A Scheme to Predict Discharge Coefficient of Long Multi-hole Orifices Perforated in PECCS Valves

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1. Introduction

The valves of PECCS (Passive Emergency Core Cooling System) of i-SMR (Innovative Small Modular Reactors) are driven by the pressure difference between the reactor pressure vessel and the containment vessel [1]. The opening and closing rates is determined by the movement of the valve disk, which can be controlled through an orifice that can appropriately regulate the pressure difference between the high-pressure section and low-pressure section. Therefore, conformance of the opening rate and the differential pressure with the design requirement depends on how the discharge coefficients of such orifices are determined. In addition, multi-hole orifices can be considered, whose holes are distributed symmetrically across the entire disk to balance the forces exerted on the disk by flow. Therefore, the discharge coefficient should be determined considering multi-hole orifice geometry.

Research on multi-hole orifices has been actively conducted to date [2]. They, however, were mostly the shape of thin-plate orifice flowmeters used for flow measurement [3]. This may differ significantly in performance from the long orifice discussed in this study.

The present study discusses a method to determine the loss factors and discharge coefficients of long multi-hole orifices. Based on Idelchik's loss factor correlation for thick, sharp-edged orifices [4], the correction equation is derived by comparing it with the Huang's experiments [5]. Based on the results, the difference in discharge coefficient behavior of a single standard orifice and a multi-hole perforated orifice is discussed.

2. Modeling

2.1 Idelchik equations for hydraulic resistance

Fig. 1 shows an illustration of thick orifice with thick edge. The loss factor of this geometry was proposed by Idelchik [4] as follows:

$$\varsigma = \Delta p/\rho {u_o}^2/2 \quad (1)$$
$$= \begin{cases} 33/Re_o, & Re_o < 10 \\ 33/Re_o + \varepsilon_{0Re}\varsigma_{quad}, & 10 < Re_o < 30 \\ \varsigma_\phi + \varepsilon_{2Re}\varsigma_{quad}, & 30 < Re_o < 10000 \end{cases}$$

where three terms mean loss factor at laminar, transition and turbulent regime, respectively.

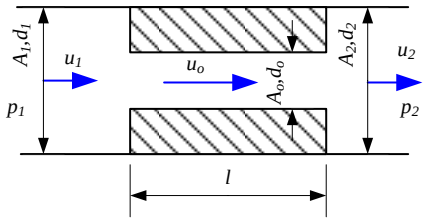


Fig. 1 Illustration of thick sharp-edged orifice

Reynolds number at the orifice, Re_o, is defined:

$$Re_o = \rho u_o d_o/\mu \quad (2)$$

Interpolation function, ε_{0Re} , was described in reference [4] as a complex function of Reynolds number and diameter ratio, $\beta = d_o/d_1$. It was simplified in [6] as follows :

$$\varepsilon_{0Re} = 0.2531 {Re_o}^{0.1103} \quad (3)$$

Another function used in transition regime, ς_ϕ , was provided as follows [6]:

$$\varsigma_\phi = C_a \cdot {Re_o}^{-C_b} \quad (4)$$

where, C_a and C_b can be found in table form as a function of Reynolds number [6]. Loss factor at the fully turbulent regime:

$$\varsigma_{quad} = 0.5[1-(A_0/A_1)]^{0.75} + \tau_{cor}[1-(A_0/A_1)]^{1.375} + [1-(A_0/A_2)]^2 + \lambda_t\, t/d_{ho} \quad (5)$$

1st term of E q(7) is for the loss by contraction at the inlet, 2nd term for loss with vena contracta, 3rd term for expansion loss at the exit, and 4th term for frictional loss within orifice hole. Especially, the vena contracta loss is as follows:

$$\tau_{cor} = (2.4 - t^*)\cdot 10^{-\varphi} \quad (6)$$

$$\varphi = 0.25 + 0.535 {t^*}^8/\left(0.05 + {t^*}^7\right) \quad (7)$$

where $t^* = l/d_1$.

