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Investigation of CO_2 leak accident in SFR coupled with S-CO_2 Brayton cycle

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ABSTRACT

Various research organizations have performed feasibility studies for applying the supercritical CO_2 (S-CO_2) Brayton cycle to the Sodium-cooled Fast Reactor (SFR) system and the studies revealed several technical challenges. The preceding studies are reviewed to identify the current status of overcoming the identified challenges and highlight knowledge gaps. One of the most challenging issues is to comprehend the CO_2 leak mechanism initiated from the pressure boundary failure in a Na-CO_2 heat exchanger. Thus, an isentropic critical flow model expanding from supercritical phase to gas phase was evaluated. To validate the selected critical flow model, an experiment of CO_2 critical flow under supercritical condition was performed and the experimental and numerical results correspond to each other reasonably. Another identified technical issue is removing Na-CO_2 reaction product from the system to improve the system economics and plant availability. In this study, candidates that can form eutectic with Na-CO_2 reaction product was newly identified. As a result, it was found that Li_2CO_3-Na_2CO_3 or Li_2CO_3-Na_2CO_3-K_2CO_3 eutectic systems can act as a potential cleaning agent to eliminate Na-CO_2 reaction product within the operating temperature range of SFR. The performance was confirmed with simple experiments.

1. Introduction

Generation IV (GEN IV) nuclear reactors are being developed around the world to achieve higher degree of sustainability, safety, reliability, economics, and non-proliferation compared to the Generation III nuclear reactors. Among GEN IV reactors, the Sodium-cooled Fast Reactor (SFR) has been most widely and actively developed throughout the world. SFRs typically utilized a steam power system in the past, but because higher level of safety and reliability are required for GEN IV reactors compared to the previous generation of nuclear reactors, a motivation to develop an alternative power conversion system for SFRs exists. The alternative power cycle option is to remove the potential sodium-water reaction (SWR) and its associated risk while maintaining or improving the power plant net efficiency. The sodium-water reaction forms corrosive sodium hydroxide (NaOH) and explosive hydrogen gas (H_2) while generating substantial amount of reaction heat in high chemical reaction rate and this can potentially threaten the system safety and economy substantially.

From this motivation, the supercritical CO_2 (S-CO_2) Brayton cycle is being considered as an alternative power conversion system to the steam Rankine cycle of SFR systems (Ahn and Lee, 2014; Cha et al., 2009; Sienicki et al., 2014). The S-CO_2 Brayton cycle can 1) improve thermal efficiency, 2) reduce total plant size with compact turbo-machineries and heat exchangers, 3) relatively simple cycle layout, and 4) eliminate the risk of potential SWR. However, several remaining technical issues should be addressed before applying the S-CO_2 Brayton cycle technology to the SFRs. One issue related to the system safety is the CO_2 reaction with liquid sodium, which has been confirmed in the previous studies (Ishikawa et al., 2005; Latgé et al., 2005). Fortunately, the behavior and the potential risks of Na-CO_2 reaction are not serious as much as SWR (Eoh et al., 2013) and the major reaction product is non-corrosive solid Na_2CO_3 while SWR produces highly reactive hydrogen. The reaction between sodium and CO_2 can occur if the pressure boundary fails at a sodium-to-CO_2 heat exchanger. Since the pressure boundary is an interface enduring a high pressure difference between sodium at 0.1 MPa and CO_2 at 20 MPa, the injection of high-pressure CO_2 into the sodium side has to be carefully investigated in mechanical, thermal, chemical, and structural aspects.

However, from the initiation of crack to the consequences of Na-CO_2 reaction as well as an expected accident scenario in Na-CO_2 heat exchanger have not been fully understood clearly

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Nomenclature

A	area [m^2]
c_p	heat capacity [kJ/(kg-K)]
D	diameter [m]
G	mass flux [kg/(m^2-s)]
H	height [m]
h	enthalpy [kJ/kg]
M	Mach number
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
n	number of moles
P	pressure [MPa]
Q	heat transfer [kJ]
R	gas constant for CO_2 [0.1889 kJ/(kg-K)]
T	temperature [K] or [°C]
t	time [s]
V	velocity [m/s] or volume [m^3]

Greek symbols

γ	specific heat ratio (c_p/c_v)
Δ	property change or difference
ρ	density [kg/m^3]
σ	uncertainty [mm], [s], [kPa], or [°C]

Subscripts

b	sodium side (past the nozzle)
critical	critical value
e	nozzle exit
t	time step

yet. Generally, the thermodynamic and kinetic characteristics of Na-CO_2 reaction were established in detail in the previous studies (Eoh et al., 2011; Ishikawa et al., 2005; Latgé et al., 2005; Miyahara et al., 2011; Simon et al., 2007). However, there are relatively few studies on before and after Na-CO_2 reaction or developing models to practically predict the consequence of an accident scenario. Although various research works have been performed, overall knowledge gap within this field or the uncertainties in the previous studies still exist. Thus, it is necessary to identify the current remaining issues in the CO_2 leak accident.

