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Experimental Study on the Molten Corium Interaction with Structure by Induction Heating Technique

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1. Introduction

When a core meltdown severe accident occurs in a nuclear power plant, the internal and external structures of the reactor vessel can be damaged seriously by the thermochemical interactions with the corium melt. Corium-structural material interaction phenomena such as molten corium-concrete interaction (MCCI) and the ablation characteristics of the reactor vessel with penetrations at the reactor lower head have been widely investigated by a number of researchers [1-3]. The corium compositions strongly depend on the accident scenarios [4], and thus the melt generation technique for various melt compositions is essential to investigate the corium-structural material interaction characteristics according to the accident scenarios.

Since 1997, KAERI has several years of experiences with melt generation to investigate the material ablation characteristics [5-10] and steam explosion phenomena [11]. Based on the experiences of the TROI (Test for Real cOrium Interaction with water) facility for the steam explosion experiments, the VESTA (Verification of Ex-vessel corium STAbilization) test facility was designed and constructed in 2010 for the development of a core catcher under the APR+ project [5]. At the same time, the VESTA-S (VESTA-Small) was established for small scale material ablation experiments [8]. Some experimental results were reported for the interactions of metallic or oxidic melt with the structural materials such as special concrete or penetration weld [5-10]. The objective of this paper is to provide the specific features of the VESTA and VESTA-S facilities including information on the melt generation technique adopted for the facilities. Some issues are also addressed in this paper for further facility improvement.

2. Induction Heating Technique in a Cold Crucible

2.1 Principle of Induction Heating

Induction heating is a non-contact heating technology of an electrically conducting object (usually a metal) by electromagnetic induction [12]. It is a mature technology extensively used in the semiconductor industry and has many applications such as surface hardening, melting, brazing, soldering and heating to fit.

A source of high frequency electricity is used to drive a large alternating current through a coil, which is called a work coil or an induction coil. A conventional induction heating system that consists of a cylindrical workpiece surrounded by a multi-turn induction coil is shown in Fig. 1. An alternating current through the coil generates in its surroundings a time-variable magnetic field that has the same frequency as the coil current. This magnetic field strength depends on the current flowing in the coil, the coil geometry, and the distance from the coil. The alternating magnetic field induces so called eddy currents in the conductive workpiece located inside the coil. These induced currents have the same frequency as the coil current; however, their direction is opposite to the coil current. In addition, they produce their own magnetic field, which has opposite directions as the main magnetic field of the coil. Therefore, the total magnetic field of the induction coil is a result of the source magnetic field and induced magnetic field. Alternating eddy currents produce heat by the Joule effect (I^2R).

The eddy currents tend to be distributed such that the current density is largest near the surface of the workpiece, and decreases with greater depths in the workpiece. This is called a skin effect and it increases the effective resistance of the workpiece to the passage of the large current and consequently greatly enhances the heating effect caused by the eddy currents in the workpiece. The skin effect becomes larger with a higher frequency and thus a high frequency is usually used in the induction heating applications.

For magnetic ferrous metals like iron and some types of steel, there is an additional heating mechanism that takes place at the same time as the eddy currents. The intense alternating magnetic field inside the coil repeatedly magnetises and de-magnetises the iron crystals. This rapid flipping of the magnetic domains causes considerable friction and heating inside the material. Heating from this mechanism is known to incur hysteresis loss, which leads to a more efficient heating of the ferrous metals.

