Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Experimental Study of Two-Phase Critical Flow for Supercritical CO_2 application

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1. Introduction

As a part of Sodium-cooled Fast Reactor (SFR) development, the supercritical CO_2 (S-CO_2) Brayton cycle is considered as an alternative power conversion system to eliminate sodium-water reaction (SWR) from the current conventional steam Rankine cycle is utilized with SFR. The major benefits are relatively higher efficiency under moderate turbine inlet temperature which significantly reduced materials and maintenance related issues, and simple layout and physically compact power plant size due to small turbo-machinery and heat exchangers [1, 2].

However, leakage in turbo-machinery cannot be avoided because S-CO_2 power cycles are highly pressurized. The parasitic loss caused by the leakage flow should be minimized since this can substantially influence the cycle efficiency. Thus, a transient simulation for estimating the critical flow in a turbo-machinery seal is essential to predict the leakage flow rate and calculate the required total mass of working fluid in a S-CO_2 power system to minimize the parasitic loss. To validate the transient simulation model, experimental data are needed with various designs and conditions. This paper presents experimental study of two-phase critical flow while special attention is given to the turbo-machinery seal design. Experimental data obtained from simple nozzle with two-phase condition are reported to study the flow characteristic and provide validation data for the numerical model.

2. Experimental Study

2.1 Designed Experimental Facility

A critical flow test facility was constructed to validate the S-CO_2 critical flow model. Fig. 1 shows the designed experimental facility for the CO_2 critical flow simulation and the design specifications are shown in Table I. For accurate measurements, total nine RTDs (Resistance Temperature Detectors) and seven pressure gauges are installed on the critical flow facility as shown in Fig. 2. Three RTDs and two pressure gauges are installed on the high-pressure tank (left) and the low-pressure tank (right), respectively. They are located at top, middle, and bottom sections of each tank. One RTD and one pressure gauge are installed at the inlet and the outlet of the nozzle as well as between high-pressure tank and a valve, respectively.

Table I: Design specifications of the experimental facility

	Design Parameters	
High/Low-pressure tank	Pressure (MPa)	22
	Temperature (℃)	150
	Volume (L)	47 (I.D.:200 mm, H: 1600mm)
Pipe connecting two tanks	Internal diameter (mm)	57
	Length (mm)	1090
Heater (Jacket-type)	Electric capacity (kW)	5
Valve type	Ball valve	

