Scaling Analysis to Design an Air-Water Loop Seal Clearing SET Facility Using MARS-KS Code

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1. Introduction

Loop seal clearing (LSC) is one of the most important phenomena in a small break or medium break loss of coolant accident in a pressurized water reactor (PWR). The loop seal formation (LSF) is closely related to the depression of liquid level of core while LSC reduce the depression of liquid level of core.

A typical PWR has U- shaped crossover pipes which connect the steam generator outlet plenum to the reactor coolant pump and water in this pipe is called loop seal. Steam venting through the break in a cold leg small break loss of coolant accident (SBLOCA) is achieved only after the water in at least one of the crossover legs is blown out to either the break or reactor vessel [1]. During a SBLOCA in a Westinghouse type PWR, the core liquid level is depressed temporarily before steam clears liquid out of the primary loop seals [2].

The LSC in SBLOCA is an important phenomenon that governs the whole thermal–hydraulic behavior of the primary system. In a physical sense, sustaining of a loop seal clearance can be interpreted using a countercurrent flow limitation (CCFL) or flooding condition suggested by Wallis [3].The most widely used correlations of CCFL phenomenon are Wallis type [4] and Kutateladze form [5] can be expressed as equation (1) and (2) respectively.

$J_g^{*1/2} + mJ_l^{*1/2}=c$ ……… (1)

$Ku_g^{*1/2} + mKu_l^{*1/2}=c$ ……… (2)

Where, $J^*_g=J_g\rho_g^{1/2}/[gD(\rho_l-\rho_g)]^{1/2}$; $J^*_l=J_l\rho_l^{1/2}/[gD(\rho_l-\rho_g)]^{1/2}$; $Ku^*_g= J_g\rho_g^{1/2}/[g\sigma(\rho_l-\rho_g)]^{1/4}$; and $Ku^*_l= J_l\rho_l^{1/2}/[g\sigma(\rho_l-\rho_g)]^{1/4}$. The parameter J^*, Ku^* J, ρ, g, σ, D, m, and c, are the dimensionless flux of Wallis type, dimensionless flux of Kutateladze type, superficial velocity of fluid, density, gravitational acceleration, surface tension, diameter, slope, and gas intercept, respectively. The subscript l and g are liquid and gas phase, respectively.

On the basis of the significance of LSC phenomenon in the PWR safety analysis, a separate effect test (SET) facility for air-water fluid is required to investigate the thermal hydraulics phenomena comprehensively. The calculation of inlet superficial air velocity (J_{air}) is necessary for the design of air blower or air fan capacity to provide air into the loop seal which requires theoretical formulation on the basis of conservation of air-water flow in a SET facility with respect to the steam-water flow in an integral effect test (IET) facility.

The main objectives of this study are to derive a generalized formula of J_{air} of SET facility with respect to steam-water IET facility by scaling analysis, to investigate the physical significance of the calculated superficial air velocity, and to verify the calculated J_{air} using MARS-KS code simulation for the proposed SET of LSC.

2. Scaling Analysis

To get the inlet superficial velocity of air in a SET facility, it is decided to use dimensionless number, Wallis parameter J_g^* and Kutataledge parameter Ku_g to ensure the similarity of governing phenomenon of air–water countercurrent flow.

To preserve the non-dimensionalized superficial air velocity of a SET facility with respect to prototype superficial velocity of steam can be written according to Wallis form as equation (3).

$J_{air}^*(SET, P_{atmospheric}) = J_{steam}^*(Prototype, P_{prototype})$ … (3)

The equation (3) ultimately provides the superficial velocity of air for a SET facility as equation (4).

$J_{air}=(D_R)^{1/2}J_{steam}\{(\rho_{steam}/\rho_{air})(\rho_{l,set}-\rho_{air})/(\rho_{l,prototype}-\rho_{steam})\}^{1/2}$ ……….. (4)

Where, $D_R= D_{SET}/D_{prototype}$ is the ratio of diameter and P is the pressure. If diameter and superficial steam velocity of prototype facility are known, J_{air} can be calculated using equation (4) from a known diameter of a SET facility.

In a similar fashion, by preserving the Kutateladze parameter of a SET facility with respect to prototype facility, the inlet J_{air} for a SET facility can be found as equation (5). The required J_{air} for a SET facility does not depend on the diameter in case of Kutateladze form.

$J_{air}=J_{steam}(\rho_{steam}/\rho_{air})^{1/2}\{(\sigma_{air,l}/\sigma_{steam,l})(\rho_{l,set}-\rho_{air}/\rho_l-\rho_{steam})\}^{1/4}$ ………… (5)

The diameter of the proposed SET facility is selected as equal in vertical and horizontal pipe, and vertical height is equal in both upward and downward leg.

