Experimental Facility for Supercritical CO_2 Leakage to High Pressure Water

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

In general, many existing ships and submarines powered by nuclear power are equipped with Pressurized Water Reactor (PWR) and a steam Rankine cycle. Despite of many advantages of the steam Rankine cycle, it has some drawbacks such as large volume of system, steam quality control at turbine, and corrosion of structure material [1]. To overcome these limitations of the steam Rankine cycle, a supercritical CO_2 (S-CO_2) cycle can be a good alternative because the S-CO_2 cycle offers many advantages in a practical application due to high thermal efficiency, high power density, and mild environmental requirement for keeping integrity of turbomachinery blade [2-4]. Due to its compactness and high efficiency, an S-CO_2 cycle is potentially considered as a candidate for marine nuclear propulsion [5].

When using the S-CO_2 cycle as an indirect cycle coupled to the traditional PWR concept instead of steam Rankine cycle, operating pressure of each system is an important parameter that should be determined with regard to operational and safety issues. Thermodynamically, higher pressure in the S-CO_2 cycle leads to higher efficiency. However, in a case of leakage in the intermediate heat exchanger (IHX), the situation where the pressure on the S-CO_2 cycle is higher than the pressure on the primary side's water could be inappropriate considering conventional safety system and operating procedure.

Therefore, it is necessary to understand the phenomenon that can occur due to the IHX failure when adopting high pressure S-CO_2 cycle. Based on this aspect, it is desirable to devise a proper concept of safety system if needed. In this paper, the facility that are designed for simulating the leakage of supercritical CO_2 into high pressure water due to failure of IHX is presented.

2. Description of the facility

In this section, a description about the situation that the facility are trying to simulate is introduced firstly. Then, design specifications of the experimental facility and experimental measurement parameters of interest are also described.

2.1 Description of the phenomenon

The phenomena depends on the amount of water and CO_2. The type of heat exchanger for IHX should be first considered. Among many types of heat exchanger, printed circuit heat exchanger (PCHE) is generally used for S-CO_2 power cycle but in-service inspection is very challenging. Instead of PCHE, micro shell and tube heat exchanger (MSTE) is also a good option for S-CO_2 - power cycle for IHX. For MSTE, the problem related to in-service inspection can be resolved easily even though it has an issue related to scalability [6]. Schematics of leakage situations for both heat exchangers is shown in Fig. 1. As mentioned in the introduction, if the IHX fails, high pressure S-CO_2 on the secondary side (20MPa) leaks to the relatively low pressure (15MPa) water on the primary side. The case of MSTE could be thought approximately as a situation that CO_2 releases into the pool of water. Thus, it is easy to mimic using two tanks shown in Fig. 2.

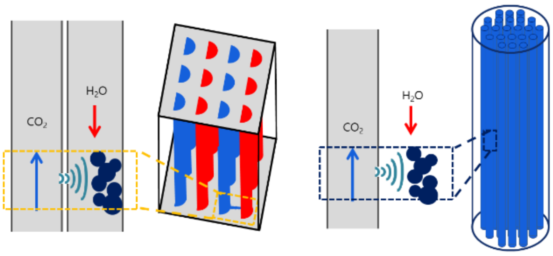

Fig. 1. Schematic of leakage situations for PCHE (left) and MSTE (right).

As shown in Fig. 2, the main process of reaction between water and supercritical CO_2 is as follows. Leaked supercritical CO_2 is dissolved into the water and a little of the aqueous CO_2 reacts with water to form carbonic species. If the water does not dissolve the leaked CO_2 anymore, the system pressure increases.

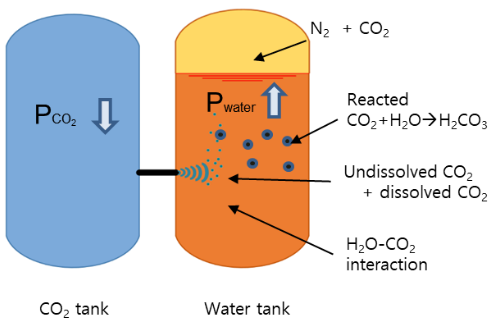

Fig. 2. Schematic of leakage process.

