<Technical Note>

EXPERIMENTAL STUDY ON MEASUREMENT OF EMISSIVITY FOR ANALYSIS OF SNU-RCCS

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SNU-RCCS is a water pool type RCCS (Reactor Cavity Cooling System) developed for VHTR (Very High Temperature Reactor) application by SNU (Seoul National University). Since radiation heat transfer is the major process of passive heat removal in a RCCS, it is important to determine the precise emissivity of the reactor vessel. Review studies have used a constant emissivity in the passive heat removal analysis, even though the emissivity depends on many factors such as temperature, surface roughness, oxidation level, wavelength, direction, atmosphere conditions, etc. Therefore, information on the emissivity of a given material in a real RCCS is essential in order to properly analyze the radiation heat transfer in a VHTR.

The objectives of this study are to develop a method for compensation of the factors affecting the emissivity measurement using an infrared thermometer and to estimate the true emissivity from the measured emissivity via the developed method, especially in the SNU-RCCS environment. From this viewpoint, we investigated factors such as the attenuation effect of the window, filling gas, and the effect of background radiation on the emissivity measurements. The emissivity of the vessel surface of the SNU-RCCS facility was then measured using a sight tube. The background radiation was subsequently removed from the measured emissivity by solving a simultaneous equation. Finally, the calculated emissivity was compared with the measured emissivity in a separate emissivity measurement device, yielding good agreement with the emissivity increase with vessel temperature in a range of 0.82 to 0.88.

KEYWORDS : Emissivity, Background Radiation, RCCS, VHTR, Infrared Thermometer

1. INTRODUCTION

The VHTR, an NGNP (Next Generation Nuclear Plants) candidate design, has been investigated widely for its feasibility as a future energy supply. A great deal of attention has focused on its inherent safety and the capability of its high temperature heat supply. The VHTR is designed to achieve passive heat removal under both normal and accident conditions by RCCS (IAEA-TECDOC-757, 1994).

The RCCS has a function according to the operation conditions. Under normal operation conditions, the RCCS removes heat loss from the reactor vessel through a cavity via natural convection and radiation heat transfer. The quantity of heat loss is known to range from 0.5 to 2.0 % for various reactor types. Under accident conditions, the RCCS should remove the decay heat even when all other active decay heat removal systems fail.

Heat loss and decay heat can be transferred from the reactor vessel to the atmosphere through several heat transfer processes such as conduction, radiation, and convection. Among these processes, radiation heat transfer has been reported to be the most important process, particularly under accident conditions, because radiation heat transfer rate becomes the main heat transfer mechanism as the vessel temperature increases. Under accident conditions, radiation heat transfer is known to be more than 70% of the total heat transferred from the reactor vessel surface to the RCCS through the cavity (N. Kuzavkov, 2000).

Because the rate of radiation heat transfer is determined by the emissivity, the temperature of the materials, and the geometry of apparatus, it is very important to know the exact emissivity of each material as well as the temperature in order to calculate the amount of heat removal by the RCCS. Previous studies have been carried out using a constant emissivity, for example 0.80 (N. Kuzavkov, 2000). However, the emissivity depends on many factors such as temperature, surface roughness, oxidation level, wavelength, direction, atmosphere conditions, and so on. Therefore, the information on the emissivity for a given material under the real conditions of the RCCS is essential for analyzing the heat transfer in the VHTR (D. Especel, 1996).

Several methods have been developed to measure the emissivity using various detectors such as an IR spetrometer, a radiometer, and an infrared thermometer (L. Chen, 1990; R. B. Johnson, 1988; D. Especel, 1996; M. Siroux, 1998). This study focused on measuring the emissivity using a single band infrared thermometer. The single band infrared thermometer is commonly employed to measure the temperature of an object. This is accomplished by using the information of the radiation emitted from the target material, whose emissivity is known. Inversely, the emissivity can also be estimated with the actual temperature of the target material; this characteristic was applied in this study.

SNU-RCCS, an experimental test facility, was constructed at Seoul National University (INEEL/ EXT-04-02459, 2004) in order to investigate the heat transfer phenomena in the RCCS of a VHTR. The aim of this experiment was to develop a water pool type RCCS and to evaluate its performance. One of the important measuring parameters was the emissivity. Other parameters were pressure, temperature, and air velocity.