2.2 Correction for standard orifice

Idelchik's correlation is presented in a systematic manner, but the range of its application of the major parameters such as the diameter ratio is not clear. In the authors' study, a considerable discrepancy was observed especially in turbulent region when the original correlation was applied to Huang's standard orifice experiments,. The discrepancy may be due to that the range of β in Huang's experiment was different from the Idelchik's study. Thus, by comparing ς_{quad} in Eq(1) with the data from the standard orifice experiments, a correction factor expressed as quadratic equation of β was derived.

$$\varsigma_{std-cor} = \begin{cases} 33/Re_o, & Re_o < 10 \\ 33/Re_o + \varepsilon_{1Re}\varsigma_{q-c}, & 10 < Re_o < 10000 \\ \varepsilon_{1Re}\varsigma_{q-c}, & 10000 < Re_o \end{cases} \quad (8)$$

$$\varepsilon_{1Re} = \frac{1 - e^{-\kappa_1(Re_o - 10)}}{1 - e^{-(10000-10)\kappa_1}}, \kappa_i = 0.003, \quad (9)$$

$$\varsigma_{q-c} = C_{\beta-std}\varsigma_{quad} \quad (10)$$

$$C_{\beta-std} = 1 - 1.48\beta + 1.77\beta^2 \quad (11)$$

Here, the term "standard orifice" refers to an orifice in which a single hole is perforated by combining the areas of multiple holes, whereas in the case of multiple holes it is called a "perforated orifice."

As shown, the loss factor in the fully turbulent region was corrected, and accordingly the correction equation for the transition process was also revised. Also, the interpolation function, ε_{1Re}, in transition region was further simplified.

Fig. 2 shows a comparison of the corrected loss factor with the original one from Idelchik. Huang's experiment data was also compared with respect to diameter ratio. One can find the correction equation leads to a good agreement for a range of β =0.25~ 0.65.

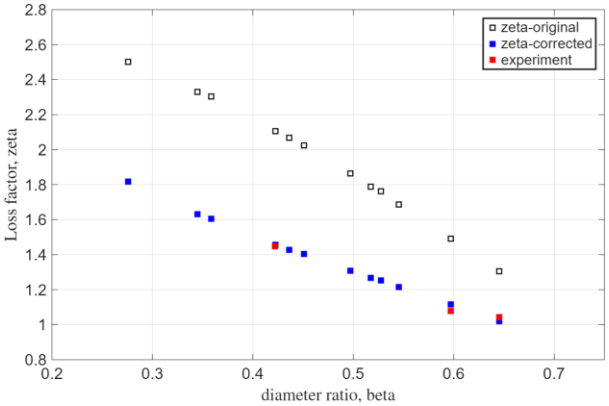


Fig. 2. Loss factor correction for standard orifice.

Conversion equation from the discharge coefficient to the loss factor in this derivation was as follows:

$$C_d = 1/\sqrt{1+\zeta} \quad (13)$$

2.3 Correction to multi-hole orifice

Twelve set of perforated orifice experiments are presented in the reference [5]. Table 1 lists conditions of the experiments. Fig. 3 shows configuration of standard and perforated orifices of no.2 experiment.

Table 1. Parameters of perforated orifices.

ID	b	d_0(mm)	d_1/D	d_2/D	d_3/D	n_1	n_2	n_3
1	0.422	5	0.69	/	/	6	/	/
2	0.597	5	0.37	0.78	/	4	8	/
3	0.668	5	0.41	0.86	/	5	10	/
4	0.517	3	0.22	0.52	0.81	3	8	14
5	0.516	4	0.38	0.78	/	5	9	/
6	0.517	5	0.38	0.79	/	3	6	/
7	0.345	5	0.69	/	/	4	/	/
8	0.343	3	0.38	0.79	/	3	8	/
9	0.439	3	0.22	0.52	0.81	3	6	9
10	0.338	4	0.69	/	/	6	/	/
11	0.414	4	0.38	0.79	/	3	6	
12	0.422	5	0	0.69	/	1	5	/