2.2 Design specification of the experimental facility

Initially, the facility was constructed to validate the S-CO_2 critical flow model [7]. The facility was modified to simulate the leakage of CO_2 into water as shown in Fig. 2. Fig. 3 shows the designed experimental facility for the simulation. The detailed design specifications are shown in Table I.

The content of the experiment is that CO_2 flows from high-pressure tank (CO_2, Left tank) to low-pressure tank (Water, Right tank) through a nozzle. The water in the low-pressure tank is pressurized by injecting N_2. Pressure and temperature of each position are measured for every second. For measurements, total nine RTDs (Resistance Temperature Detectors) and six pressure gauges are installed on the critical flow facility as shown in Fig. 3.

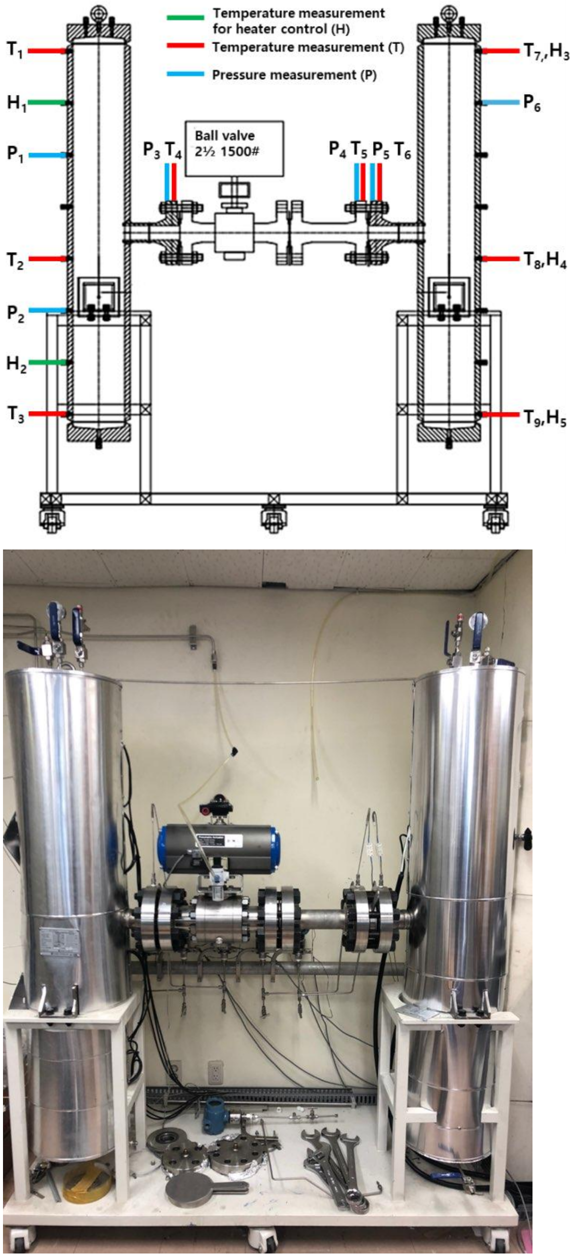

Fig. 3. Schematic (Top) and Photograph (Bottom) of the experimental facility.

Table I: Design specifications of the experimental facility.

	Design parameter	
High/Low pressure tank	Pressure (MPa)	22
	Temperature (℃)	150
	Volume (L)	47 (I.D : 200 mm, H : 1600 mm)
Pipe connecting two pressure tanks	Internal diameter (mm)	57
	Length (mm)	1090
High pressure tank heater (jacket-type)	Electric capacity (kW)	5
Low pressure tank heater (jacket-type)	Electric capacity (kW)	12
Valve type	Ball valve	

2.3 Experimental measurement parameters

In this experiment, a mass flow rate of S-CO_2 and pressure behavior in the water system are objects to be identified.