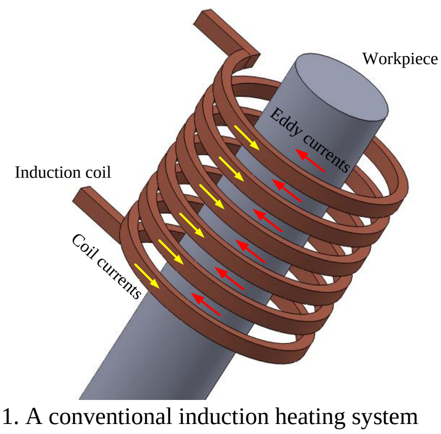

Fig. 1. A conventional induction heating system

2.2 Melt Generation in a Cold Crucible

In order to generate melt stably by using an induction heating technique, we need a crucible for melt retention and it should be thermally and electrochemically stable during the long melt generation process. For this reason, a crucible is generally made of oxidic refractory materials such as sintered zirconia and alumina. However, we adopted a cold crucible to generate pure melt by preventing the impurity generation due to direct contact of the melt with the crucible itself. The cold crucible is made by a palisade-like copper tube assembly and surrounded by an induction coil. Water is allowed to flow into each tube to cool down the interface between the melt and the tube assembly. Therefore, the crust layer of the melt itself is produced at the inner wall of the crucible and we can avoid the impurities.

For metallic melt generation, a protecting material such as sintered magnesium oxide (MgO) is usually attached at the inner wall of the crucible to protect the crucible, not only thermally but also electro-magnetically. On the other hand, for oxidc or suboxidc melt generation, it is not necessary because the oxidic crust layer produced at the inner wall of the crucible during the melt generation serves as the protecting material.

3. Experimental Facility

3.1 VESTA Facility

VESTA is a facility for massive oxidc melt generation and material ablation experiments by jet impingement. As shown in Fig. 2, the facility is composed of a furnace vessel, a melting system including an intermediate melt catcher and a high frequency power generator (450 kW, 100 kHz) for induction heating, a melt delivery system, a coolant supply system, and an auxiliary system.

The cold crucible for melt generation has dimensions of 360 mm in diameter and 550 mm in height, and thus it is expected that up to 400 kg of corium melt can be generated. A material specimen to be ablated has the dimensions of 216 mm in diameter and 50 mm in thickness, and is positioned at the center of the test section and supported by a MgO plate with a MgO-lined stainless steel structure. Once the melt jet impinges onto the specimen, the melt spreads out and then flows down into the annular space between the supporting structure and the MgO wall. Several thermocouples can be embedded in the specimen to analyze the ablation kinetics by monitoring the temperature distributions during the melt-specimen interaction.

Figure 3 shows the filling process of ZrO_2 power for the melt generation. Firstly, a hole at the bottom center of the crucible is covered with a mica plate (Fig. 3(a)) and then a Zr ring is located inside the ZrO_2 layer for initial induction heating. That is, the Zr ring is heated first

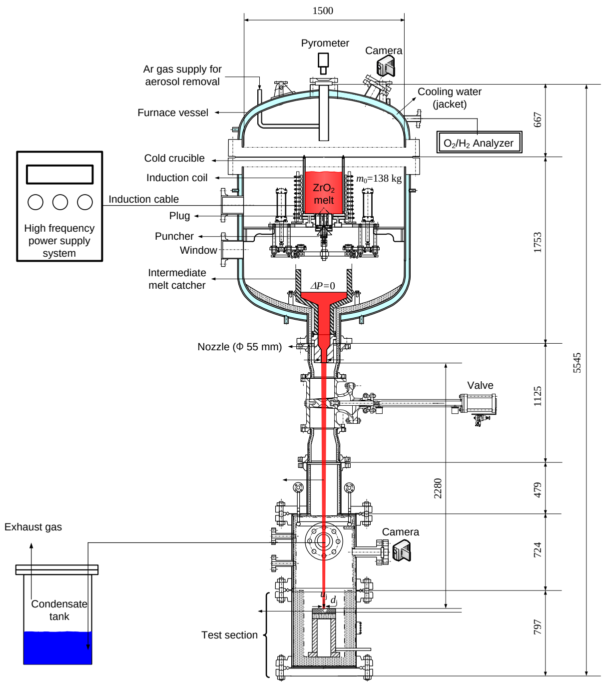

Fig. 2. A schematic of VESTA facility

and the ZrO_2 layer near the ring starts to melt. The melt spreads out gradually by the exothermic Zr oxidation. In order to remove gas during the melt generation and measure the melt temperature by an optical pyrometer, several holes are made using the tubes and making the layer compact (Figs. 3(c) ~ (f)).