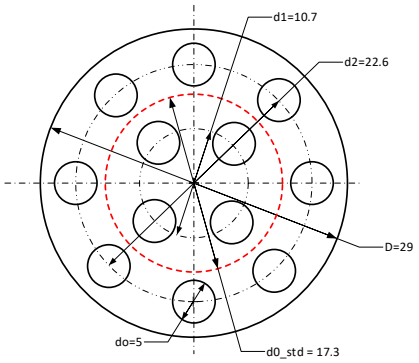


Fig. 3. Configuration of standard orifice and perforated orifice for no 2 experiment

This experiment aimed to investigate the effects of factors such as the number of holes, the diameter of the holes, the diameter of the circle in which the holes are allocated, and the thickness of the orifice.

Various attempts were made to derive a correlogram covering the those important parameters. But it was ultimately found that, except for β, it was difficult to develop a correlogram, or the resulting correlogram would have high uncertainty. Accordingly, we derived a correction factor equation for β that follows the data mean. And to cover data that deviates from this equation, both upper bound and lower bound correction factors were also presented.

$$C_{\beta-per} = 0.2157e^{m_c\beta} \quad (14)$$

Where m_c means an exponent for correction: 1.2823 for mean, 1.8 for upper bound, and 0.6 for lower bound, respectively.

Figure 4 shows a comparison of the predicted loss factors with the measured loss factors for perforated orifices in a fully turbulent region. Predicted were obtained by multiplying two correction factors to the Idelchik's original formula

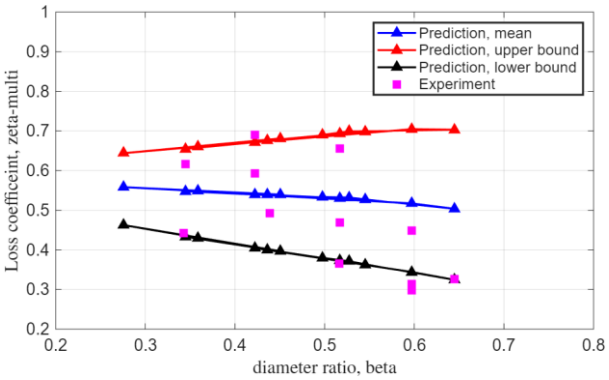


Fig. 4. Comparison of the multi-hole corrected loss factors with the experiment

2.4 Correction of orifice length

Huang's experiments were mostly conducted on thin plate orifices with a thickness of 3 mm, and to specifically observe the length effect, additional orifices with thicknesses of 6, 9, and 12 mm were tested under the No. 2 experiment. From the graph presented in the paper, the following thickness correction factor could be obtained.

$$C_{\beta-thick} = 0.13(t^*)^{-1.07} \qquad (15)$$

Fig. 5 shows the loss factor for orifices of various thicknesses, calculated using this correction factor, compared with the measured values. In this comparison, the loss factors calculated with the mean of the multi-hole correction factor and thode with an upper bound are compared together. This indicates that although there is uncertainty in the current multi-hole correction factor, there would be no problem applying it to long orifices, as the orifice thickness increases, the uncertainty decreases.

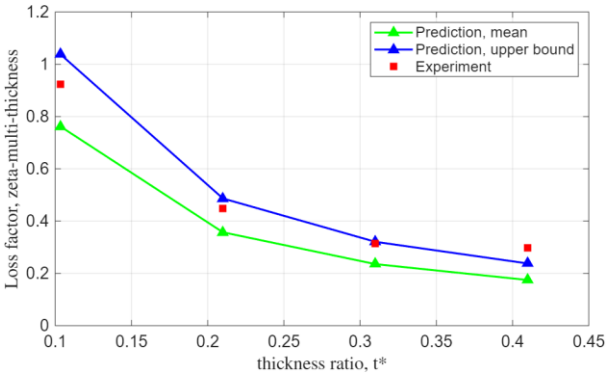


Fig. 5. Comparison of the thickness-corrected loss factors with the experiment

3. Discharge Coefficient Behavior

The basis for obtaining the correction factor equation so far was based on the loss factor in the fully turbulent region. The loss factor in laminar and transition regions may have an effect on valve movement. Thus, behavior of the corrected discharge coefficient for multi-hole orifice over the full range of Reynolds number should be checked.