The mass flow rate of leakage can be calculated using the measured pressure and temperature data of the high pressure tank.

$$\dot{m} = \frac{V_{tank}(\rho_{t+\Delta t} - \rho_t)}{\Delta t} \quad (1)$$

$$\dot{m} : \ mass\ flow\ rate\ of\ S - CO_2$$
$$\rho : \ density\ calculated\ using\ measured\ P\ , T$$
$$\Delta t : \ measurement\ time\ interval$$
$$V_{tank} : high\ pressure\ tank\ volume$$

Pressure behavior in the water system is related to dissolution rate and solubility. These are related but they are different concept. Solubility is an endpoint representing dissolution capacity at equilibrium state and dissolution rate is a kinetic process [8]. Especially, dissolution rate depends on the interaction area between the fluids and the area is also related to various things such as properties, flow rate, flow model, rupture area and so on. Thus, the goal is to find out which of the following assumptions are suitable through the experiment.

1. Dissolution of S-CO_2 is a much slower or faster process than the leakage of S-CO_2 into water.
2. Apparent molar volume change due to the dissolution is negligible or not.

The second assumption could be predicted approximately without the experiment because dissolution rate and solubility of CO_2 in water have been studied by many prior researchers in various fields. The solubility of S-CO_2 into water at P and T similar to the conditions of IHX has been measured and predictive models are also developed for various solutions. Thermodynamically, CO_2 solubility in aqueous solutions is determined from the balance between its chemical potential in the liquid phase $\left(\mu^L_{CO_2}\right)$ and that in the gas phase $\left(\mu^V_{CO_2}\right)$ [9, 10].

$$\mu^V_{CO_2}(T,P,y) = \mu^{V(0)}_{CO_2}(T) + RT \ln f_{CO_2}(T,P,y) \quad (2)$$

$$\mu^L_{CO_2}(T,P,m) = \mu^{L(0)}_{CO_2}(T,P) + RT \ln a_{CO_2}(T,P,m) \quad (3)$$

Where

μ : *chemical potential*
f : *fugacity*
a : *activity*

Among the developed predictive models, the model of Duan and Sun (273-533 K, 0-2000 bar) [10] is widely used and applicable to the facility condition range. The model is based on an assumption that the fugacity coefficient of CO_2 in the vapor phase of CO_2-H_2O mixture is very similar to that in pure CO_2. If the fugacity coefficient becomes very different at the condition of interest, S. Mao et al (273.15-723.15 K, 1-1500 bar) presented the model that could be applied to higher temperature conditions [11]. The calculated solubility of CO_2 at the facility condition using the model of Duan and Sun is presented in Fig. 4.
The mixture volume of dissolved CO_2 and water could be represented using apparent molar volume ($V_{\emptyset,CO_2}$).

$$V_{solution} = V_{H_2O} n_{H_2O} + V_{\emptyset,CO_2} n_{CO_2} \quad (4)$$

Apparent molar volume can be calculated using the model proposed by Hu, Q et al (up to 573.15 K, 120MPa) [12]. The calculated apparent molar volume at the facility test condition is also presented in Fig. 5. Based on the above models, the authors compared the apparent volume of dissolved CO_2 and the volume of 1kg pure water as shown Fig. 6. This result shows that if the solution reaches equilibrium, the solution volume increases about 4% at the evaluated conditions.

2.4 Experimental measurement result of preliminary test

Initial results are presented in Fig. 7 and 8. Fig. 7 is the measured pressure behavior of the tanks and Fig. 8 shows the measured mass flow rate of S-CO_2 leakage without any filter. Table II shows the initial conditions of the test before the opening of the valve.

