

# Investigation of Sodium-CO<sub>2</sub> Interaction in Advanced SFR Power Conversion System

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## 1. Introduction

The supercritical CO<sub>2</sub> Brayton cycle option for the innovative power conversion of a sodium-cooled fast reactor (SFR) is very attractive as it can achieve a more reliable system design that is completely free from the risks associated with a sodium-water reaction (SWR). In spite of its superiority, there is still a high pressure boundary between liquid sodium and CO<sub>2</sub> gas at a sodium-to-CO<sub>2</sub> heat exchanger. To this end, safety issues regarding a potential pressure boundary failure and the consequent intermixing of CO<sub>2</sub> and liquid sodium should be taken into account.

The potential pressure boundary failure generally involves the following technical design issues: i) A high-pressure blow-down of CO<sub>2</sub> gas into the liquid sodium would cause system pressurization coupled with a significant chemical reaction, and could threaten the structural integrity of the heat exchanger unit. ii) The introduction of solid reaction products into the primary coolant system could result in the plugging of narrow flow channels in the reactor core or PCHE type heat exchangers due to particle formation.

Since these features depend on the amount and rate of the chemical reaction as well as on the type of reaction products, the potential for a boundary failure accident and its consequences should be assessed to confirm its effect on plant safety.

In the present study, fundamental tests for a chemical interaction between liquid sodium and CO<sub>2</sub> gas were carried out, and major consequences were investigated.

## 2. Methods and Results

Experimental work on a surface reaction test was carried out to investigate the kinetics of the interaction. Detailed descriptions of the test procedures and the consequences are provided in the following sections.

### 2.1 Experimental setup and test conditions

The experimental loop consists of a main test section where the chemical reaction takes place and associated components including a sodium storage tank, a gas supply system, vapor traps, instrumentation, and gas sampling systems. A flow diagram of the test loop is shown in **Figure 1**.

The main test section is made up of an STS304 and has a rectangular shape with an outer size of 180 mm in length, 60 mm in width, and 50 mm in height. A sodium tray is installed at the bottom center of the test section, and its size is 30mm x 30mm with a 15-mm

depth. CO<sub>2</sub> gas flows within a rectangular duct channel (40mm × 20mm), which is formed above the free surface of the sodium pool filled in the sodium tray. The configurations of the sodium tray and thermocouple positions are shown in **Figure 2**.

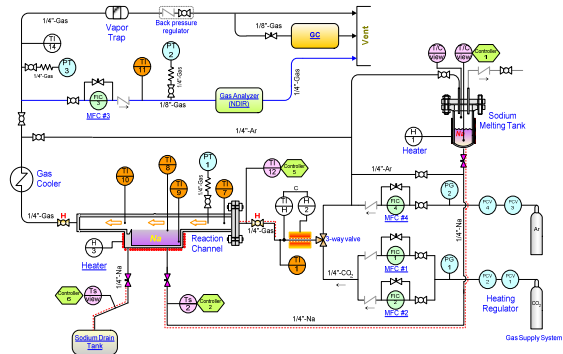


Fig.1 Flow diagram of the experimental loop

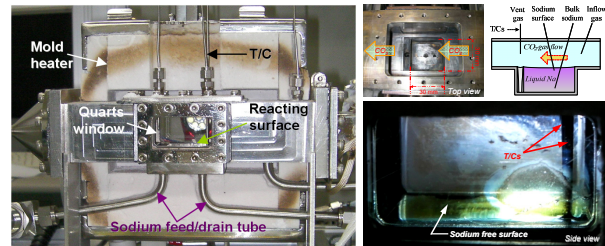


Fig.2 Images of the test section

A larger CO<sub>2</sub> flow rate of 5 SLPM was also made to investigate the mass-diffusion effect on the reaction mechanism, as mentioned previously. The flow rates controlled in the tests were equivalent to an interfacial CO<sub>2</sub> gas velocity of 2-10cm/sec at the sodium free surface, and the corresponding ranges of the Reynolds numbers are 10-24 (1 SLPM) and 50-120 (5 SLPM). The CO<sub>2</sub> supplying time was made to be from 20 minutes (for nominal) to 120 minutes according to the status of the chemical reaction. The set values of the experimental conditions [1] are listed in **Table 1**.

Each test was carried out three times for every pivot of sodium temperature from 200°C to 600°C at intervals of 50°C. Changes in the concentration of the vent gas mixture were measured with respect to the measurement range at the outlet using four non-dispersive infrared (NDIR) analyzers (SAXON, Germany), and each analyzer channel was periodically calibrated with respect to the CO concentration every two weeks using standard CO/CO<sub>2</sub> gas mixtures (10 ppm ~18 vol% with a CO<sub>2</sub> balance).