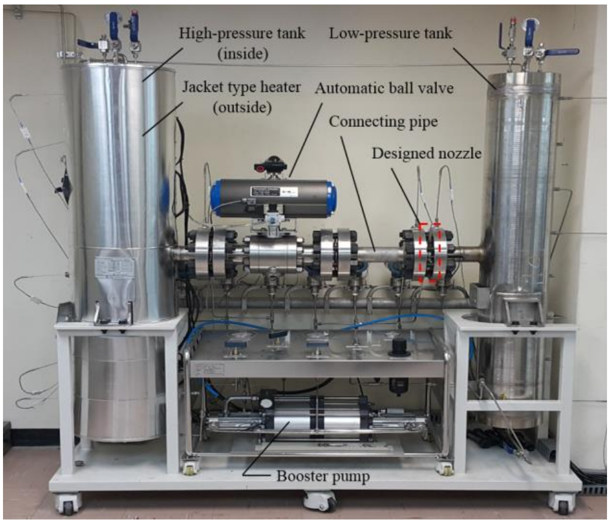

Fig 1. S-CO_2 critical flow experimental facility

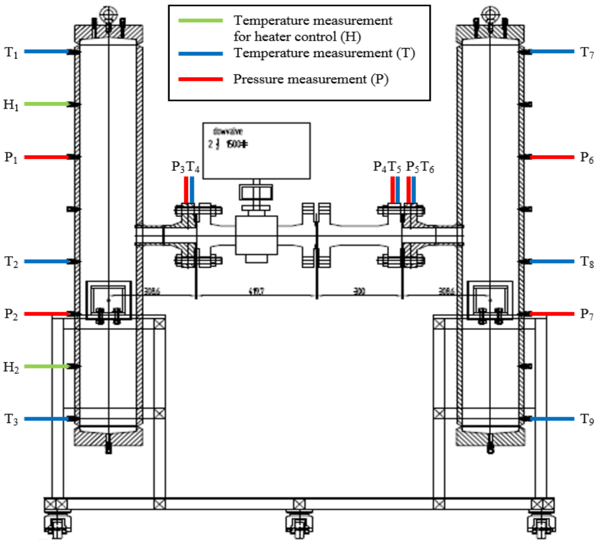

Fig. 2. The location of measurements in the experimental facility

Table II: Known constant values and uncertainties for calculation

	Known value	Uncertainty		Uncertainty
D_{nozzle} (mm)	1.5/0.5	±0.02	P (kPa)	±(0.00025P)
D_{tank} (mm)	200	±0.5		
H_{tank} (mm)	1600	±1.2	T (℃)	±(0.15+0.002T)
△Time (sec)	1	±0.03		

Moreover, one RTD and one pressure gauge are installed between high pressure tank and a ball valve. The known constant values and the uncertainties are summarized in Table II.

Initial conditions of the low-pressure tank is maintained at room condition (about 15℃, 0.101MPa) to maximize the pressure difference and have a long depressurization time for stable measurement of the CO_2 critical flow. The initial temperature and pressure of the high pressure tank were set to 34.5℃ and 8.1MPa which is similar to the compressor inlet conditions of S-CO_2 Brayton cycle. The CO_2 phase of high pressure tank will be changed from supercritical state to liquid state, and then to the gaseous state after the expansion.

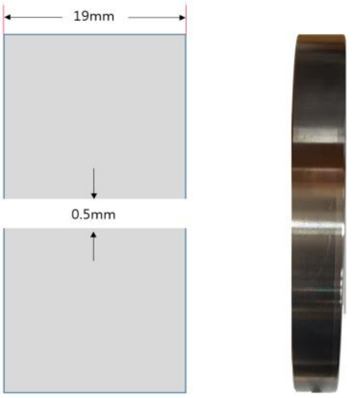

Fig. 3. Internal and external geometry of simple nozzle

The internal and external of experimented nozzle are shown in Fig. 3, and the length and nozzle diameter are 19mm and 0.5mm, respectively.

2.2 Experimental Results

The two-phase critical flow experiment obtained from simple nozzle with two-phase condition were performed to study the flow characteristic and provide validation data for the numerical model as well. The experiment results are shown from Fig. 4 to Fig. 7. These figures show Mach number and results of pressure, temperature, and mass flux from the experiment. It is noted that the temperature in Fig. 4 is obtained from the energy balance equation and each tank was divided into three sections to reflect the all temperature range of each tank.

However, Fig. 7 shows the results of temperature at nozzle exit and at top, middle, and bottom of low-pressure tank. After expansion through the nozzle, the temperature at nozzle exit sharply decreases under -10℃ due to the Joule-Thomson effect. This phenomenon identified that application of labyrinth seal on S-CO_2 compressor has a potential to form an ice inside of labyrinth seal geometry due to the big pressure drop.

