Transactions of the Korean Nuclear Society Autumn Meeting
Yeosu, Korea, October 25-26, 2018

Experimental Investigation of Critical Flow Model of Supercritical CO_2 Cycle for the Next Generation Nuclear System Application

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1. Introduction

Understanding flows and predicting leakages past seals are important for designing supercritical CO_2 (S-CO_2) rotating machinery, since the seal leakages can have a direct impact on the cycle efficiency. If pressure and temperature trends of leakage flow can be predicted analytically then recovery system can be optimized for better system's overall efficiency. Furthermore, the authors are interested in the transient behavior of seal leakage flow, since the S-CO_2 power system can loose inventory during part-load operation as well as during start-up and shut down sequences which was experienced in a few operating test facilities. Therefore, the off-design seal performance is also equally important while this is not dealt thoroughly yet. Thus, a transient simulation for estimating the critical flow in a turbo-machinery seal is essential to predict the leakage flow rate and to calculate the required total mass of working fluid in an S-CO_2 power system.

In this paper, the number of tooth effect in a labyrinth seal geometry nozzle are presented by using the same experimental facility described in the previous paper. In addition, this paper includes the experimental results under various conditions including not only single phase flow such as supercritical, and gaseous state only but also two phase flow condition.

2. CO_2 Critical Flow Experimental Facility

Kim et al. constructed a critical flow test facility to validate the S-CO_2 critical flow model [1]. Fig. 1 shows the designed experimental facility for the CO_2 critical flow. The CO_2 flows from a high-pressure tank (left) to a low-pressure tank (right) through the designed nozzle, and pressure and temperature of each position are measured every second. Two tanks are connected by a 1090mm pipe and the designed nozzle that simulates a labyrinth seal geometry is installed between the ball valve and the low-pressure tank. Each tank has 200 mm of inner diameter, 1600 mm in height, and 47 liters of volume. Temperature and pressure limits are 150ºC and 22 MPa, respectively. To control the initial temperature of the high-pressure tank, electrical jacket-type heaters are installed on the external surface of the high-pressure tank. The pressure of the high-pressure tank can be controlled by injecting the CO_2 gas through a booster pump. The ball valve is automatically opened and driven by hydraulic pressure (1MPa) from an air compressor to minimize the valve opening time.

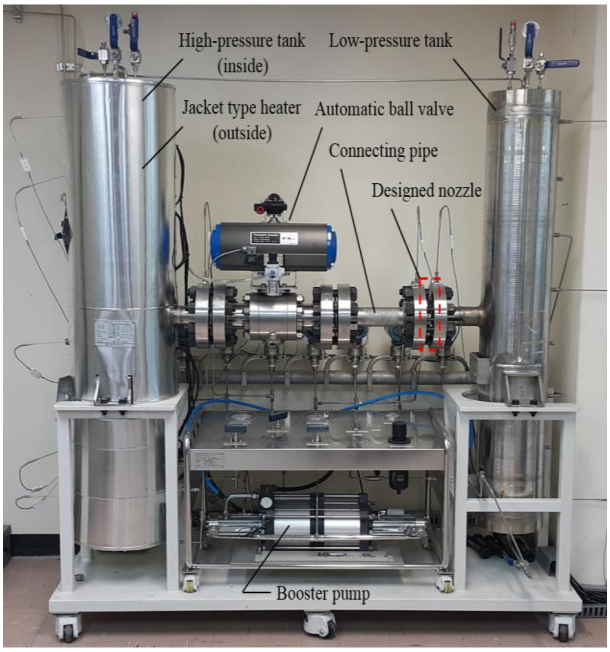

Fig. 1. S-CO_2 critical flow experimental facility

3. Numerical Model

To model the labyrinth seal geometry, Hodkinson's equation was adopted in this study [2]. Hodkinson modified Egli's approach [3] to provide a semi empirical relation that was based on assumptions of a gas jet geometry. Hodkinson's assumption was as follows. The fluid jet expands conically from the tip of an upstream tooth at a small angle, β. A part of the jet impinges on the downstream tooth to recirculate in the cavity, dissipating the kinetic energy associated with it, while a portion of the jet travels under the downstream tooth and carries over the kinetic energy to the next cavity. He assumed the angle β to be only a function of seal geometry. The Hodkinson's equation is shown in equations from (1) to (4).

$$G = \alpha\psi\gamma\sqrt{\rho_i P_i} \quad (1)$$

$$\alpha = \frac{8.52}{\frac{s-w}{c} + 7.23} \quad (2)$$

$$\psi = \sqrt{\frac{1-(\frac{P_e}{P_i})^2}{n - ln(\frac{P_e}{P_i})}} \quad (3)$$

$$\gamma = \sqrt{\frac{1}{1-\alpha}} \quad (4)$$

where, G is mass flux, α is relative amount of kinetic energy present upstream of tooth, ψ is expansion coefficient, γ is kinetic energy carry coefficient, P_e and P_i is pressure of low- and high-pressure tanks, ρ_i is density of high-pressure tank, s is tooth pitch, w is tooth width, n is tooth number, and c is radial clearance.