The Wallis parameter, $J_{steam}^{*1/2}$ value varies from 0.53 to 1.11 and the Kutataledge parameter, ku_{steam} varies from 1.75 to 8.23 in the ATLAS SBLOCA tests [3].The value of Wallis and Kutataledge parameter varies from 0.47 to 0.55 and from 1.81 to 2.54

respectively in the LSTF [2] power decreasing tests [3]. Moreover, the value of Wallis and Kutataledge parameters by 0.70 and 3.2 are also used to calculate the inlet J_{air} of a SET facility. The summary of the calculation of inlet J_{air} using equation (4) and (5) for the proposed SET is shown the Table I.

Table I: Calculation summary

Calculation Approach	Superficial Air Velocity (m/s)
$J_{steam}^{*1/2}$=0.53 -1.11 (ATLAS)	6.605-28.451
Ku =1.75 - 8.23 (ATLAS)	8.28-38.94
$J_{steam}^{*1/2}$=0.47-0.55 (LSTF)	5.194 -7.113
Ku_{steam} =1.81 to 2.54 (LSTF)	8.564-12.017
$J_{steam}^{*1/2}$=0.70	11.52
Ku_{steam} =3.2	15.14

The calculated J_{air} range is form 5.194 m/s to 38.94 m/s for the proposed SET with diameter 0.067m. It is predicted that the minimum range of J_{air} is the beginning of LSC and the maximum value is the complete LSC. The calculation was done using the following values of fluid properties and other required values which is shown in the Table II.

Table II: Fluid properties and other required values

Parameter	D (m)	ρ_{air} (Kg/m^3)	ρ_f (Kg/m^3)	σ (N/m)
Air-Water	0.067	1.184	997.05	0.0719

3. MARS-KS Simulation of Conceptual SET

3.1. CCFL Model in MARS-KS Code

A general CCFL model used in MARS-KS code allows an user to select the Wallis [4] form, the Kutateladze form, or a form in between the Wallis and the Kutateladze form. This general form was proposed by Bankoff et al. [6]. It has the structure of the equation as 6.

$$H_g^{1/2} + mH_f^{1/2}=c \quad \ldots\ldots\ldots (6)$$

Where, $H_g=J_g[\rho_g/gw(\rho_f-\rho_g)]^{1/2}$;$H_f=J_f[\rho_f/gw(\rho_f-\rho_g)]^{1/2}$; $w= Dj^{1-\beta} L^{\beta}$; and $L= [\sigma/g(\rho_f- \rho_g)]^{1/2}$. The parameter H, m, c, J, ρ, g, w, Dj, L, σ ,and β are the dimensionless flux, slope, gas intercept, superficial velocity, density, gravitational acceleration, interpolative length, junction hydraulic diameter, Laplace capillary constant, surface tension, and scaling constant, respectively. The subscript f and g are for liquid and gas phase, respectively. It is flexible to implement CCFL correlations in MARS-KS code by giving input for β = 0, the Wallis form, for β = 1, the Kutateladze form, a form in between $0 < \beta < 1$, the Bankoff. The slope m must be greater than 0 [7].

3.2. MARS-KS Nodalization and Simulation Matrix

The geometrical configuration of MARS-KS input model for loop seal simulation is shown in MARS-KS nodalization Fig. 1 as vertical height 1.025 m, horizontal length 0.924 m and diameter 0.067 m. The inlet and outlet flow were modeled by the time dependent junctions and single junction, respectively connecting by time dependent volume. The inlet and outlet conditions were the atmospheric pressure and temperature conditions. The loop seal section was modeled using as a pipe component which is divided into 12 volumes with 4 section in each downward, horizontal and upward leg.

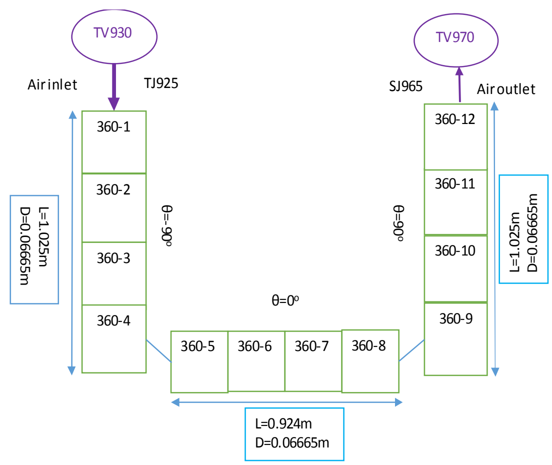

Fig. 1. MARS-KS nodalization of SET for LSC

After the completion of nodalization, an input file describing the geometrical and thermal-hydraulic conditions of the nodalized volumes representing the flow path of a proposed SET for air-water flow condition was prepared. The simulation is run for 250 s with stepwise increasing inlet air velocity as 0, 1, 2, 5, 10, 15, 20, 25, 30, 35 and 40 m/s, shown in the Fig.2.