As a first step, experiments in separate emissivity measurement devices were performed in order to verify the methodology for measuring the emissivity, using an infrared thermometer as well as by determining the uncertainty factors. The transmittance of a Zinc Selenide (ZnSe) window was measured to compensate for the attenuation effect of the window. The effect of the filling gas on the emissivity measurements was also evaluated, because the type of gas filling the cavity as well as its concentration can vary according to the accident conditions or the type of coolant. The type of gas was varied from air, helium, steam, and a combination of these gases.

As a second step, the experiments in separate emissivity measurement devices, the emissivity of a reactor vessel made from ASTM A36 steel was measured through the sight tube in the SNU-RCCS facility. In general, in order to measure emissivity accurately, the measurement should be conducted in an environment where conditions such as environmental temperature, target surface condition, configuration of the surrounding material and its emissivity, etc are controlled. However, such conditions in the SNU-RCCS facility could not be controlled for the emissivity measurement, because the facility is not exclusively designed or utilized for emissivity measurement. Therefore, it was necessary to consider the effects of window, filling gas, sight tube, and background radiation. The effects of the window and filling gas were accordingly compensated. A radiation heat transfer analysis was carried out to remove the effect of background radiation with view factors and background temperatures. The calculated emissivity is then used as input data for the thermal hydraulic analysis of the SNU-RCCS instead of the constant emissivity.

2. EXPERIMENT AND RESULTS

2.1 Separate Emissivity Measurement

Fig. 1 shows the experimental device used in this study. The device consists mainly of a stainless steel chamber

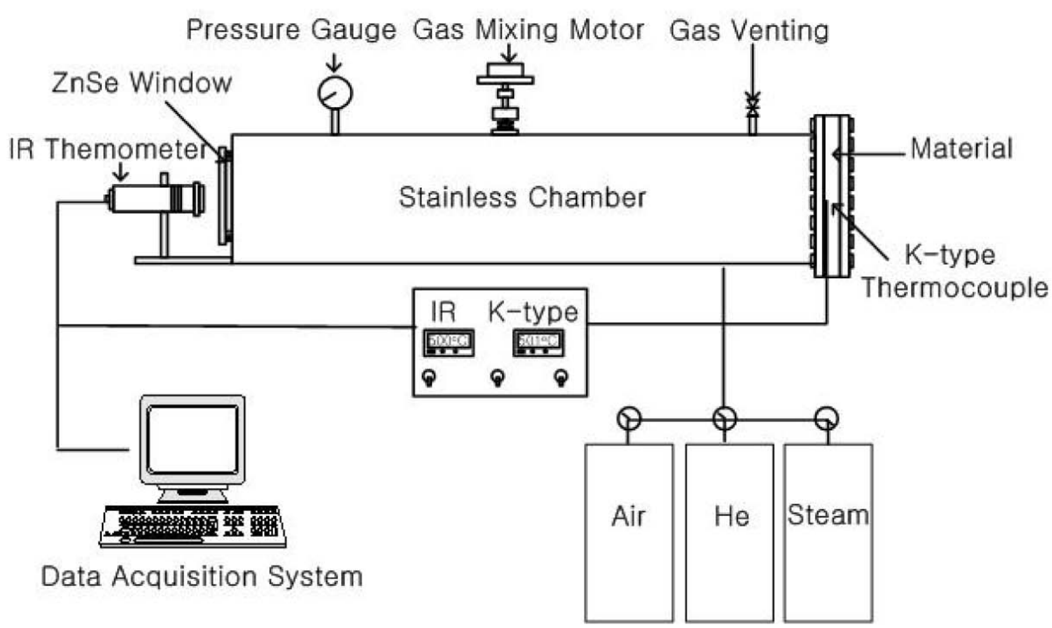

Fig. 1. Schematic Diagram of the Separate Effect Test Facility

equipped with an infrared thermometer, a target material, and a thermocouple. The infrared thermometer is a single band type and has a measuring temperature range of -32~900 °C, a wavelength range of 8~14 μm, an accuracy of 1 %, and a spot size of 16 mm at a distance of 800 mm. The thermocouple was installed at the center of the target material in order to compare to obtain results for comparison with the temperature measured by the infrared thermometer. The target material was made from carbon steel and was oxidized sufficiently before the experiments. Although the target material in the separate emissivity measurement device was different from the reactor vessel material of the SNU-RCCS, the attenuation effect of the window and filling gas could be investigated independently of the type of target material.

