High Temperature Experimental Apparatus to Study Plate-out of HTGR Metallic Fission Product

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1. Introduction

Metallic fission product (FP), such as silver (Ag), cesium (Cs), and strontium (Sr), can be released from defected TRISO which is a fuel of high temperature gas-cooled reactor (HTGR). These metals may subsequently diffuse from the fuel, become plate-out on the internal walls of primary components and become stored either within carbon components of the reactor or in the carbon dust in the primary loop components. FP borne dusts are highly mobile and potentially reach the coolant circuit, leading to the introduction of radioactive impurities into many components of the reactor. It is therefore important to be able to quantify the plate-out FP on primary components in source term estimations for HTGR, particularly in design basis accidents (DBA).

Although FP interactions with primary components have been a subject of study for more than four decades, the prediction of FP interactions with alloy surfaces is empirical and still incomplete. It is usual to test the interaction of a specific FP with a specific material at different temperatures to generate data on interaction kinetics as a function of temperature. Each material, each FP and each of its compound form have different kinetics and so, potentially, very large number of experiments are necessary. It should be understood that the empirical knowledge of FP–alloy interactions makes no distinction between the different adsorption/ absorption/reaction mechanisms. KAERI prepare a lab-scale apparatus to study plate-out characteristics of metallic FP focused on the heat exchanger which is the major plate-out component of HTGR. The apparatus is an out-of-pile test device and is able to simulate HTGR core temperature at helium flow condition or argon flow condition.

2. FP interactions with components wall

2.1. Interactions with Alloy Structures

The interaction process is not the same for each FP: there is the initial heterogeneous interaction occurring on the alloy surface which is generally highly temperature dependent and reversible (Figure 2). This first step is governed by mass-transfer mechanisms and vapor-pressure driven or governed by absorptivity. The adsorption or condensation is followed, depending on the FP, by absorption into the bulk or diffusion and chemical reaction in the bulk. This subsequent interaction may be only partially reversible [1]. It is known, for example, that Cs interaction with alloys is stronger and less reversible the higher at the temperature at which it occurs. In particular, a significant fraction of the Cs diffusing in steel alloys to form a silicate that is very stable and immobile below about 1000 ℃. In addition, silver has a significant solubility in nickel so it might be expected that Ag (110m) would accumulate in the IHX and/or the gas turbine; the expectation that the turbine will constitute a preferential site for Cs and Ag plate-out is well established [2].

The major parameter effect on plate-out is the temperature of both coolant and alloy surface. The vaporized FP can be either condensed down or continued on vaporized state by coolant temperature. We can imagine this fact more well if we see Figure 3 that represents the vapor pressure change to coolant temperature for the Cs, Sr and Ag. Surface temperature also allows either plate-out on their surface or not. The other parameters related on plate-out amount are alloy materials and surface oxidation condition as listed in Table 1. Generally, oxidized surface captures FP more.

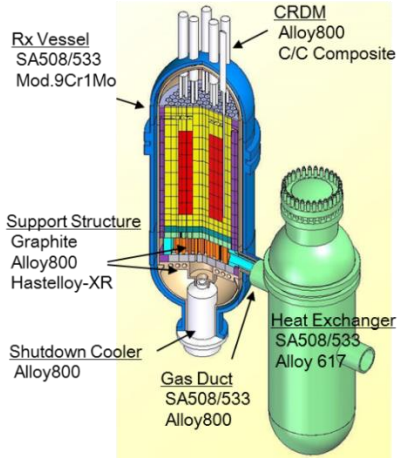


Fig. 1. Materials of VHTR primary components

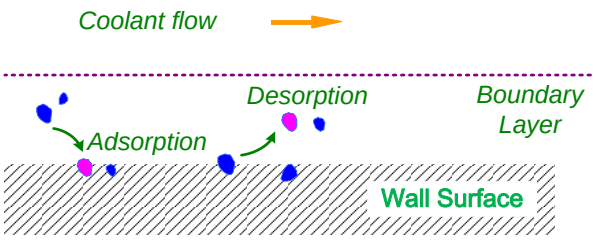


Fig. 2. Concept of FP interactions on the wall

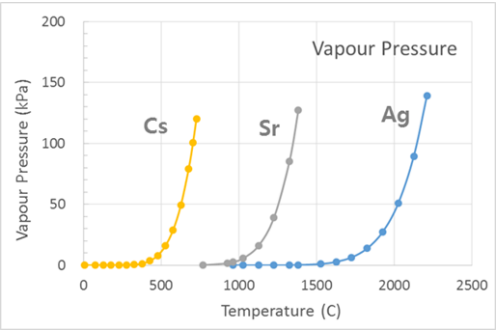


Fig. 3. Vapor pressures of FP metals [3]

Table 1. Test Matrix

FP Metal (3)	Coolant Temp. (℃)	Material (2)	Surface (2)
Strontium Silver Cesium	300, 400 500, 600 700, 800 950	Carbon Base Nickel Base (Alloy 617 Hastelloy-XR)	Non-Oxide Oxide

2.2. Sorption Model

The adsorption (plate-out) is the accumulation of atoms or molecules onto the adsorbent's surface by either chemical or physical attraction (Fig. 2), while the absorption indicates a process that the substance being collected diffuses or penetrates into the other substance. For the adsorption, molecules are adsorbed just on the surface, but the molecules undergoing absorption are taken up by the volume, not by the surface.