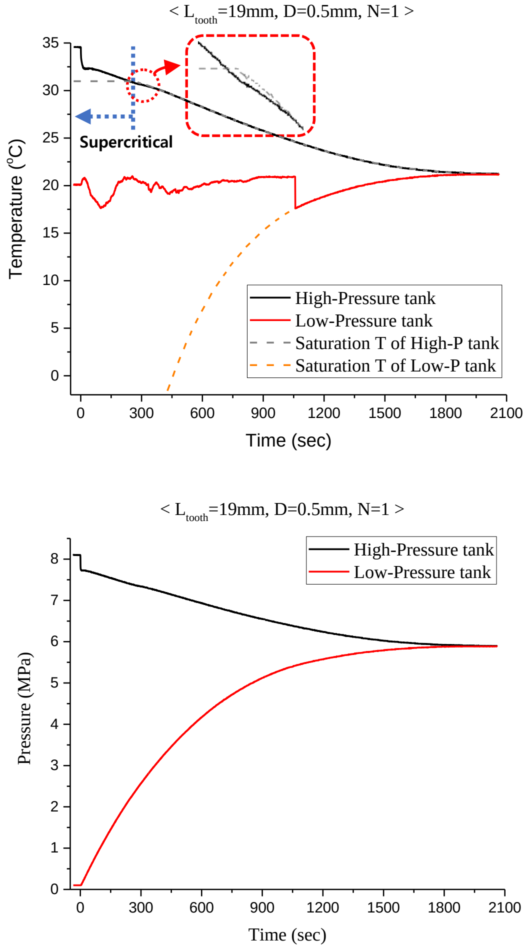

Fig. 4. Temperature and pressure of the experimental results

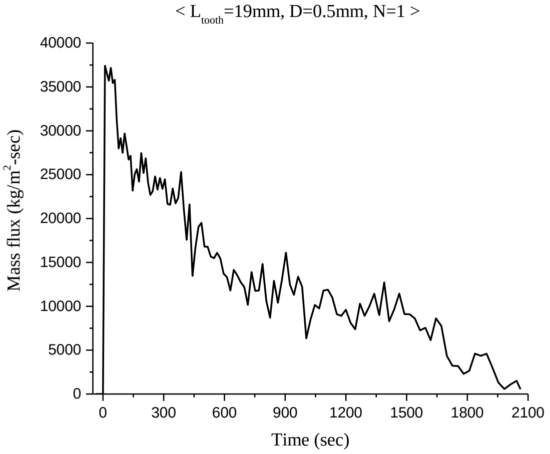

Fig. 5. Mass flux of the experimental results

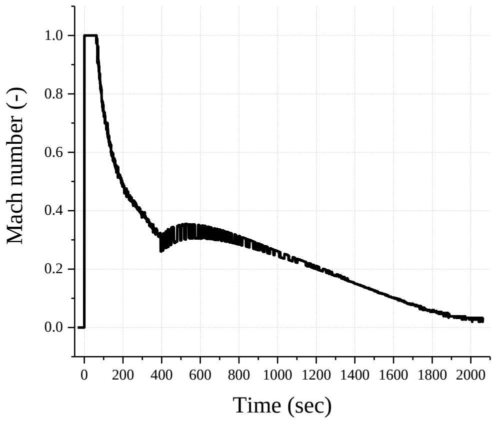

Fig. 6. Mach number of the experimental results

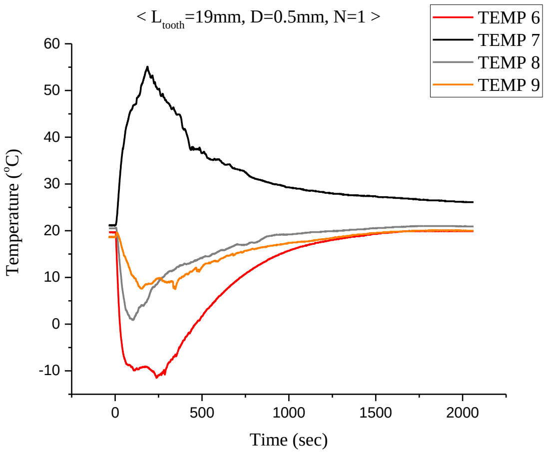

Fig. 7. Temperature results at various location

3. Conclusions

Predicting the leak flow rate is imperative to maintain the high performance of S-CO_2 power cycle. Thus, experiment of two-phase critical flow was conducted to obtain the validation data for transient simulation model while special attention is given to the turbo-machinery seal design. The experiment results identified that the temperature at nozzle exit sharply decreases under -10℃ due to the Joule-Thomson effect after expansion through the nozzle. Therefore, a care is needed when using a labyrinth seal for the S-CO_2 turbomachinery.

To identify the icing phenomenon inside of labyrinth seal geometry, further experiments with labyrinth seal geometry nozzle under various conditions will be conducted. In addition, further study for transient simulation of critical flow with thermal-hydraulic system analysis code will be performed in the near future.

REFERENCES

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