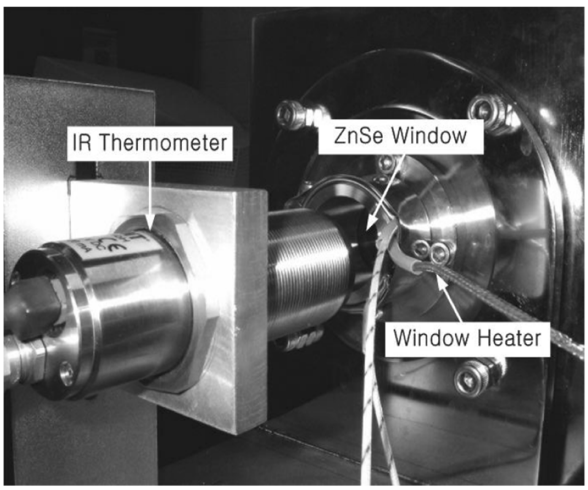

Fig. 2. ZnSe Window and Window Heater

For a closed system, a 5 mm thick Zinc Selenide (ZnSe) window was placed at the left sidewall of the chamber, as shown in Fig. 2. Steam condensation on the inner window surface can yield erroneous results as a result of absorption and reflection. Therefore, a window heater was installed in order to prevent steam condensation on the window surface. The gas concentration was controlled by a vacuum pump and the maximum degree of the vacuum was 20 %. Steam and helium, supplied from a steam generator and a helium tank, respectively, were mixed using a gas mixer.

For the emissivity measurements, the temperature was measured within a temperature range of 100 to 500 °C with both the infrared thermometer and the thermocouple. The temperature range of the reactor vessel under both normal and accident conditions.

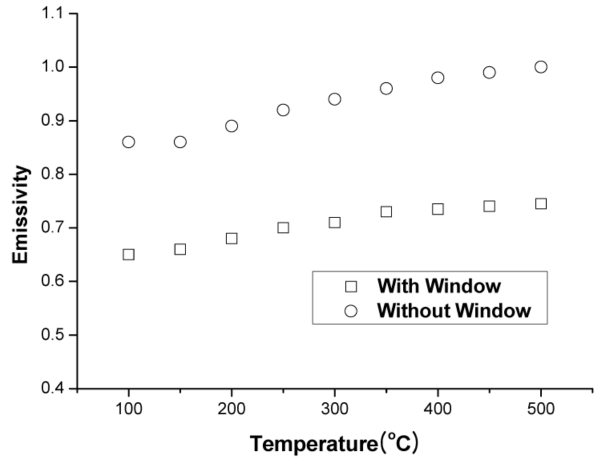

Fig. 3. Temperature Variation of the Emissivity with or Without the Window

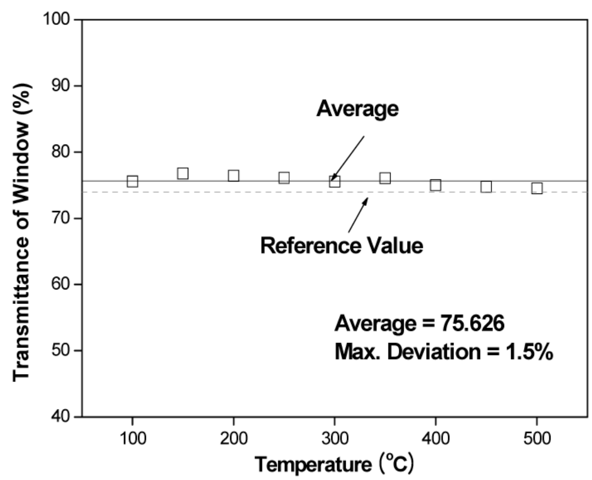

Fig. 4. Transmittance of the ZnSe Window

2.1.1 Effect of Window

The ZnSe window has a transmittance of approximately 72~76 % at a wavelength range of 0.6~20 μm. That is, infrared light through the ZnSe window undergoes attenuation of 24~28 %. Therefore, the quantity of the radiation decreases after passing through the ZnSe window, thereby decreasing the radiation reaching the infrared thermometer. This in turn results in a decreased value for the measured emissivity. Hence, this attenuation must be compensated for in order to obtain the accurate emissivity.