**Table 1.** Experimental conditions

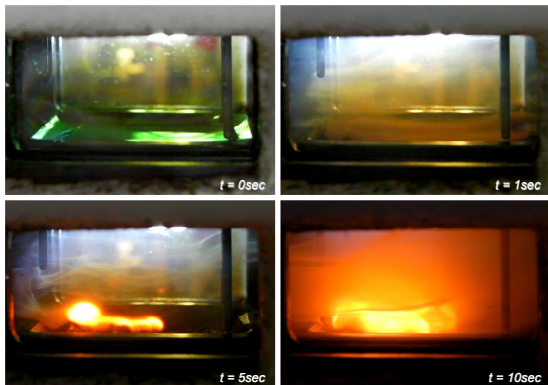
Parameters	Set value	Remarks
Sodium mass	< 20g	$\sim f(T_{Na})$
Reacting surface area	9 cm <sup>2</sup>	3cm × 3cm
Sodium initial temp.	200 ~ 600°C	± 5°C for set values
CO <sub>2</sub> preparative heating	200 ~ 600°C	Isothermal condition
CO <sub>2</sub> feeding flow rate	1~5 SLPM	Design basis leakage
CO <sub>2</sub> supplying time	20~120 min	Status of the reaction
System pressure	~ 1 bar	Practical condition
Sodium purity	99.999 %	Oxygen : < 10 vppm
Gas purity (CO <sub>2</sub> & Ar)	99.999 %	Moisture : < 3 vppm

## 2.2 Results and discussion

Surface reaction tests for sodium-CO<sub>2</sub> interaction were carried out under normal operating temperature conditions of the SFRs, and it was found that the reaction kinetics depends heavily on temperature and is not sensitive to the velocity of CO<sub>2</sub> supplied into the reacting surface.

The reacting surface conditions after the tests show very different features depending on the initial sodium temperatures. At temperatures below 400°C, the reacting surfaces were relatively clean, and the reaction was limited to the free surface of the sodium pool. On the other hand, above a sodium temperature of 450°C, a more vigorous chemical reaction took place, and large amounts of reaction products were formed, covering the entire reacting surface. This mechanism was accelerated as the sodium temperature increased.

When the initial sodium temperature reached around 600°C, sodium ignition was observed with an orange-colored flame. This seemed to be an auto-combustion phenomenon, as shown in **Figure 3**, and proceeded until the liquid sodium in the tray was completely depleted.

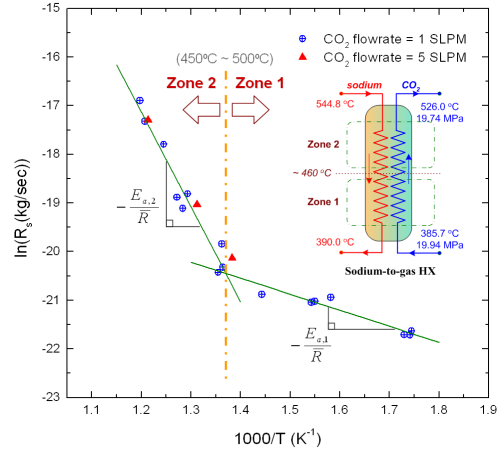


**Fig.3** Sodium-ignition ( $T_{Na} \sim 600^\circ\text{C}$ )

The rate of chemical reaction was determined by measuring the concentration of carbon-monoxide gas in the vent gas (CO/CO<sub>2</sub> mixture), and the two-zone reaction model was then proposed with a threshold temperature of 460°C as shown in **Figure 4** [2]. It was also found that the activation energies for each temperature zone are not sensitive to the CO<sub>2</sub> flow rate. Therefore, the model parameters were obtained by

reflecting the features of the rate-determining process as summarized in **Table 2**.

The threshold temperature has a physical meaning in that it is equivalent to the mean temperature of the liquid sodium flow inside a sodium-CO<sub>2</sub> heat exchanger. Therefore, the interaction has a strong dependence on the leak position, which is one of the major differences from a sodium-water reaction (SWR).



**Fig.4** Two-zone reaction model

**Table 2.** Summary of the model parameters

	Zone 1	Zone 2
Zonal Arrhenius formula [ $\text{kg}/\text{s}$ ]	$R_{s,1} = K_1 \cdot \exp(-\frac{E_{a,1}}{R \cdot T}) \cdot A_s$	$R_{s,2} = K_2 \cdot \exp(-\frac{E_{a,2}}{R \cdot T}) \cdot A_s$
Temperature range	$300^\circ\text{C} < T_{Na} < 460^\circ\text{C}$	$460^\circ\text{C} < T_{Na} < 550^\circ\text{C}$
Activation energy ( $E_{a,i}$ )	27.34 [ $\text{kJ} \cdot \text{mol}^{-1}$ ]	162.07 [ $\text{kJ} \cdot \text{mol}^{-1}$ ]
Pre-exponent factor ( $K_i$ )	$1.32 \times 10^{-4}$ [ $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ]	$5.80 \times 10^5$ [ $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ]

## 3. Conclusions

This study aims to provide basic information on sodium-CO<sub>2</sub> interactions. From the test results, it was found that the reaction kinetics over a sodium temperature range of 300°C to 550°C depends heavily on temperature, but is not sensitive to a mass transfer effect. The two-zone reaction model was proposed with a threshold temperature of 460°C. Finally, it was found that the consequences of a sodium-CO<sub>2</sub> interaction were quite different from those of a sodium-water reaction.

## ACKNOWLEDGEMENT

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## REFERENCES

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