This study mainly concerns about the process of adsorption. The experimental forms of sorption isotherms are used in order to evaluate the boundary layer concentration with ideal gas law, and it plays a major role in predicting the FP behavior near the surface of components within a gas-cooled system. In general, the boundary layer concentration can be correlated with the surface concentration. It is usually expressed as a non-linear form, but specific types of correlations based on experimental observations are available for typical species and specific surface materials at a certain condition.

A well-known empirical relation of FP concentration in boundary layer for sorption isotherms proposed by GA is as follows [1];

$$B = \frac{N_A P_{B.L}}{RT} \qquad (1)$$

Where,

$$p_{B.L} = \sum_{l=1}^{3} b_l S_l^{n_l} \quad \text{for cesium,}$$

$$p_{B.L} = \frac{S_l}{a_l \cdot (K - S_l)} \quad \text{for silver and iodine}$$

$$a_l = a_l^0 \cdot \exp\{-Q_l/(RT)\} \quad [\mathrm{Pa}^{-1}],\ l = 1,2,3$$

$$b_l = b_l^0 \cdot \exp\{-Q_l/(RT)\} \quad [\mathrm{Pa}/(\mu\mathrm{g}/\mathrm{cm}^2)],\ l = 1,2,3$$

S = surface concentration,
Q = activation energy.

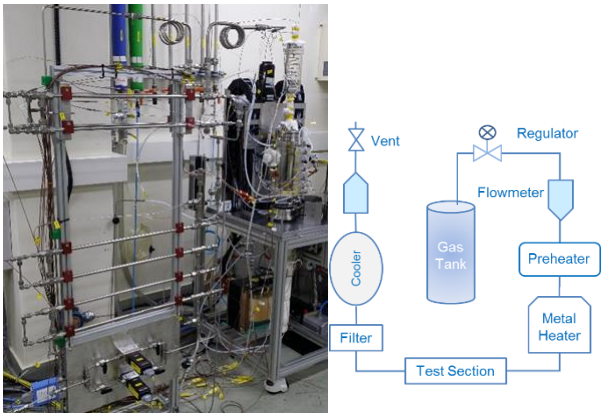
Here, the constants a, b, n and K are the parameters which depend on FP species, oxidized conditions, and pipe materials. The effects of the surface roughness are considered also.

3. Experimental Apparatus

3.1. Description of Experimental Apparatus

The experimental apparatus simulates the VHTR core temperature and reduced helium flow condition. The apparatus is an open loop that composed of a helium tank, a helium heater, a FP heater, a test section, an air cooler and a filter as shown in Figure 4. The operating condition of plate-out test apparatus is as follows;

- Working Fluid — Helium or Argon
- FP Heater — 2000 ℃
- Helium Temperature — ~ 950 ℃
- Helium Flow — ~ 65 liter/min
- Operating Pressure — 1~ 3 bar



(a) Picture (b) Layout

Fig. 4. Plate-out experimental apparatus in KAERI

3.2. Test Section

The test section is simulated single channel of the PCHE (printed circuit heat exchanger) type heat exchanger which is a candidate of VHTR IHX (intermediate heat exchanger) [4]. PCHEs are plate-type compact heat exchangers in which flow channels are etched into flat metal plates as a half circle form using a photochemical process. The etched metal plates are stacked together and diffusion bonded to create a solid block heat transfer element as shown in Figure 5.

A PCHE block has thousands of half circled flow channels. But we just consider single flow channel to study plate-out experiment for the convenience in preparing test section. The half-circle area of the PCHE flow channel is adjusted to equivalent area of circular tube (1/8 inch or 1/4 inch commercial tube). The circular tube test section is coiled as shown in Figure 6 and every turn of coil is clipped a TC by wire. The test section is connected a DC power supply to control the surface temperature of coil to IHX operating condition.

