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Hydraulic Simulation of In-vessel Downstream Effect Test Using MARS-KS Code

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1. Introduction

In-vessel downstream effect test (IDET) has been required to evaluate the effect of debris on long term core cooling following a loss of coolant accident (LOCA) in support of resolution of Generic Safety Issue (GSI) 191 [1]. Head loss induced by debris (fiber and particle) accumulated on prototypical fuel assembly (FA) should be compared with the available driving head to the core for the various combinations of LOCA and Emergency Core Cooling System (ECCS) injection. A hydraulic simulation of the IDET has been frequently requested to understand the head loss behavior and to support the validity of the test.

In the simulation, the form loss factors for the FA and for the gap between the FA and the enclosure of the test facility are important and they should be defined for the clean state and debris laden one. In the present paper, a simple model to determine the form loss factors of FA and gap in both states is discussed. The actual simulation was conducted using MARS-KS code. Also the influence of small difference in gap size which was found in the actual experiment [2] is evaluated using the present model.

2. Model Description

2.1 Model for Form Loss Factor

For the streams from the inlet (i) through the FA bottom nozzle (N) and the gap (G) to the exit (e) of the test section (Fig. 1), the continuity equations and Bernoulli equations can be expressed as follows:

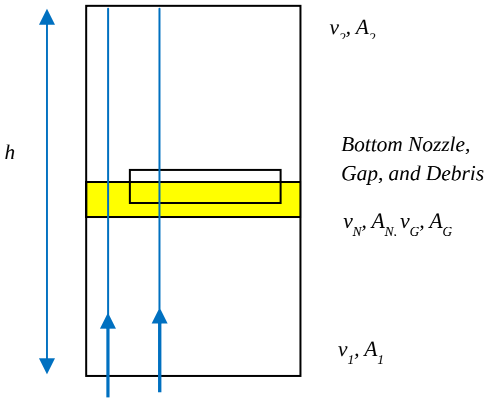

Fig. 1. Configuration of IVDET Simulation

$$Q = A_i v_i = A_N v_N + A_G v_G = (A_N + A_G) v_A \quad \text{......................... (1)}$$

$$\begin{aligned} p_i + \frac{1}{2}\rho v_i^2 &= p_e + \frac{1}{2}\rho v_e^2 + \rho g h + (k_N + k_{N,D})\frac{1}{2}\rho v_N^2 \\ &= p_e + \frac{1}{2}\rho v_e^2 + \rho g h + (k_G + k_{G,D})\frac{1}{2}\rho v_G^2 \\ &= p_e + \frac{1}{2}\rho v_e^2 + \rho g h + (k_A + k_{A,D})\frac{1}{2}\rho v_A^2 \end{aligned} \quad \text{....... (2)}$$

where, Q, and subscripts A and D denote mean flow rate, the averaged stream for nozzle and gap and the debris. After some treatment, the following relation can be obtained:

$$\frac{A_G}{\sqrt{k_G + k_{G,D}}} + \frac{A_N}{\sqrt{k_N + k_{N,D}}} = \frac{A_G + A_N}{\sqrt{k_A + k_{A,D}}} \quad \text{...................... (3)}$$

The right hand side of the equation can be obtained from the measured pressure drop for the clean state and debris accumulated state, respectively.

$$(A_G + A_N) / \sqrt{k_A + k_{A,D}} = \sqrt{\rho Q^2 / 2dP_{Debris}} \quad \text{...................... (4)}$$

where, ρ and dP mean density and differential pressure, respectively. For the clean state, $k_{G,D}= k_{N,D}= k_{A,D}=0$, k_A is as follows:

$$(A_G + A_N) / \sqrt{k_A} = \sqrt{\rho Q^2 / 2dP_{clean}} \quad \text{.............................. (5)}$$

To solve the eq.(3), additional constraint is needed. In the present study, however, possible combinations of (k_G, k_N) and $(k_G + k_{G,D}, k_N + k_{N,D})$ are considered using the eq.(4) and (5) within the reasonable range of velocities at the nozzle and gap.

2.2 MARS-KS model

Combinations of form loss factors in clean state (k_G, k_N) determined from the above equation are applied to the junctions denoting inlets to the gap and the nozzle, respectively, for the MARS-KS code calculation. The pairs of $(k_{G,D}, k_{N,D})$ were implemented to the outlet junctions. Fig. 2 shows a MARS-KS model to simulate the IDET conducted at the test facility of Central Research Institute (CRI) of KHNP [3]. All the pressure losses due to wall friction and the form loss are to be simulated only by the form loss at the junctions for nozzle and the gap. Also abrupt area change option was applied to those junctions in order to evaluate the effect of geometric difference of the gap.

