Preliminary Study on Critical Flow Model of S-CO_2 for Nuclear Power Cycle Application

Jae Jun Lee, Jeong Ik Lee*
Department of Nuclear and Quantum engineering, Korea Advanced Institute of Science and Technology (KAIST)
291 Daehak-ro, (373-1, Guseong-dong), Yuseong-gu, Daejeon 34141, Republic of KOREA
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

A Small Modular Reactor (SMR) is considered as a promising future reactor technology. For SMR development, many innovative power cycles have been proposed and among them, a Supercritical CO_2 (S-CO_2) power cycle is seriously being considered [1].

To ensure the safety of Nuclear Power Plant (NPP), a safety analysis is performed for Design Basis Accident (DBA). Loss of fluid is one of the main causes of DBA initiating events and this is no exception for the S-CO_2 system also. For this reason, an accurate loss model of fluid should be developed for an accurate safety analysis.

An S-CO_2 power cycle system retains the system pressure beyond the pressure at the critical point of CO_2 (7.3773 MPa) in general. When the S-CO_2 leaks out from the high pressure system to surrounding at low pressure, the flow becomes choked. Thus, the critical flow model or the choked flow model for S-CO_2 is needed to predict the loss.

In this paper, the region of interest is limited to near the critical point. This region also corresponds to the operating point of the compressor. Since the S-CO_2 power cycle is characterized of consuming a small amount of power for compression by using that the physical property of CO_2 changes drastically near the critical point. In this paper, the authors reviewed a homogenous equilibrium model (HEM) and a non-homogeneous model (Non-HEM with Moody's slip ratio) for this region and evaluated them with experimental data presented by J. Edlebeck et al [3].

2. Critical flow model

When the upstream condition is close to the critical point, the second phase appears on the choked plane as seen in Fig. 1. Thus, two phase critical flow models were selected.

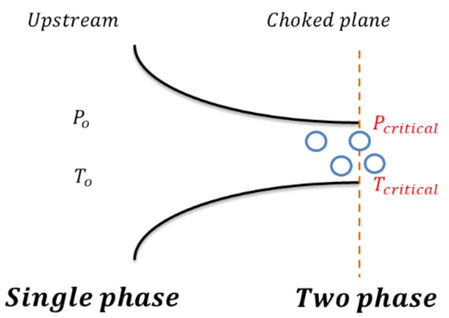

Fig. 1. Schematic of critical flow with appearance of the second phase

There are many proposed two phase critical flow models. Among them, the authors applied HEM and Non-HEM that satisfying Eq. 1 in this study.

$$\left.\frac{\partial G}{\partial P}\right|_S = 0 \qquad (1)$$

2.1 Homogeneous equilibrium model (HEM)

HEM is the simplest model and it assumes mechanical equilibrium (homogeneous) and thermal equilibrium. The mass flux (Eq.4) could be derived from Eqs. 2 and 3.

$$h_o = x_E\left(h_{g,E} + \frac{V_g^2}{2}\right) + (1 - x_E)\left(h_{l,E} + \frac{V_l^2}{2}\right) \qquad (2)$$

$$S_o = x_E(S_{g,E}) + (1 - x_E)(S_{l,E}) \qquad (3)$$

h: Enthalpy $[J/kg]$, S: Entropy $[J/kg \cdot K]$
V: Velocity $[m/s]$, x: quality
subscript − E: Equilibrium, l: Liquid, g: Gas, o: upstream

$$G_{HEM} = \frac{\sqrt{2(h_o - (1 - x_E)h_{l,E} - x_E h_{g,E})}}{(1 - x_E)v_{l,E} + x_E v_{g,E}} \qquad (4)$$

v: specific volume $[m^3/kg]$

2.2 Non-homogeneous equilibrium model (Non-HEM with Moody's slip ratio)

Gas and liquid phases have different velocity in non-homogeneous equilibrium model. The different velocity can be represented with the ratio of the speed of each phase (slip ratio) in the model. The slip ratio can be defined using various correlations or assumptions. Among them, F. J. Moody [2] obtained slip ratio by selecting the slip ratio that maximizes the mass flux. The mass flux is calculated with Eq.5.

$$G_{Moody} = \frac{\sqrt{2(h_o - (1-x_E)h_{l,E} - x_E h_{g,E})}}{\sqrt{\left(x_E v_{g,E} + (1-x_E)v_{l,E}S_r\right)^2\left(x_E + \frac{(1-x_E)}{S_r^2}\right)}} \qquad (5)$$

$$S_r = \left(\frac{V_g}{V_l}\right) = \left(\frac{v_g}{v_l}\right)^{\frac{1}{3}} \text{ that satisfies } \frac{dG}{dS_r} = 0$$

3. Evaluation results

J.Edlebeck et al [3] presented critical mass flow rate and critical pressure ratio (Pr) data for orifices A and B.