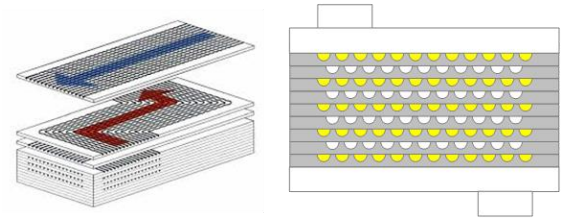


Fig. 5. Channel layout of printed circuit heat exchanger

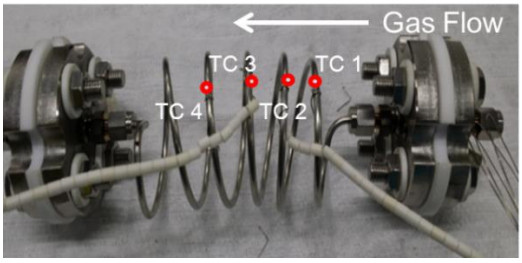


Fig. 6 Test section (coil type)

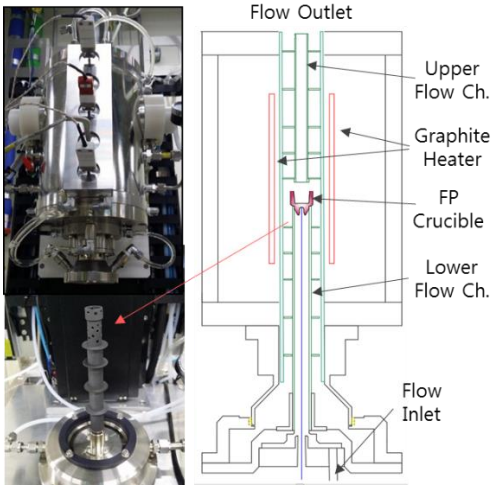


Fig. 7. Details of FP heater assembly

3.3. FP Heater Assembly and Flow Channel

Figure 7 shows the details of FP heater assembly and its major parts. IG-11 graphite which could be withstand over 2000℃ in an oxygen free environment are used to compose of heater element, flow channels, channel liner and spacers, and FP crucible. The FP filled in crucible can be heated over 1500℃ by radiation emitted from the IG-11 liner. The liner is also heated by radiation emitted from heater element. The location of crucible can be adjustable up and down along to the test condition of FP metals by simply controlling the distance of lower channel length.

Gas flow comes into from the bottom side of FP heater device and is heated at the lower channel inside and goes out through the many flow holes penetrated at the end of lower channel. The FP metal vapor are entrained by flow come into the crucible (crucible also has many flow holes). The gas flow containing FP vapor get heated more when passing through the heating zone located in upper channel inside.

The body temperature of the FP heater assembly can be controlled by a water supply system and the inside of assembly was filled with insulator to protect the body from very high-temperature. The body of the heater is designed to open and close automatically by a stepping motor.

3.4. Measurement and Control

The physical parameters which will be measured at the loop are the pressure, temperature, flow rate and the amount of plate-out metal on the tube surface. Surroundings of both FP crucible and graphite heater are prepared four C-type thermocouples, one for measuring crucible bottom temperature and the others for monitoring graphite heater temperatures. All the other locations are installed K-type thermocouples. Gas flow rate is measured and controlled by mass flow controller connected between experimental apparatus and pressure regulator as shown in Figure 4-(b). The pressure regulator keeps the outlet pressure of gas supply tank less than 5 bar. The mass flow rate is measured again at the outlet of the experimental apparatus to confirm the flow rate. Gas entering into the coil test section is heated by both a pre-heater and a graphite heater. Power of both heaters are controlled manually by using the potentiometers.

4. Results and Discussion

The experimental apparatus is assembled and currently under commissioning test. Figure 8 shows one of pretest results for the exiting argon gas temperature from heater assembly. The outlet gas temperature is increased gradually with power of graphite heater. A ramp rise of gas temperature is observed when flow rate increased abruptly as shown in the Figure 8. A difficulty of plate-out experiment is the contamination of apparatus and test section by sample FP metal after test. If we do a pretest with FP metal, the apparatus and test section are deposited (plate-out) by sample of FP metal. The FP metal deposited on both apparatus and test section should be removed perfectly before next test. Various pretests without FP metals are done for effectively filing up the pretest data that would be used to obtain reliable plate-out experiments.