3. Results and Discussion

3.1 Form Loss Factor

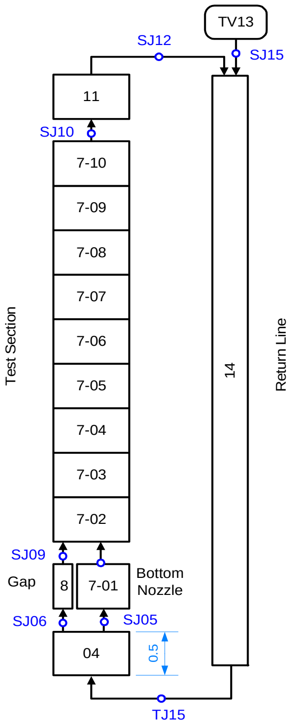

Fig. 2. MARS-KS model for CRI's IVDET

Fig.3 shows the possible combination of (k_G, k_N) and ($k_{G,D}$, $k_{N,D}$) predicted by eq.(3) for the measured pressure drop in clean state (0.2 kPa) and one in debris laden state (207 kPa). Regarding the clean state, velocity at the nozzle and the gap was ranged 0.046~0.054 m/s and 0.01~0.27 m/s for the three points selected as shown in Fig.3, respectively.

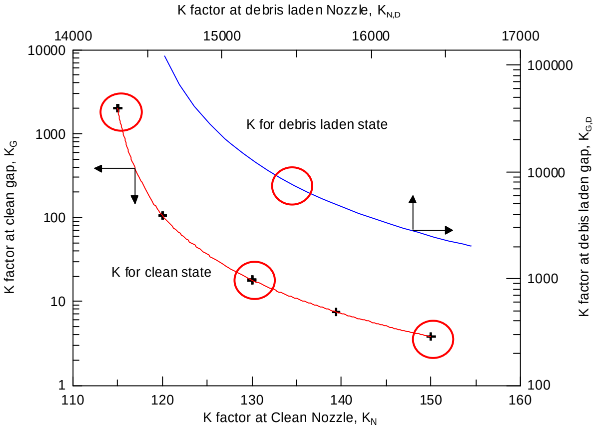

Fig. 3. Combination of (k_N, k_G) and ($k_{N,D}$, $k_{G,D}$)

For the debris laden state, the range of $k_{N,D}$ matching the measured pressure drop was predicted as 14500 ~16500 while velocities at the nozzle and the gap was predicted 0.046~0.052 m/s. The deviation of precicted pressure drop around the central point shown in the Fig. 3 was within 1%. The calculation result also indicated that almost homogeneous velocity distribution can be expected in debris laden state. This result indicates that the heal loss at final debris laden state can be simulated by the present model on form loss factor and the consequent MARS-KS calculation..

3.2 Difference in Gap Size

It was found that the measured size of the gap between the FA and the enclosure of the test section was slightly different from the design one [3]. The real gap size was a little higher than that in design while the FA was in the same size. Thus, it was concerned how much impact of the difference on the pressure drop for the case that the test might have been conducted for the design configuration. Eq.(3) can be expressed for the design configuration, where superscript * means design value.

$$\frac{A^*_G}{\sqrt{k^*_G + k^*_{G,D}}} + \frac{A^*_N}{\sqrt{k^*_N + k^*_{N,D}}} = \frac{A^*_G + A^*_N}{\sqrt{k^*_A + k^*_{A,D}}} \quad \text{..............} (6)$$

Considering that the actual nozzle k factor is the same as the one in design ($k^*_N = k_N$), that changes in debris related k factors can be neglected due to small change in geometry ($k^*_{G,D} \cong k_{G,D}$, $k^*_{N,D} \cong k_{N,D}$), and that the significantly high k-factor due to debris ($k^*_G \ll k^*_{G,D}$), eq.(3) can be consistently used for the design condition. Thus, it can be stated that the influence on pressure drop by the difference in gap size comes from the change in velocity due to geometric change.

The predicted pressure drop using the same k factors as the actual condition was 211.5kPa, which was increased by 1.8% from the pressure drop in the actual condition.

4. Conclusions

A simple model to determine the form loss factors of FA and gap in clean state and the debris laden state is discussed based on basic fluid mechanics. Those form loss factors were applied to the hydraulic simulation of a selected IDET using MARS-KS code. The result indicated that the present model can be applied to IDET simulation. The pressure drop influenced by small difference in gap size can be evaluated by the present model with practical assumption.

REFERENCES

[1] USNRC, Final Safety Evaluation by the Office of Nuclear Reactor Regulation Topical Report WCAP-16793-NP, Rev 2 "Evaluation of Long-term Cooling Considering Particulate, Fibrous and Chemical Debris in the Recirculating Fluid" Oct. 2013.

[2] KHNP, "Test Procedure for the APR1400 In-vessel Downstream Effects," DC-DG-11-02, Rev. 4, Sept. 2014.

[3] J.K. Suh, et al, "In-vessel Downstream Effect Tests for the APR1400," Proceedings of ICAPP 2013, Jeju Island, Korea, April 14-18, 2013.