When the ZrO_2 melt is formed stably inside the crucible and the melt reaches a desired temperature higher than 3000 K, a plug at the bottom center of the crucible is removed and a puncher is then remotely actuated to perforate the sintered bottom ZrO_2-layer for the melt delivery. A cone-shaped intermediate melt catcher is mounted beneath the crucible in order to collect the melt temporarily and deliver the melt to the nozzle. After passing through the nozzle, a compact jet is formed to impinge onto the specimen in the test section.

Figure 4 shows the cold crucible covered with ZrO_2 crust layer at the inner wall and a concrete specimen inside the test section after the interactions with the ZrO_2

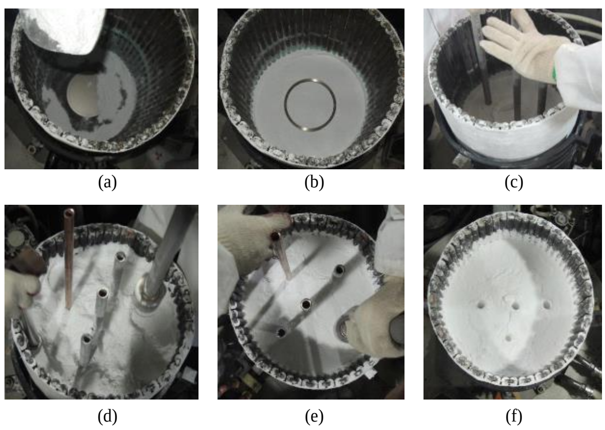

Fig. 3. ZrO_2 power filling process in a cold crucible

(a) (b)

Fig. 4. Images after the experiment; (a) cold crucible, (b) concrete specimen in the test section

melt. The cold crucible was filled with 138 kg of ZrO_2 and 70 kg of melt was delivered successfully as a coherent jet into the test section.

3.2 VESTA-S Facility

VESTA-S is a small scale facility for the metallic or suboxidic melt generation and long-term material ablation experiments without the jet impingement effect. A high frequency power generator of 225 kW and 76 Hz is equipped with this facility; however, if needed, a larger generator for the VESTA facility can be flexibly used.

A schematic of the VESTA facility is displayed in Fig. 5. There are two cold crucibles installed in the test chamber; melt and interaction crucibles. They have basically the same features as shown in Fig. 6. The melt crucible has 70 mm in inner diameter and 130 mm in height; therefore, nearly 3 kg of melt can be generated. If the melt is generated in the melt crucible and the melt temperature reaches the temperature higher than 2000 K, it is delivered slowly down into the interaction crucible by a remote-controlled rotating system. The melt-delivery system was designed to prevent both the melt impingement effect and chemical changes of the concrete specimen owing to preheating during the long melt generation process. Basically, all kinds of melts can