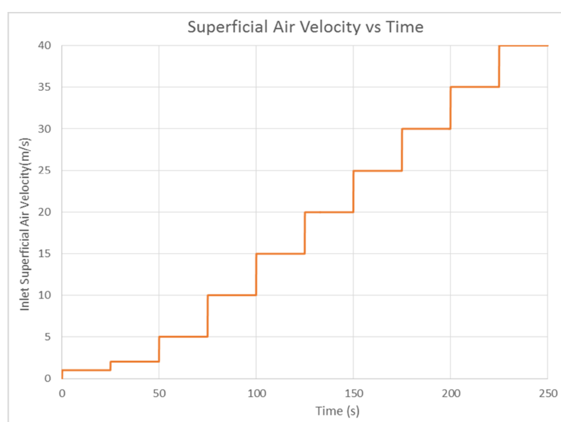

Fig. 2. Superficial air velocity with time

Table III: Simulation matrix for variable diameter

Cases	Diameter (m)	Vertical Height (m)	Horizontal Length (m)
1	0.025	1.025	0.924
2	0.05		
3	0.067		
4	0.1		
5	0.15		
6	0.762		

The MARS-KS simulation matrix was made on the basis of various diameter and length cases which are shown in Table III and IV, respectively. It can be mentioned that the loop seal was completely full with water at the beginning of simulation and the Wallis CCFL model was applied.

Table IV: Simulation matrix for variable vertical height

Cases	Vertical Height (m)	Horizontal Length (m)	Diameter (m)
1	2.235	2.014	0.067
2	1.025	0.924	
3	1.025	0.5	
4	0.5	0.5	

3.3. Diameter Effect of MARS-KS Simulation

The collapsed liquid level of horizontal leg is shown in Fig.3 for the simulation matrix of Table III. It is clearly seen that the initiation of LSC occurs at the same time in all the cases but the complete LSC requires higher J_{air} for larger diameter. The highest J_{air}, 25 m/s requires for diameter 0.762 m and the lowest value is 10 m/s for diameter 0.025 m. The liquid level of upward leg shows fluctuating liquid level until the complete clearing of horizontal leg.

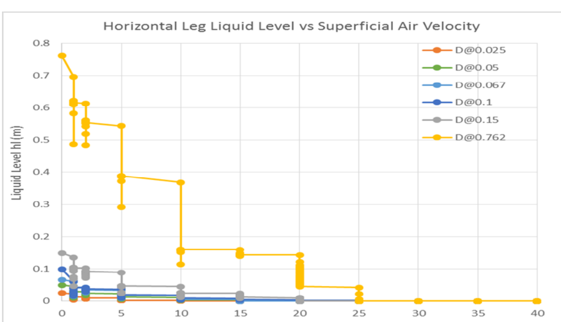

Fig. 3. Collapsed liquid level of horizontal leg

The residual water levels according to the Wallis parameter, in the horizontal region of the loop seal, are shown in Fig.4. Residual water level is defined as the ratio of water level in horizontal part (h_l) to the diameter (D). It is clear from Fig.4 that h_l/D decreases with air flow rates through the loop seal. The h_l/D becomes zero at smaller $J_{air}^{*1/2}$, for larger diameter test section. The parameter shows a wide range of scattered values.

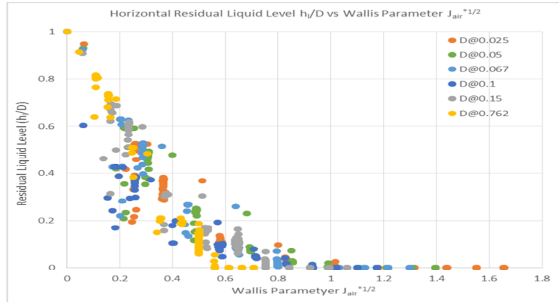

Fig. 4. Residual liquid level and Wallis parameter

The pressure drop between the downward leg (node 360-01) and upward leg (node 360-12) with respect to inlet J_{air} is shown in Fig.5. The higher diameter requires larger pressure drop for LSC and the differential pressure is almost double for 0.762 m diameter with comparison to the 0.025 m diameter.