However, the above equation (2) is an empirical formula from the steam experiment. With experimental results of CO_2 leak flow in single phase condition regardless of the upstream condition at the supercritical state or the gaseous state, it was found that by taking 4.72 instead of 8.52 in equation (2), the numerical model gave results within 10 per cent of the measured values. Taking 4.72 as the constant, the empirical formula especially suitable for CO_2 single phase condition regardless of the upstream condition at the supercritical state or the gaseous state is as follows.

$$\alpha_{CO_2} = \frac{4.72}{\frac{s-w}{c} + 7.23} \quad (5)$$

4. Experimental Results

To observe the number of tooth effect in the labyrinth seal and to validate the CO_2 critical flow model further, the experiments with various labyrinth seal geometry nozzles were performed. The detail internal geometry of a labyrinth seal simulating orifice is shown in Fig. 2. The information of three experimental cases is summarized in Table I.

Table I: Summary of experimental cases

	Case 1	Case 2	Case 3
D (mm)	0.5	0.5	0.5
L_{tooth} (mm)	19	3	3
L_{cavity} (mm)	-	13	5
n (-)	1	2	3
Diameter ratio (-)	1	6	6
Pressure ratio (-)	105.0	105.0	105.0

It is noted that the total length and tooth length of nozzle geometry is kept constant while changing the tooth number and the cavity length. This means that when the tooth number is increased, the cavity length is reduced accordingly. The initial conditions of the high pressure tank were set to 10.6MPa and 133ºC to maintain the gaseous state after the expansion.