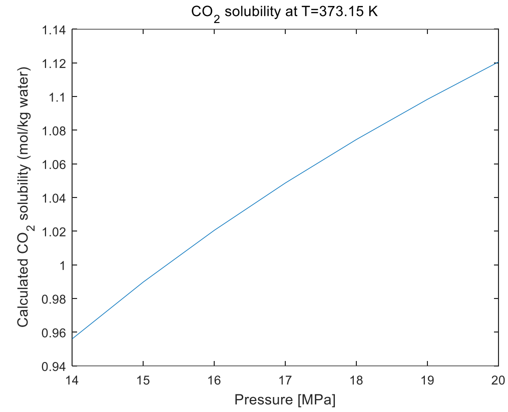

Fig. 4. Solubility of CO_2 in water

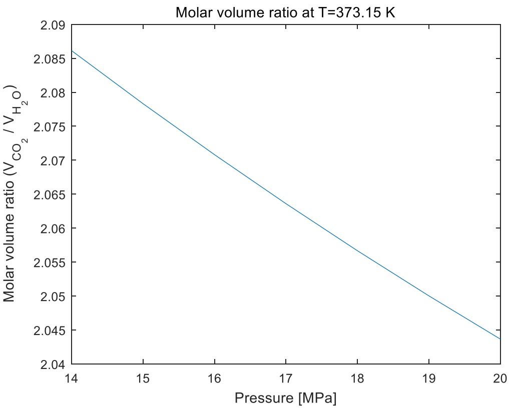

Fig. 5. Molar volume ratio between water and CO_2

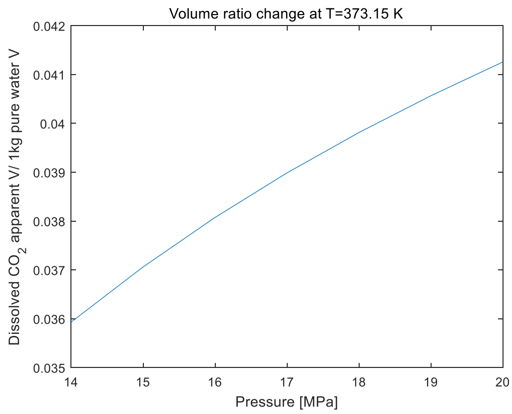

Fig. 6. Volume ratio between pure water and dissolved CO_2

Table II: Initial conditions of the test.

	Parameter	
High pressure tank	Pressure (MPa)	10.60 ±0.003
	Temperature (℃)	80.4 ±0.31
Low pressure tank	Pressure (MPa)	3.18 ±0.001
	Temperature (℃)	65.5 ±0.28
	Mass of N_2 (kg)	0.324 ± 0.01450
	Mass of water (kg)	36.933 ± 0.4889

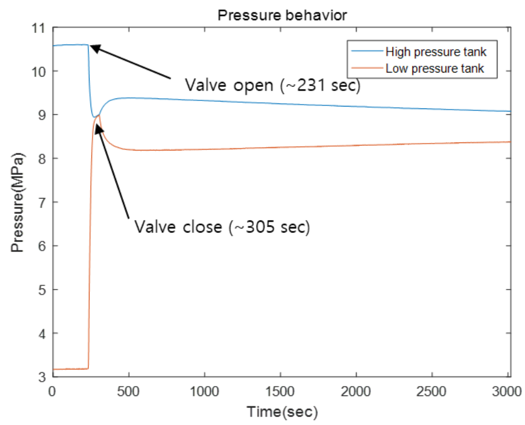

Fig. 7. Pressure behavior in the test

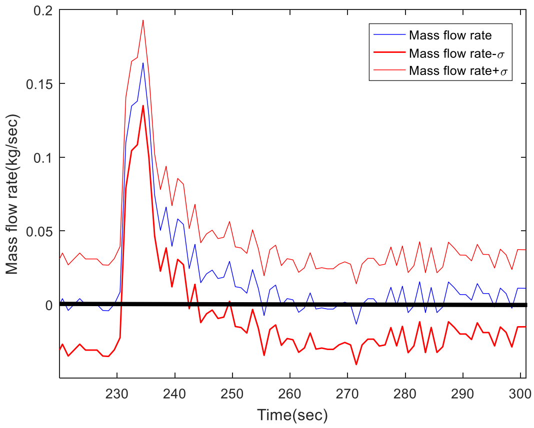

Fig. 8. Mass flow rate of S-CO_2 leakage

3. Conclusions and Further works

An experimental facility that could simulate the leakage of supercritical CO_2 into high pressure water in IHX such as MSTE is being set up and introduced in the paper. The pressure behavior and leakage flow are set as the object of measurement. In particular, apparent molar volume change due to the dissolution is assumed for estimation using the models proposed by prior researchers. It is concluded that this volume change could be negligible if the dissolution process is much slower than the leakage or the total mass of the water system is much larger than the mass of leakage flow.

The experiment will be conducted to identify the phenomena and some additional research results will be presented at the conference.

ACKNOWLEDGEMENT

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