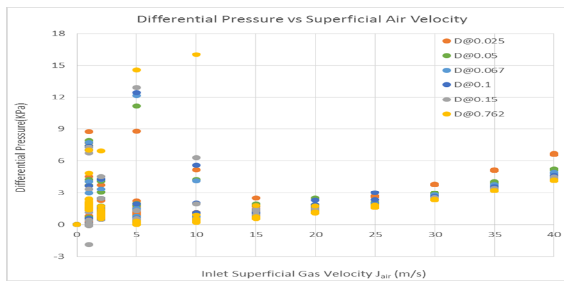

Fig. 5. Differential pressure and inlet J_{air}

3.4. Vertical Height Effect of MARS-KS Simulation

The collapsed liquid level of horizontal leg is shown in Fig.6 for the simulation matrix of Table IV. The LSC initiates from the very beginning of simulation for all the cases except the case of height by 2.235 m, which starts at 1 m/s. The complete LSC occurs at 15 m/s except the case of height by 2.235 m, which completes at 20 m/s. The increasing height and horizontal length require more J_{air} to complete the LSC with constant diameter.

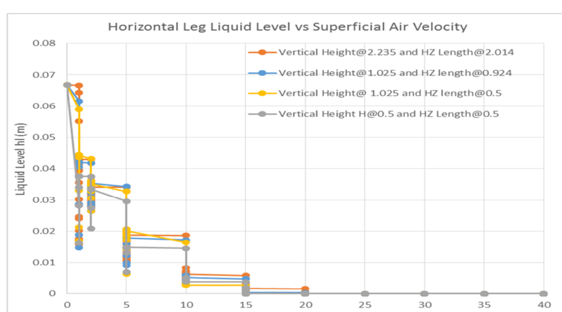

Fig. 6. Collapsed liquid level of horizontal leg

The h_l/D and $J_{air}^{*1/2}$ in the horizontal section of the loop seal is shown in Fig.7. The h_l/D becomes zero for $J_{air}^{*1/2}$ at 0.92 for height 2.235 m and other cases this value is 0.79. The increasing height requires higher pressure drop for initiating LSC. A larger pressure drop, 18.38 kPa is observed for J_{air} at 1 m/s of height 2.235 m. The decrease of horizontal length for height 1.025 m also makes slight decrease of pressure drop.

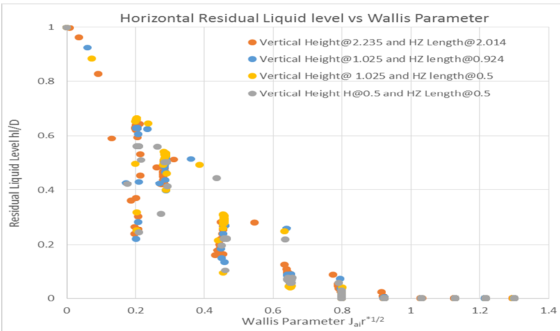

Fig. 7. Residual liquid level and Wallis parameter

4. Results

The scaling analysis to get the inlet J_{air} for the proposed air-water SET facility is conducted and the theoretical calculated J_{air} is found as the minimum and the maximum 5.194 m/s and 38.94 m/s, respectively. In the MARS-KS calculation, the complete LSC for 0.067 m diameter and 0.125 m height case is 20 m/s. The reasons of slight deviations from theoretical value to the calculated results, may be different initial conditions of the simulation from the real loop seal phenomenon. The horizontal diameter of a SET differs from that of ATLAS [8] which can be also the reason of this discrepancy.

It is clear from this study that the initiation of LSC does not depends on diameter but complete LSC requires higher J_{air} for larger diameter. The higher diameter requires larger pressure drop and the larger pressure drop is also required for the initiation of LSC in case of larger height which is a hydrostatic effect.

The residual water level decreases with Wallis parameter in the horizontal region of the loop seal with a wide range of scattered data in the MARS-KS calculation. The experimental results are required to investigate the relationship between h_l/D and $J_{air}^{*1/2}$ in the horizontal section more comprehensively. Besides, the behavior of pressure drop for the initiation of LSC requires more investigation with experimental results.

5. Conclusion

In this study, a generalized superficial air velocity formula was derived by scaling analysis and the maximum and the minimum range of superficial air velocity for the proposed air-water SET facility of LSC was calculated. The residual water level with respect to Wallis parameter in the horizontal section of the loop seal was analyzed as well as the dynamic behavior of pressure drop was investigated in this study.

From the scaling analysis, it is found that both diameter and height have importance on pressure drop for the initiation of LSC. In this study, it is considered that the loop seal is initially completely full and air is flowed to clear the loop seal. But, there is a condensed liquid flow from steam generator to the loop seal and also liquid can flow to the loop seal from emergency coolant injection in an SBLOCA case. This case is not considered in this study which is a limitation. The design, installations, and preliminary tests of the proposed SET facility will be conducted on further study.

Acknowledgements

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