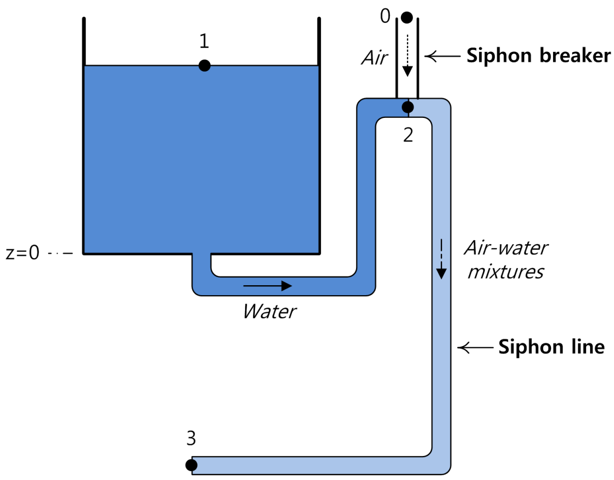

Fig. 1. Schematic of a simple siphon system with a siphon-breaking hole

$$P_1 + \rho_w g z_1 = P_2 + \frac{1}{2}\rho_w V_{12}^2 (1 + K_{12}) + \rho_w g z_2 \tag{1}$$

where ρ_w is the density of water, and K_{12} is the pressure loss coefficient between the points 1 and 2. Likewise, the Bernoulli equation between the points 0 and 2 is

$$P_0 = P_2 + \frac{1}{2}\rho_g V_{02}^2 K_{02} \tag{2}$$

where ρ_g is the air density, K_{02} denotes the pressure loss coefficient between the points 0 and 2, and V_{02} is the air velocity through the siphon-breaking hole. Provided that the mixture density of two-phase flow is constant under a homogeneous flow assumption, one can obtain

$$P_2 + \rho_{2\phi} g z_2 = P_3 + \rho_{2\phi} g z_3 + \frac{1}{2}\rho_{2\phi} V_{23}^2 \left(K_{23}\Phi^2 + \left(\frac{A_2}{A_3}\right)^2 - 1 \right) \tag{3}$$

in which K_{23} is the pressure loss coefficient between the points 2 and 3, Φ^2 is the two-phase multiplier, and A_2 and A_3 are the cross-sectional area of the siphon line and the break area, respectively. The mixture density $\rho_{2\phi}$ is defined by

$$\rho_{2\phi} = (1-\alpha)\rho_w + \alpha\rho_g \tag{4}$$

where the void fraction in the two-phase flow region that connects the points 2 and 3 is

$$\alpha = \frac{A_0 V_{02}}{A_0 V_{02} + A_2 V_{12}} \tag{5}$$

Here A_0 denotes the cross-sectional area of the siphon-breaking hole. Then, the relationship between the water velocity V_{12} and mixture velocity V_{23} can be obtained from the continuity equation

$$V_{12} = (1-\alpha)V_{23} \tag{6}$$

In Eq. (3), the two-phase multiplier Φ^2 is computed by

$$\Phi^2 = \frac{\rho_w}{\rho_{2\phi}} \tag{7}$$

Meanwhile, the mass balance equation reads as

$$A_1 \frac{dz_1}{dt} = -A_2 V_{12} \tag{8}$$

where A_1 is the cross-sectional area of the reservoir.

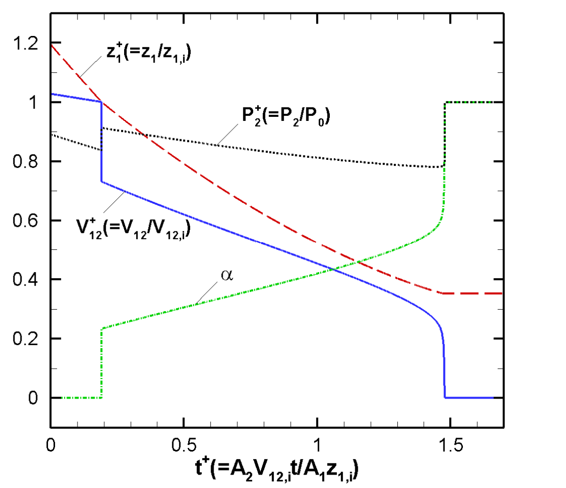

Fig. 2. Temporal variations of pool water level, water velocity and void fraction in the siphon line, and pressure at point 2