One of the major remaining issues is reducing uncertainties in predicting CO_2 critical flow under various conditions. The amount of CO_2 leaked during the accident depends on the leak rate, in other words, the speed of CO_2 and pressure and temperature conditions at the release location will determine the following accident consequence. Furthermore, the reaction kinetics and the amount of CO_2 reacting with sodium can vary with the speed of CO_2 as well as its amount. While the CO_2 is leaking from the supercritical CO_2 power conversion system to sodium side at atmospheric pressure, CO_2 experiences phase change. The phase change includes supercritical state to gas state and only a few studies for the CO_2 critical flow under these conditions can be found in the open literature. Furthermore, there are limited amount of studies testing the CO_2 flow when both pressures of upstream and downstream are varying together, which can be important data for the future validation of the safety analysis code targeting a sodium cooled fast reactor coupled to the supercritical CO_2 power cycle. Thus, the existing critical flow model is first described and examined if the existing model can be applied to the supercritical CO_2 critical flow prediction under varying conditions. The challenge of the existing critical flow model for gas is that it was not thoroughly tested for the case when the fluid is changing phase from supercritical state to gaseous state. The selected critical flow model was validated with an experiment, which was conducted to simulate the CO_2 critical flow during the leakage of a Na-CO_2 heat exchanger. Furthermore, an experimental study was performed to search cleaning agents to remove Na-CO_2 reaction byproducts. While the CO_2 is being released to the sodium side, the Na-CO_2 reaction product channel plugging can help reducing the accident consequence. However, after the accident phase is terminated, the reactor system has to return back to the original state for continuous operation and cleaning activity will be necessary to remove any Na-CO_2 reaction products attached to the piping, valve, heat exchanger channels and so forth. This is because the reaction product contaminates the surface as well as degrades the component performances. Therefore, if there is a method to clean up the contaminants, it is much more economical by injecting the cleaning agent and filtering it out after the leak incident takes place, and it can improve economy of the system overall. Finding a cleaning agent that can form eutectic with the Na-CO_2 reaction product is first suggested and a few candidate materials were chosen and tested in this study. The identified materials were tested with simple experiments and the approach of using eutectic to clean the SFR with S-CO_2 power system was conceptually proven.

2. Review of previous studies

The sequence of events when there is a major leak in the Na-CO_2 heat exchanger can be described as follows: (1) the failure of pressure boundary will cause a high-pressure CO_2 to flow into the sodium side (2) Na-CO_2 reaction follows and the product of Na-CO_2 reaction will be dispersed in the system (3) the leak will be detected and the system will shut down for restoration. During the first event the understanding and prediction of critical flow is important since the critical flow will determine how fast CO_2 will be injected to sodium. For the second event, kinetics of reaction, reaction surface area, reaction surface temperature and speed of reaction heat dissipation are important physical phenomena. Furthermore, the solid product generated from Na-CO_2 reaction will flow with the sodium flow and understanding the deposition of the product within the system will be very important. For the last event, the leak detection and cleanup of the reaction product in the system are two important points. In the following sections, the major findings in the previous studies are categorized and reviewed. The review works are summarized in Table 1.

2.1. Critical flow

As an initial event of the pressure boundary failure, CO_2 in a critical flow state will flow into the sodium side due to a large pressure difference within a Na-CO_2 heat exchanger. Under a critical flow state, CO_2 is released at the maximum mass flux and the quantity of CO_2 is also at maximum. Mignot et al. (2009) described the results of an experiment to measure the critical mass flux for numerous stagnation thermodynamic conditions, geometry and outlet tube roughness (Mignot et al., 2009). The 1D homogeneous equilibrium model showed relatively good (less than 10% error) prediction of the test data. However, it is not directly relative to the critical flow in the CO_2 leak accident scenario because the tests