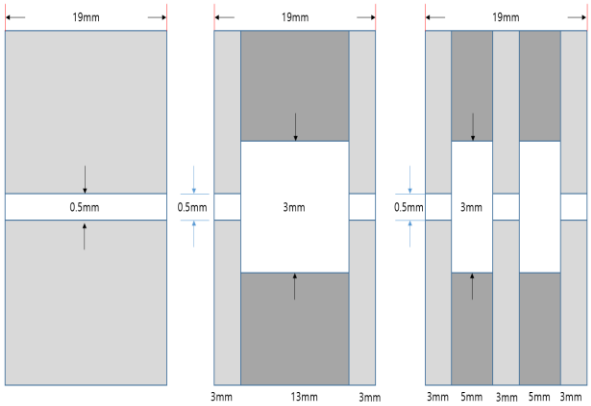

Fig. 2. Internal geometry of labyrinth seal geometry nozzle

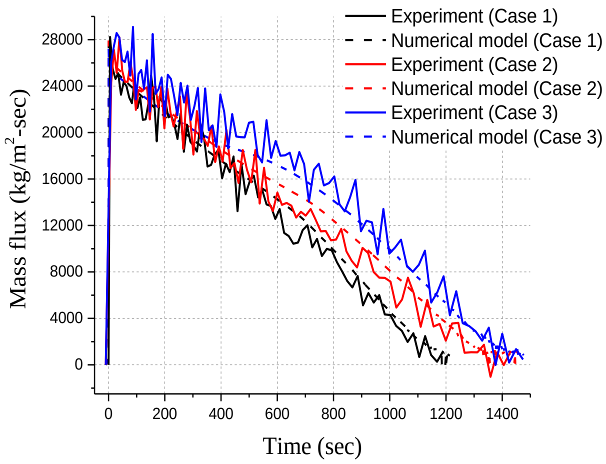

Fig. 3. Comparison of mass flux between the experimental and numerical results

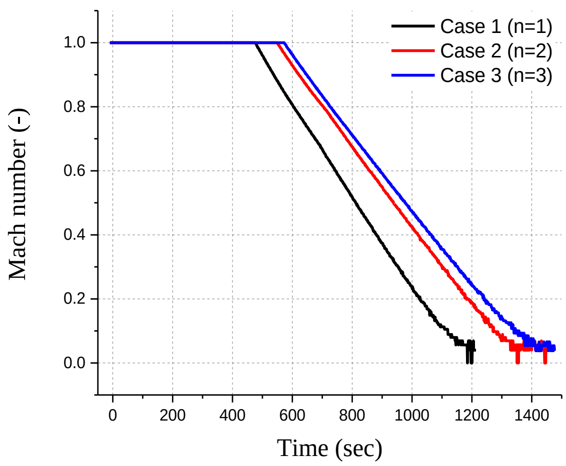

Fig. 4. Mach number of experimental result

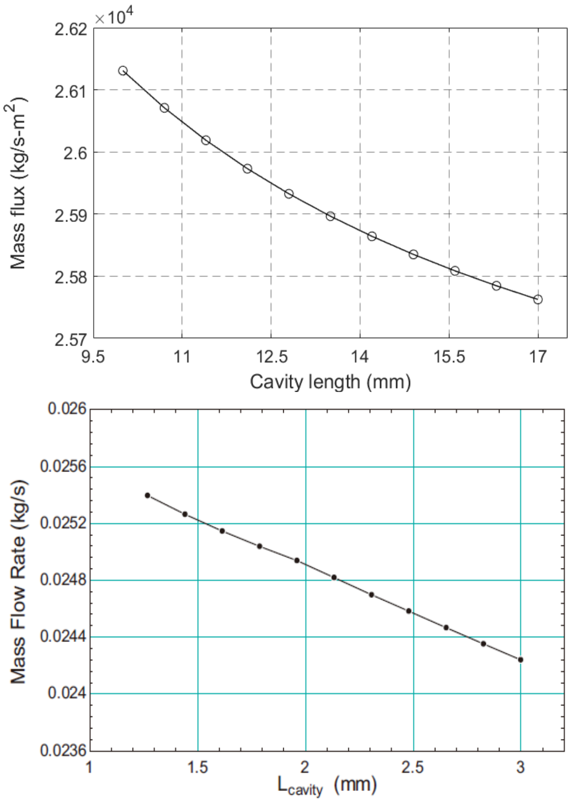

Fig 5. Mass flux change with cavity length (upper: KAIST, bottom: University of Wisconsin-Madison[4])

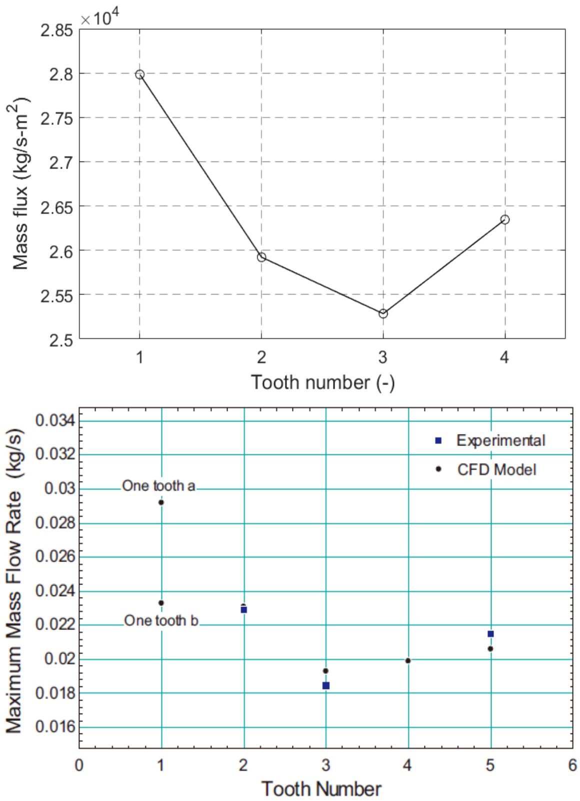

Fig 6. Mass flux change with tooth number (upper: KAIST, bottom: University of Wisconsin-Madison[4])

The experimental results are shown in Fig. 3. This figure shows that as the number of tooth increases, the time required for reaching equilibrium is delayed. Fig. 3 shows that as the number increase from one to three, the equilibrium reaching time is delayed about 291s. Thus, the experimental data confirms that the leak rate is reduced as the number increases even though the total nozzle length is the same. The mass flux of the CO_2 experiment and the model agrees with each other quite well in critical and sub-critical flow regimes. The CO_2 critical flow model based on the Hodkinson's equation has a good accuracy for predicting the real CO_2 leak flow in single phase condition regardless of the upstream condition at the supercritical state or the gaseous state.

With CO_2 critical flow model based on the Hodkinson's equation, mass flux change with cavity length was verified. Fig. 5 shows that the mass flux is decreased as cavity length is increased, and this result trend really well matched with previous study result from university of Wisconsin-Madison [4].

Also, mass flux change with different tooth number was verified. Authors know that the larger cavity length leads to lower leakage. This means the minimum tooth length results in the lowest leakage rate. As a result, in this part, authors are using a fixed tooth length for all teeth. By inserting more teeth into the seal, the leakage rate initially decreases. However, after a certain number of teeth is inserted, the leakage rate increases. It seems there is an optimum tooth number which leads to the minimum leakage rate. From the analysis of mass flux change with cavity length, authors know that the increasing the cavity length reduces leakage. In this study, as the teeth are inserted into the seal, the cavity length decreases. As a result, at a certain point, inserting more teeth cannot bring more benefits to decrease leakage as cavity length becomes too small. As shown in Fig. 6, the mass flux change trend is really similar with previous study of university of Wisconsin-Madison.