Fig. 3 shows the effect of the ZnSe window, which was estimated by experiments performed with and without the window in air. The transmittance of the window was

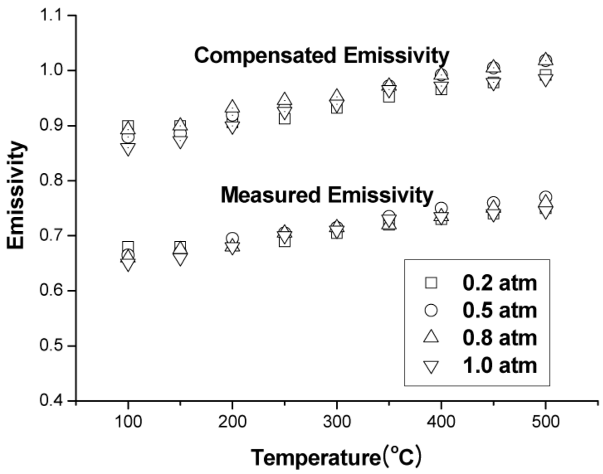

Fig. 5. Temperature Variation of the Emissivity with Different Air Concentrations

estimated to be 74.7 to 76.7 % by dividing the experimental value with the window by that without the window. The results were within the maximum deviation range of 1.5 % from the average value, as shown in Fig. 4. The result satisfies the range of the reference transmittance over the wavelength range of 8~14 μm, i.e. 72 to 76 %. The reference value was obtained from the specifications of the window. Although the measured transmittance of the ZnSe window was higher than the reference value, approximately 2 % in this wavelength range, it agrees fairly well within an acceptable error. Thereafter, the final compensated emissivity could be acquired by dividing the measured emissivity by the transmittance.

2.1.2 Effect of the Gases

The type of filling gas in the cavity as well as its concentration can affect the emissivity measurements (S.S. Sazhin, 1996; N. Lallemant, 1996). Under normal operation conditions of the VHTR, the cavity would be filled with air. However, if the vessel is broken, a coolant such as helium can be released into the cavity. In addition, water could spill into the cavity and evaporate when the inner surface of the water tank is broken. For these reasons, experiments were performed using three types of gas at various concentrations in order to determine the effects of the filling gas. Table 1 shows the test matrix.

2.1.2.1 Effect of Air

Experiments were performed at various air pressures, 0.2, 0.5, 0.8, and 1.0 atm, in order to evaluate the effects of air concentration on the emissivity measurements. Fig. 5 shows the measured emissivity as a function of pressure. In the figure, the compensated emissivity means that the attenuation effect of the window was compensated by dividing the measured emissivity value by transmittance.

The compensated emissivity increased with temperature, varying from 0.85 to 1.0. This value was slightly larger than the reference emissivity for oxidized carbon steel, which is in a range of 0.80~0.95 (Aleksander Sala, 1986). It is considered that the discrepancy was attributed to the background radiation, which is discussed in section 2.1.3.

The variations in the measured emissivity with the air concentration were quite small, within 3 % of the average value. The calculated transmittance of atmosphere by LOWTRAN7 code, a commercial code to calculate the transmittance of atmosphere, was about 96 % in our experimental conditions. However, this result was not clearly

Table 1. Test Matrix

		Air (%)	Helium (%)	Steam (%)	Pressure (atm)
Case A	1	100	0	0	0.2
	2	100	0	0	0.5
	3	100	0	0	0.8
	4	100	0	0	1
Case H	1	20	80	0	1
	2	50	50	0	1
	3	80	20	0	1
Case S	1	20	0	80	1
	2	30	0	70	1
	3	40	0	60	1
	4	50	0	50	1
	5	60	0	40	1
	6	70	0	30	1
	7	80	0	20	1