Figures 6 and 7 compare the behavior of the predicted discharge coefficient (C_d) with respect to Reynolds number for Huang's perforated orifice experiments No. 1 and No. 4. The data for the standard orifice in Experiment No. 4 were not published in the reference paper, so they were omitted here as well. All the calculations were carried out using MATLAB [7].

As shown in the figure, the behavior of the C_d calculated by the corrected loss-factor correlation agrees well with the experimental data within an acceptable range.

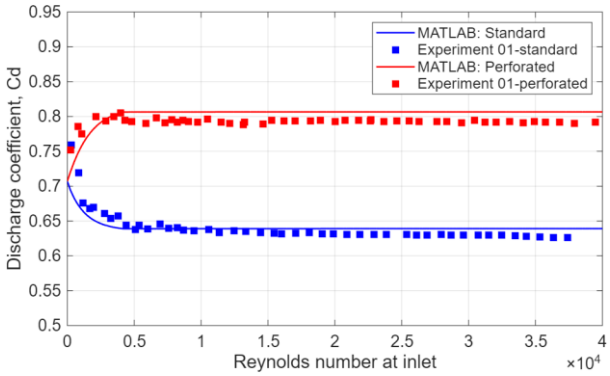


Fig. 1. Comparison of discharge coefficients for standard orifice and perforated orifice, experiment no.1.

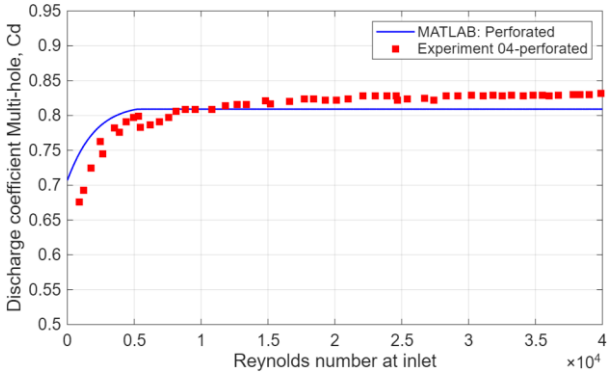


Fig. 7. Comparison of discharge coefficients for standard orifice and perforated orifice, experiment no.4

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Through this comparison, we were able to understand the behavior of C_d of a standard orifice and a perforated orifice. As an important matter,

(1) In the turbulent regime, the C_d of a multi-hole perforated orifice, in general, has a larger value than that of a single standard orifice.
(2) In the transition regime, a perforated orifice exhibits behavior in which the C_d increases, unlike a standard orifice. This is due to a tendency to decrease from a larger loss factor in laminar regime to a smaller loss factor in turbulent regime. The applied correction factor appropriately implements it.
(3) Some, rather than all, experimental data indicate that the C_d in standard orifices changes from a laminar to a transition regime at lower Reynolds numbers than the C_d in perforated orifices. Those experimental facts have not been sufficiently addressed in the present study, and further studies are needed.

4. Conclusions

In this study, correction factors were developed to fit Huang's experimental data, based on Idelchik's loss factor correlation for thick sharp-edge orifices to predict the discharge coefficients applicable to long multi-hole orifices. The followings are concluded:

1) The correction process consists of standard orifice correction, multi-hole orifice correction, and orifice thickness effect correction. Due to the limitation of data and variety of parameters, the multi-hole orifice correction led to the additional correction factors for upper and lower bounds.
2) Idelchik's loss factor correlation and the correction factors developed in the present study can properly implement Huang's experimental data. Through the analysis results, we were able to understand the behavior of the discharge coefficient between the perforated orifice and the standard orifice.
3) The method for predicting the discharge coefficient of the multi-hole orifice presented in this study is thought to be helpful in implementing the orifice characteristics in the dynamic behavior prediction method for valves currently under development.

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