Transactions of the Korean Nuclear Society Autumn Meeting, October 21-22, 2021

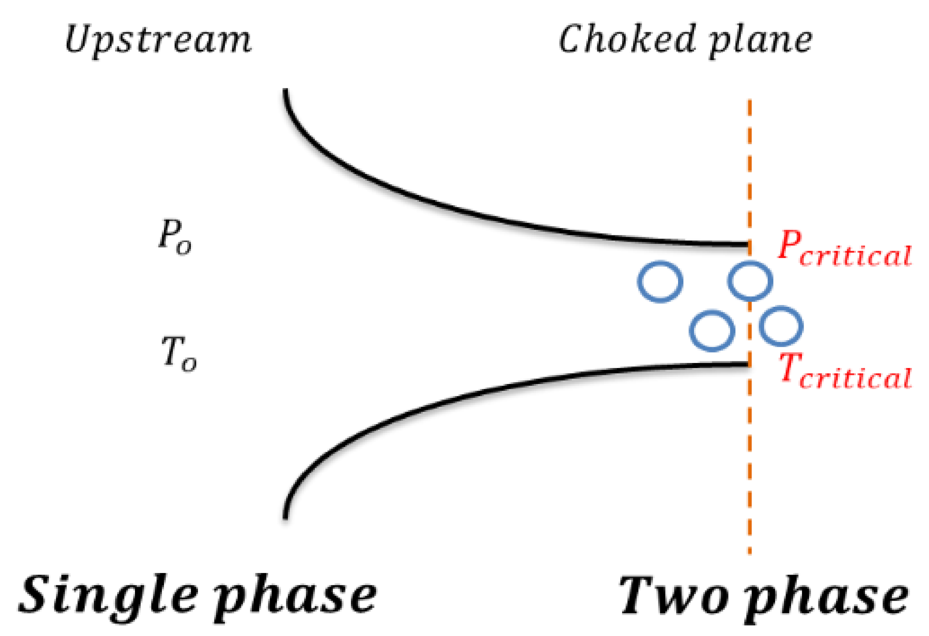
Preliminary Study on Critical Flow Model of S-CO_2 for Nuclear Power Cycle Application

Jae Jun Lee, Jeong Ik Lee*
Department of Nuclear and Quantum Engineering, KAIST
*Corresponding author: jeongiklee@kaist.ac.kr

NQe
KAIST Nuclear & Quantum Engineering

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.
- 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 for S-CO_2 is needed to predict the loss.
- In this study, the upstream condition of interest is limited to above and near the critical point. Thus, the second phase could exists on the choked plane. Considering that the appearance of second phase, 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.



✓ Description of choked flow with appearance of second phase

Brief description of critical flow model

- There are several equivalent methods that could define critical condition. Using the phenomenological definition of choked flow is a one of them.

$$\frac{dG}{dP} = 0$$

- HEM is the simplest model for two phase choked flow. it assumes mechanical equilibrium (homogeneous) and thermal equilibrium

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

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*

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

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

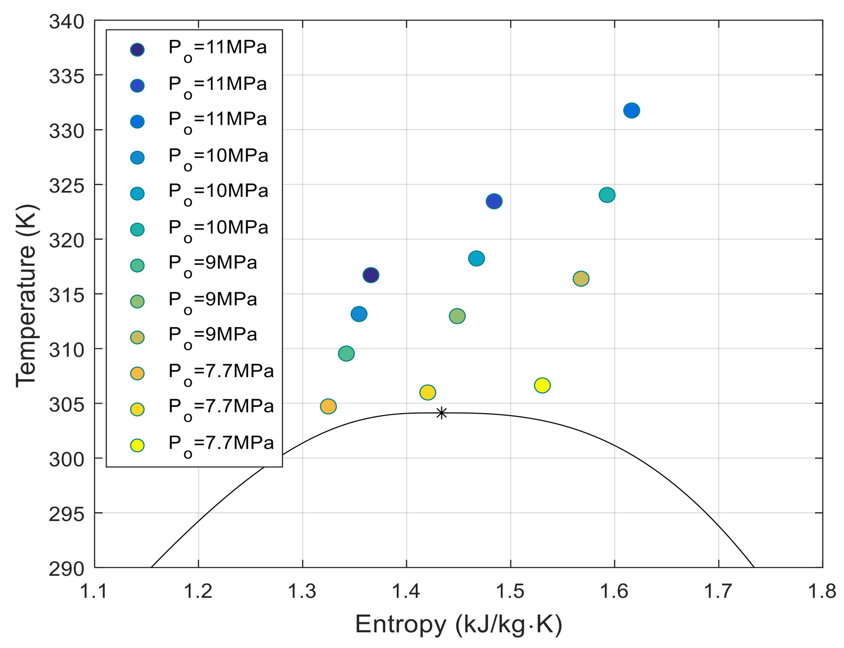
- Slip model is a kind of Non-HEM. F. J. Moody obtained slip ratio by selecting the slip ratio that maximizes the mass flux. It is widely used due to conservative result although there is no physical background.