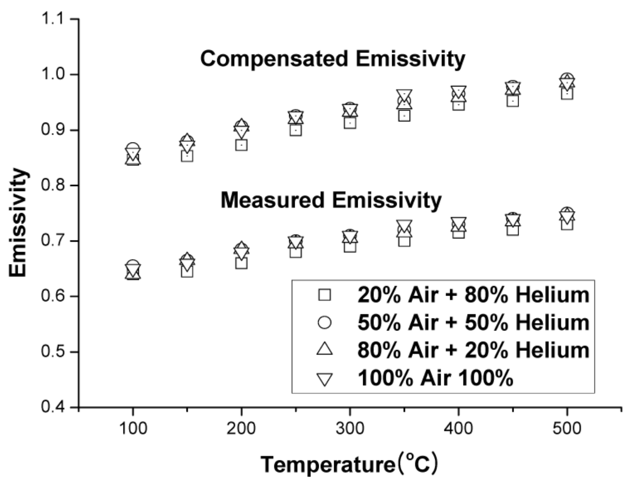

Fig. 6. Temperature Variation of Emissivity with Different Helium Concentrations

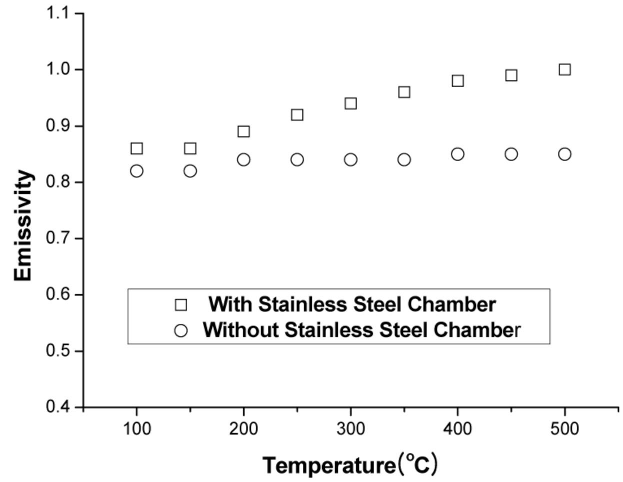

Fig. 8. Effect of Background Radiation on the Measured Emissivity

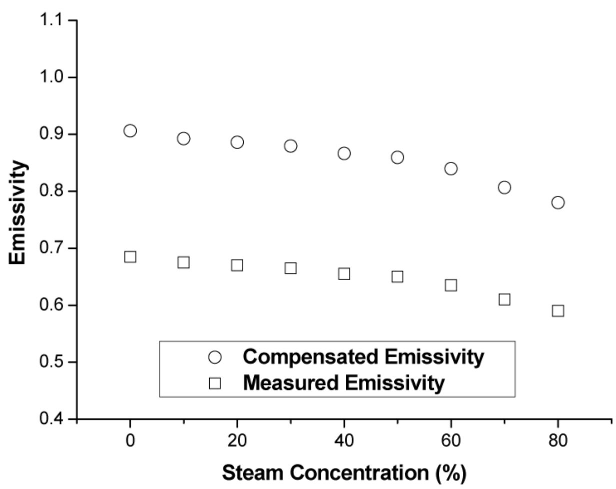

Fig. 7. Effect of Steam on the Measured Emissivity

presented in the experiment because the absorption is not significant compared with the uncertainty of the measurement. Therefore, in the main experiment, the effect of the atmosphere absorption was compensated using the calculated transmittance and then the deviation between the calculated transmittance and experimental transmittance was considered as the uncertainty of the infrared thermometer.

2.1.2.2 Effect of Helium

Using a similar method, the effect of the helium concentration on the emissivity measurements was examined. The total pressure in the chamber was maintained at 1 atm. The air partial pressure corresponded with that of the air experiment, i.e., 0.2, 0.5, 0.8, and 1.0, and the remaining part was filled with helium. Similar to the case of air, variations in the measured emissivity according to the helium concentration were within 3 % of the average value, as shown in Fig. 6. In addition, the compensated emissivity showed a similar range to that in the air experiment, 0.84~0.99 with temperature.

These results demonstrate that the air and helium concentration had a minor effect on the emissivity measurement. This means that, if the pass length is in the order of meters, air and helium do not substantially absorb or reflect radiation at a wavelength range from 8 to 14 μm, and a pressure range of 0.2~1.0 atm.

2.1.2.3 Effect of Steam

The effect of steam on the emissivity measurements was estimated. At low temperatures the steam injected into the chamber was condensed at the inner surface of the chamber, and as a result the proportion of steam could not be precisely controlled. Thus, the effect of the steam concentration was examined at 400 °C so as to prevent condensation.

During the experiments, the total pressure was maintained at 1 atm and the steam concentration was varied from 0% to 80%. The steam concentration was determined by the partial pressure. As the steam concentration was increased, the measured emissivity decreased gradually because of the absorption or reflection effect of steam, as shown in Fig. 7 (Leonid A. Dombrovsky, 2000).