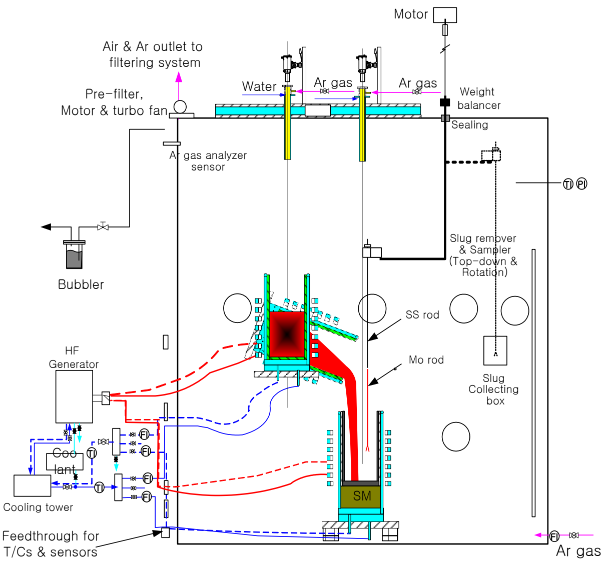

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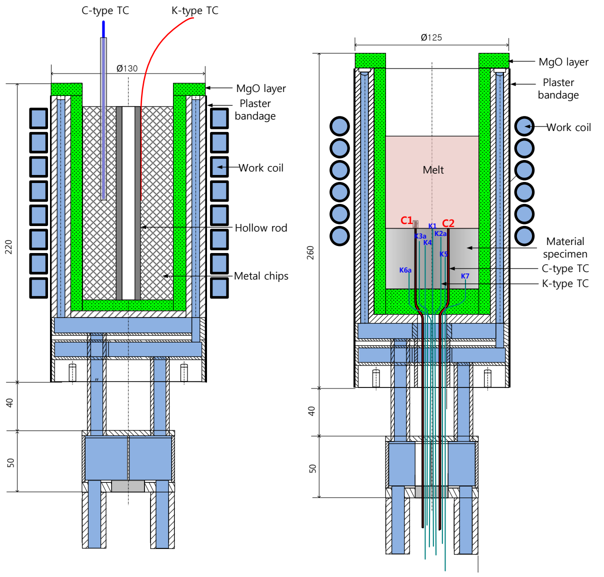
Fig. 5. A schematic of VESTA-S facility



(a) (b)

Fig. 6. Configurations of the cold crucibles; (a) melt crucible, (b) interaction crucible

be generated in the VESTA-S facility; however, the facility is mainly focused on metallic or suboxidic melt generation because the melt delivery method is not suitable for the oxidic melt due to rapid solidification of melt and difficulties in sustained heating after the melt delivery.

During the whole experimental process, argon gas is purged into the test chamber through a guide tube installed between the top of the melt crucible and the optical pyrometer to create an inert atmosphere inside the chamber and secure the optical path by removing aerosols produced from the melt. A hollow rod is also installed at the center of the melt crucible to make rays emitted from the melt into blackbody radiation. A material specimen has dimensions of 75 mm in diameter and 50 mm in thickness, and is located at the bottom of the interaction. Once the melt is delivered, the specimen initiates immediately and the delivered melt into the interaction crucible is instantaneously heated up for sustained heating by switching the power supply from the melt crucible to the interaction crucible.

Some images after the experiments of metal ingot with a material specimen are given in Fig. 7. As shown in the figures, the shapes are totally different from the melt composition, temperature and thermophysical properties of the structural materials. Therefore we can investigate the ablation kinetics of structural material due to the long-term interaction with the melt.

3.3 Issues for Facility Improvement

As mentioned in the preceding sections, an induction heating technique in a cold crucible adopted for the VESTA and VESTA-S facilities has many advantages such as various and pure melt generation and decay heat simulation during the severe accident. However, it is very difficult to analyze the heat transfer between each component, and thus the melt temperature control for

Fig. 7. Metal ingot and material specimens; (a) metallic corium melt-concrete, (b) stainless steel melt-concrete, (c) stainless steel melt-Inconel 690

various melt compositions is strongly dependent upon the experiences and requires a great deal of trial and errors. Moreover, there are some limitations to simulate the decay heat affecting the material ablation because the sustained trace heating of melt during the material ablation is impossible in the current systems. The movable induction coil can be a one of the solutions for the trace heating in the VESTA-S facility. Therefore, it is necessary to improve the facilities and establish an analytic tool for better melt temperature control.

4. Conclusions

In the present paper, the principles of induction heating adopted for the VESTA and VESTA-S facilities were summarized briefly and the system features for the melt-structural material interaction experiments were explained. As a major characteristic of the VESTA facility, up to 400 kg of corium melt is expected to be generated using the currently installed system. The jet impingement effect on the material ablation characteristics was demonstrated successfully in the VESTA facility. In the VESTA-S facility, the small scale material ablation experiments by long term melt interaction were performed properly by adopting the melt delivery method. However, for a more realistic severe accident simulation, we need to improve the melt temperature control system by analyzing the heat transfer mechanisms during the melt generation process.

ACKNOWLEDGMENTS

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