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

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

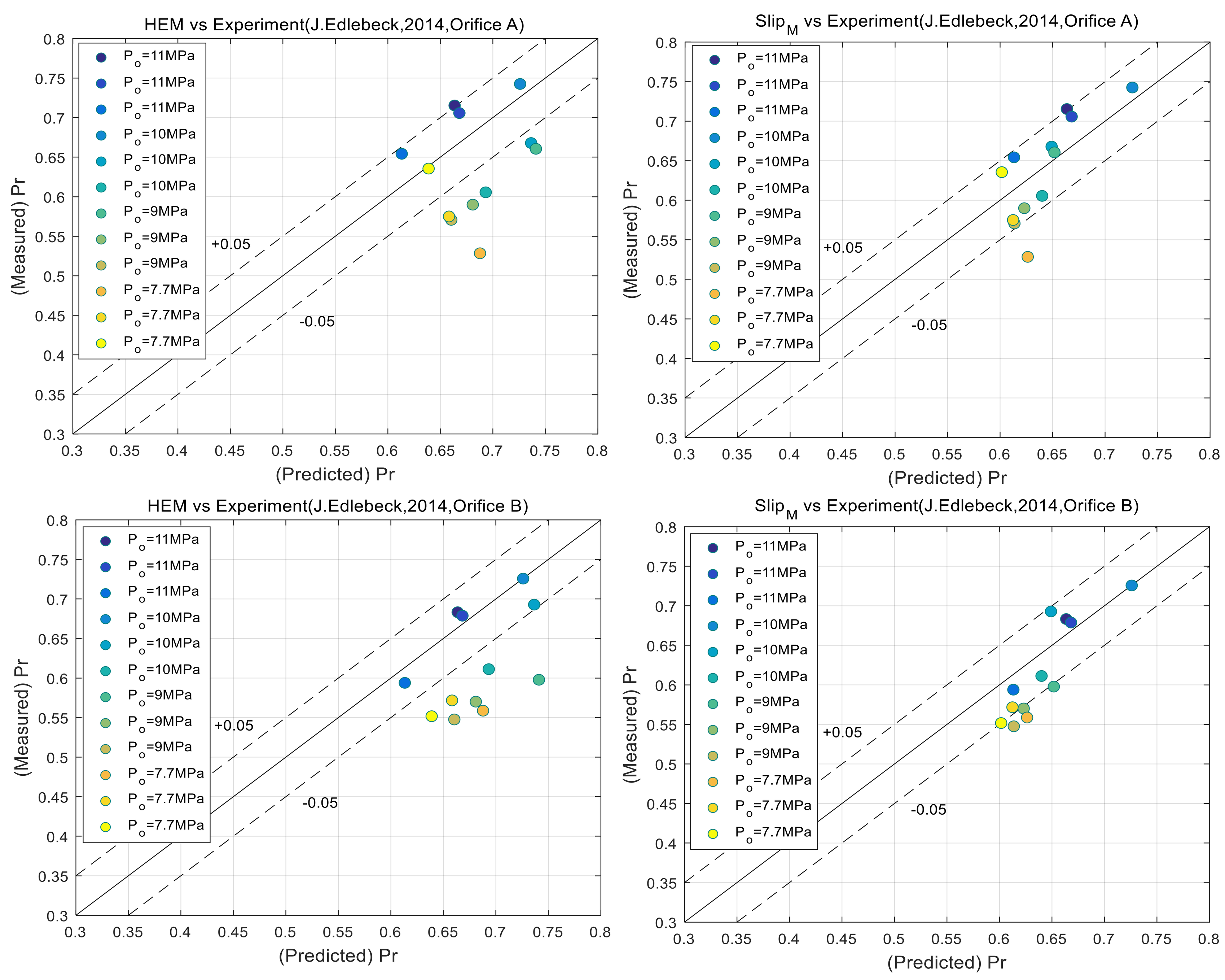
Evaluation results

- J.Edlebeck et al 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



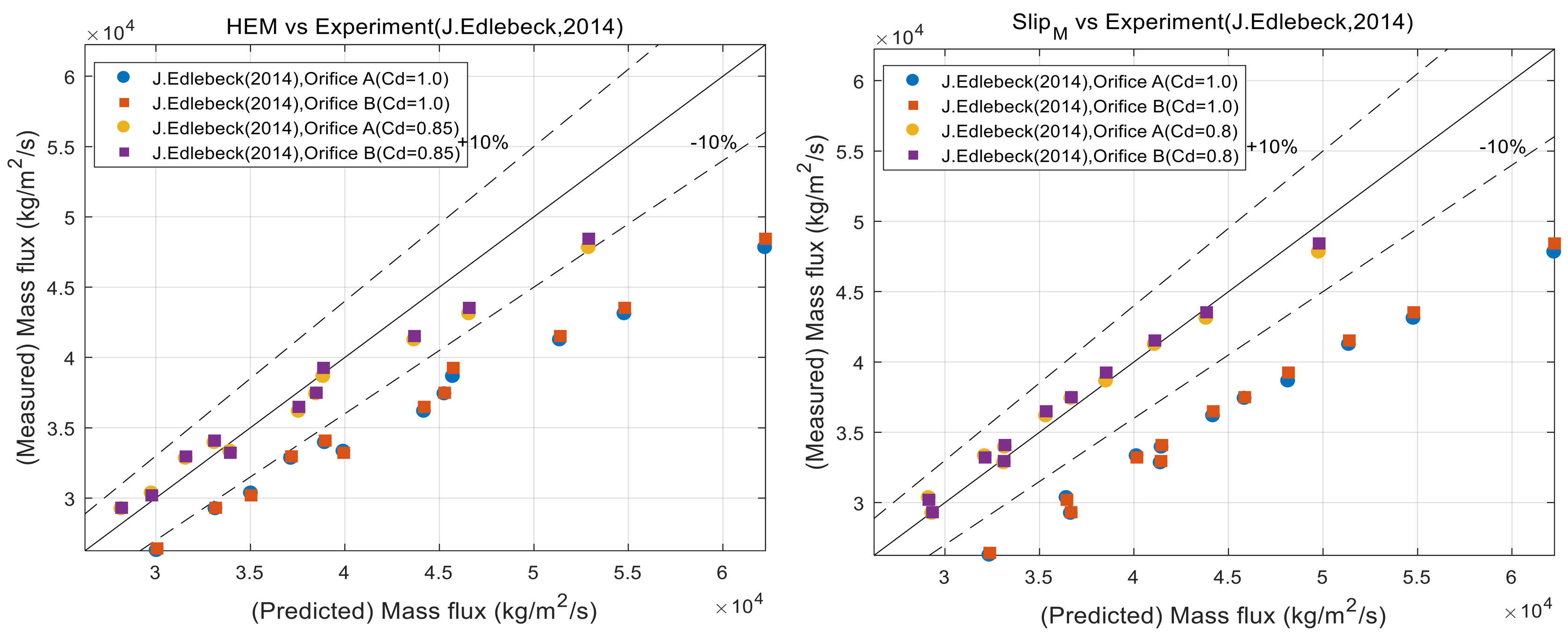
✓ Upstream conditions of the experiment

- When the pressure falls into two phase dome, it has sufficient quality. A sufficient mixture is known to be more non-homogeneous, which is consistent with the Non-HEM's relatively good agreement with the experimental values.
- The reason why some data do not move in both methods 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.



✓ Comparison of Pr between HEM(Left), Non-HEM(Right) and the experiment

- 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%. This result is reasonable when considering inlet effects such as the vena contracta.



✓ Comparison of mass flux(G) between HEM, Non-HEM and the experiment

Summary and Conclusion

- Two critical flow models are evaluated near the critical point of CO_2 using the presented experimental data by J.Edlebeck et al.
- 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 can predict the critical pressure ratio more accurately than HEM considering Pr.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (No. NRF-2016R1A5A1013919).