Crucible temperature is a major concern in the FP plate-out experiment because it determines the amount of FP release. Liquid FP is released with increasing temperature and the releasing amount of FP greatly depend on vapor pressure. Figure 3 shows saturated vapor pressure curves of cesium, strontium and silver in closed space with no flow. If FP Metal is strontium, it will be kept in liquid state in the experiment. The temperature window of liquid state is from melting point to boiling point, for example temperature window of strontium is from 769℃ (MP) to 1384℃ (BP). Figure 9-(a) shows the crucible temperature solely increases beyond the boiling point of strontium (>1450 ℃) while outlet gas temperature only approaches 505℃ which is

far below the desired temperature, 750℃ (reactor condition). After moving crucible to less hot location in the heater assembly, we can more increase the heater power and obtain higher outlet gas temperature of 706℃ than previous experiment for the case of crucible location 1 as shown in Figure 9. The crucible temperature was 1408℃ at the location 2 when the outlet gas temperature reaches to 706℃. The optimal crucible location is depend on the gas outlet temperatures listed in test matrix (Table 1). The reason why the temperature at the graphite heater is lower than the temperature at the crucible in Figure 9-(a) is that the thermocouple for graphite heater is not contacted on the surface of graphite heater while the thermocouple for crucible is contacted on the bottom of crucible.

Figure 10 shows the results of surface temperature control of test section by using DC power. Coil-type test section has four k-type thermocouples clipped coil surfaces. Before turn on the DC power the coil surface temperature increases as the test section inlet temperature increases. Thus, as shown in Figure 10, the coil-1 shows the highest temperature since it is the nearest one to the inlet of test section. After turn on the DC power, all the coils get heated and their surface temperature increases. However, the surface temperature is redistributed to similar values each other by joule-heating. This temperature redistribution of the coil surfaces is affected by many different variables such as heat loss by in and out flanges, heat loss by radiation & convection, insulation, installation method (vertical or horizontal) and gas inlet temperature etc. That means it is not difficult to control the coil surface temperatures either uniformly or non-uniformly with minor adjustment of related variables.

5. Conclusion

KAERI has prepare a lab-scale apparatus to study plate-out characteristics of metallic FP on the HTGR heat exchanger. The apparatus is an out-of-pile test device and is able to simulate HTGR core temperature at gas flow condition. Various pretests without FP metals are almost done and filing up the pretest data that would be used to obtain reliable plate-out experimental data at the end of this year.

ACKNOWLEDGEMENTS

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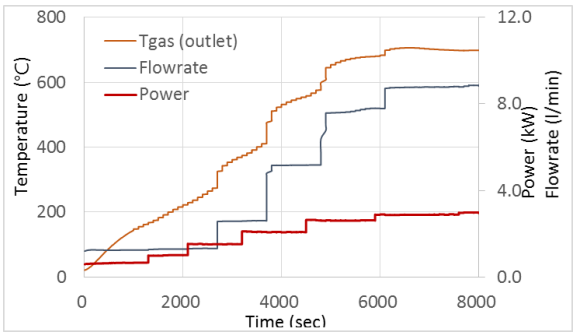
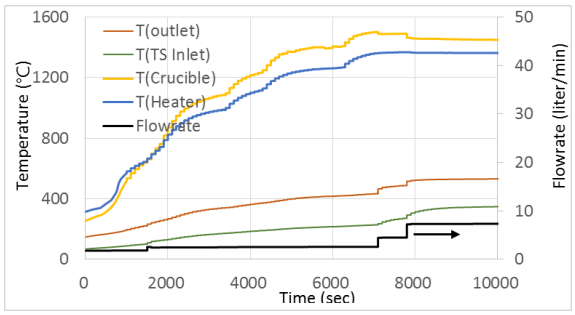
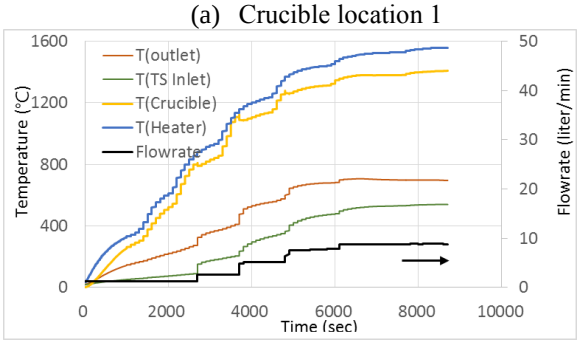


Fig. 8: Parametric trend on gas temperature (flow rate & power)



(a) Crucible location 1



(b) Crucible location 2

Fig. 9: Metal heater internal temperature vs. crucible location.

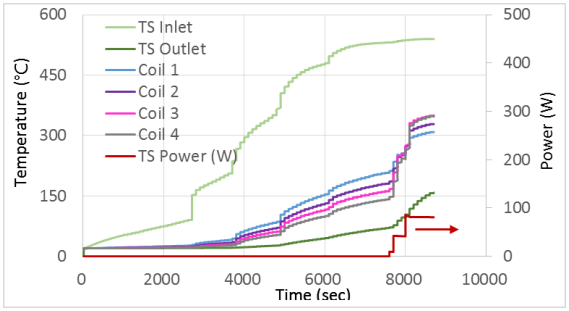


Fig. 10: Results of surface temperature control using DC power at the coil-type test section.