The diameters of both orifices are about 1mm and length to diameter ratios are 3.2(A) and 5.0(B) respectively. The upstream conditions are the same for each case and these conditions are shown in Fig. 2.

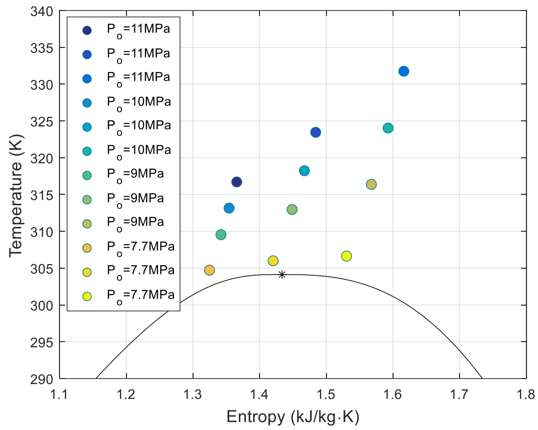

Fig. 2. Upstream conditions of the experiment

3.1 Prediction of pressure ratio (Pr)

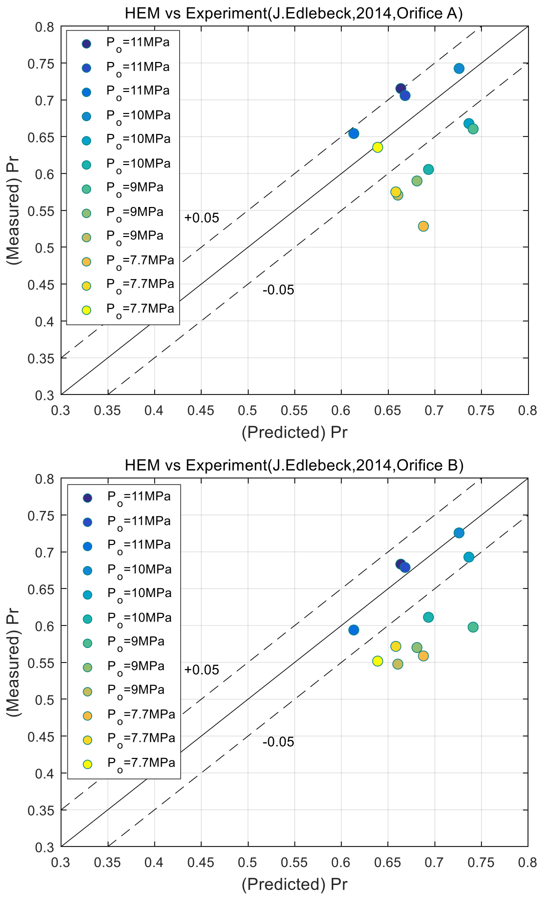

Fig. 3. Comparison of Pr between HEM and the experiment

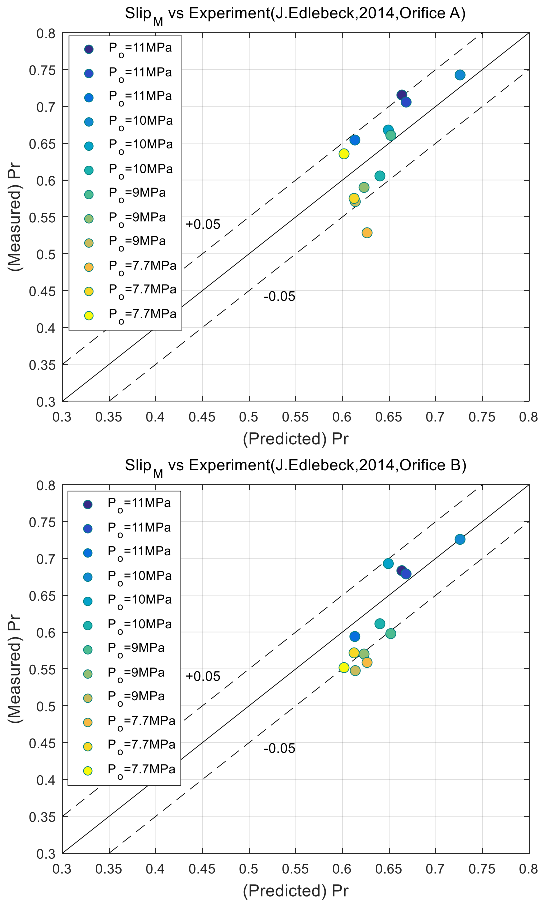

Fig. 4. Comparison of Pr between Non-HEM (Moody's slip ratio) and the experiment

Figs. 3 and 4 show the results of the pressure ratio calculated using HEM and Non-HEM, and measured data for orifices A and B. The results show that the predicted pressure ratios using Non-HEM are lower than HEM. It is well known that the critical flow rate increases as the degree of non-equilibrium increases. Therefore, this tendency is consistent with the fact that a lower critical pressure is needed for a faster velocity, as indicated by the conservation of energy in Eq. 2.

In Figs. 3 and 4, some data does not move. The reason why these points are fixed is that the critical pressure is equal to the saturated pressure, which corresponds to the point where the discontinuity of the sound speed occurs. Thus, the pressure ratios of the points are equal to the ratio of saturated pressure to upstream pressure.