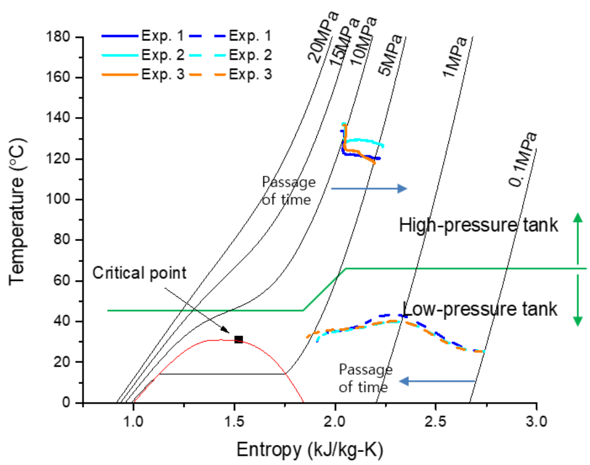

Fig 7. T-s diagram of high- and low-pressure tank

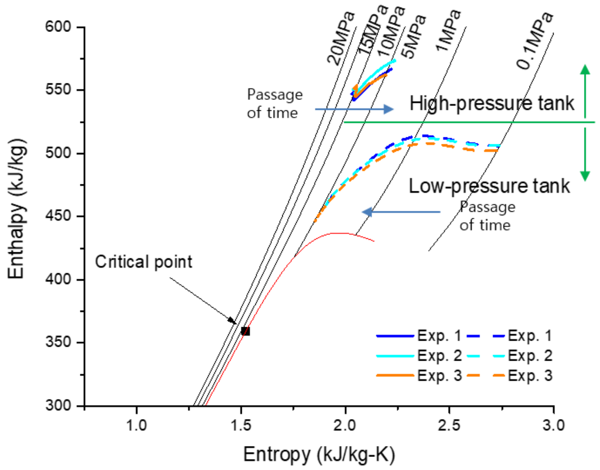

Fig 8. h-s diagram of high- and low-pressure tank

3. Conclusions

Predicting the leak flow rate in turbo-machinery seals is imperative to secure high performance of an S-CO_2 power cycle. Thus, the Hodkinson's equation was selected from the literature and compared to the experimental results to identify the mass flow rate of CO_2 leakage in turbo-machinery. To develop the critical flow model especially suitable for CO_2 single phase condition regardless of the upstream condition at the supercritical state or the gaseous state, an empirical constant of relative amount of kinetic energy present upstream of tooth is updated. By taking 4.72 instead of 8.52 in empirical formula, the numerical model gave results within 10 per cent of those obtained with the more rigorous derivation.

To validate the CO_2 critical flow model based on the Hodkinson's equation with experimental results, experiments with nozzles that simulate the condition in the labyrinth seal were performed. As the number increases, the equilibrium reaching time is delayed further. the CO_2 critical flow model based on the Hodkinson's equation for predicting the critical flow in the seal geometry gave a good agreement with the experimental data.

This paper verified that the mass flux is decreased as cavity length is increased. Also, the authors identified that there is an optimum tooth number leads to a minimum leakage rate since inserting more teeth cannot bring more benefits to decrease leakage as cavity length is too small.

ACKNOWLEDGEMENTS

This study was conducted with the support of Civil-Military Technology Cooperation Program (Project No.: 17-CM-EN-04, Development of the supercritical CO2 power generation system for the exhaust heat recovery of surface ships) as part of the core industrial technology development project supported by the Ministry of Trade, Industry and Energy, which is gracious acknowledged.

REFERENCES

[1] M. S. Kim, B. S. Oh, J. S. Kwon, H. Jung, J. I. Lee, Transient Simulation of Critical Flow With Thermal-Hydraulic System Analysis Code for Supercritical CO2 Applications, ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition

[2] Hodkinson, B., 1939, "Estimation of the Leakage through a Labyrinth Gland,"Proceedings of the Institution of Mechanical Engineers 141, pp. 283–288.

[3] Egli, A. , 1935, "The leakage of Steam through Labyrinth Seals,", Trans. ASME, 57, pp 115-122.

[4] Yuan, H., Pidaparti, Wolf, M., Edlebeck, J., Anderson, M., 2015. Numerical modeling of supercritical carbon dioxide flow in see-through labyrinth seals. Nucl. Eng. Des. 293, 436–446.