2.2 Siphon Breaking Phenomenon

We first investigate the fundamental features of the siphon breaking phenomenon. The prediction is carried out using a computation-aided siphon breaking analysis (CASBA) code, which is developed to solve the present 1-D model with the Euler method [4], while the input parameters are set based on the previous experimental conditions [2]: water density ρ_w=1000 kg/m^3; air density ρ_g=1.2 kg/m^3; siphon-breaking hole diameter D_0=30 mm (A_0=7.069×10^{-4} m^2); reservoir area A_1=14.4 m^2; siphon line area A_2=0.1198 m^2; break area A_3=0.051 m^2; initial water level in the reservoir $z_{1,0}$=4 m; siphon-breaking hole location z_2=3.35 m; pipe rupture location z_3=−8.25 m; ambient pressure P_0=P_1=P_3=101.3 kPa; pressure loss coefficients K_{02}=0.5, K_{12}=0.6, K_{23}=4.85. Also note that the siphon-breaking hole is assumed to be open with no delay, when the water level inside the reservoir (or pool) falls below z_2.

Figure 2 now displays the temporal variations of pool water level, superficial velocity inside the siphon line, pressure at point 2, and void fraction in the two-phase flow region, which are normalized by z_2, $V_{12,i}$, and P_0. Here the subscript i denotes the initial stage at which the water in the siphon line is exposed to the surrounding air. At a siphoning stage (e.g. t^+<0.2), it is shown that the pool water level and pressure at point 2 decrease as water siphons out from the reservoir. Once the siphon-breaking hole is open (e.g. t^+>0.2), ambient air is then entrained into the siphon line by the pressure difference between the points 0 and 2, two-phase flow of air-water mixtures is formed downstream of the siphon-breaking hole, resulting in sudden increases in pressure and void fraction as well as a rapid drop in superficial velocity. It follows that the superficial velocity decreases, pressure at point 2 decreases with the decreasing water level, and the void fraction in the two-phase flow region increases. Consequently, siphoning is broken completely and the pool water level reaches the saturated value. All these results are consistent with the experiment, implying that the present 1-D model predicts well the basic features of the siphon breaking phenomenon.

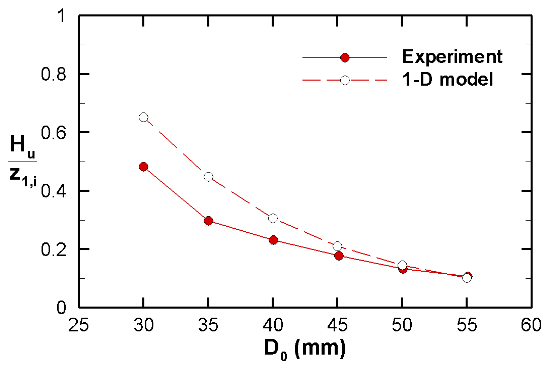

Fig. 3. Undershooting height *vs.* siphon-breaking hole size relationship

2.3 Undershooting Height

Figure 3 shows the size effect of the siphon-breaking hole on the undershooting height H_u, which is defined by the elevation difference between the siphon-breaking hole and the saturated water level. As expected, it can be seen that the undershooting height decreases with an increase in the siphon-breaking hole diameter, because the air entrainment becomes more prominent at a larger-sized hole. It is also noteworthy that overall agreement between the prediction and experiment is fairly good, although the present 1-D model slightly overestimates the undershooting height.

3. Conclusions

In this paper, a theoretical model to predict the siphon breaking phenomenon is developed. It is shown that the present model predicts well the fundamental features of the siphon breaking phenomenon and undershooting height.

Acknowledgement

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