3.2 Prediction of mass flux (G)

Both models overestimate the mass flux and it can be seen that if the discharge coefficients (Cd) 0.85 and 0.8 are applied, respectively, the errors fall within 10% in Figs. 5 and 6. As mentioned in section 3.1, it is natural that the predicted mass flux of the slip ratio model is larger due to the non-equilibrium effect.

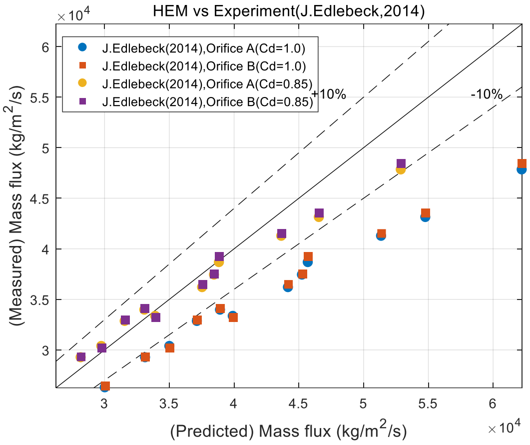

Fig. 5. Comparison of mass flux between HEM and the experiment

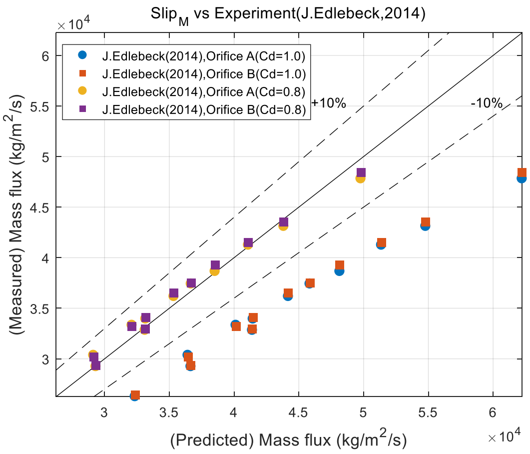

Fig. 6. Comparison of mass flux between Non-HEM (Moody's slip ratio) and the experiment

4. Summary and Conclusions

Two critical flow models (HEM and Non-HEM with Moody's slip ratio) are evaluated near the critical point of CO_2 using the presented experimental data by J. Edlebeck et al [3]. The evaluation results are as follows. Both models can predict the critical mass flux by using the discharge coefficient. However, Non-HEM with the slip ratio proposed by F. J. Moody [2] can predict the critical pressure ratio more accurately than HEM.

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