2.1.3 Effect of Background Radiation

The results of the two experiments for air and helium show that the measured emissivity increased with temperature, which was attributed to background radiation and the inherent characteristics of the material. Background radiation is composed of two radiation sources (Adam Mazikowski,

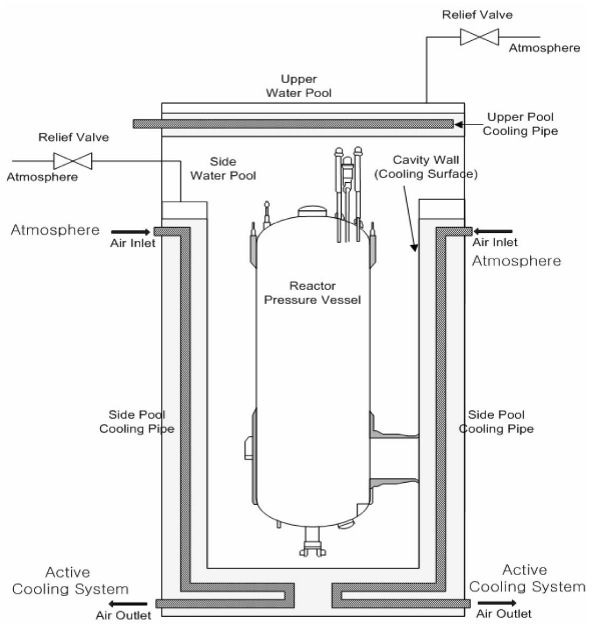

Fig. 9. Schematic Diagram of the SNU-RCCS Test Facility

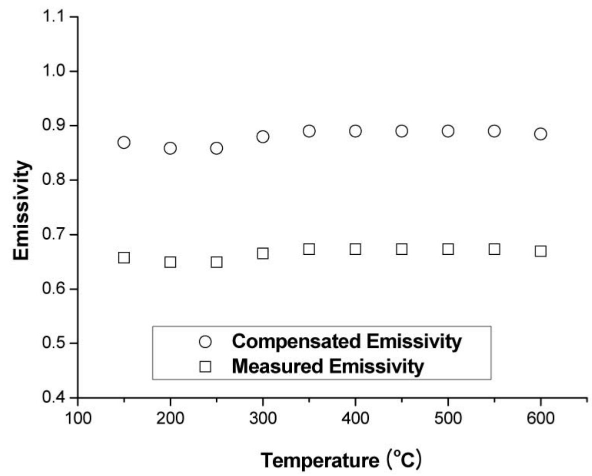

Fig. 11. Temperature Variation of Emissivity with the Sight Tube

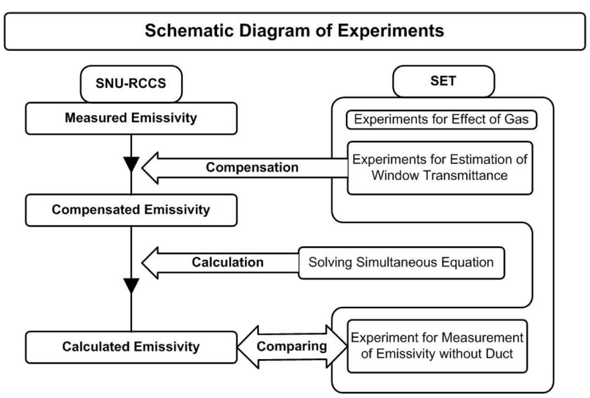

Fig. 10. Schematic Diagram of the Experiment Process

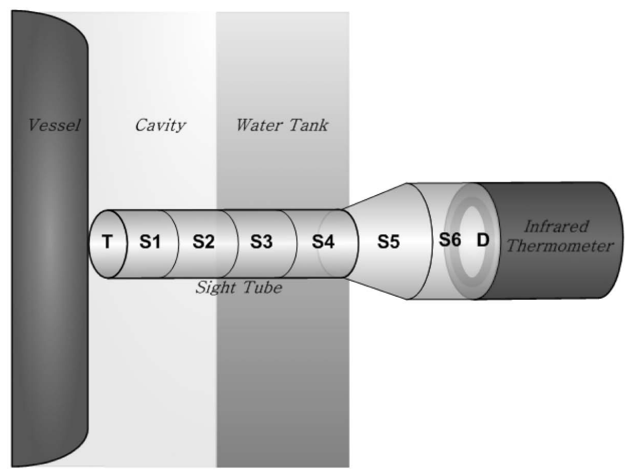

Fig. 12. Simplified Geometry for the Estimation of the True-emissivity

2002), the radiation emitted from the surface of the chamber at its own temperature according to the Stefan-Boltzmann law and the radiation reflected from other surfaces in the chamber.

In order to verify the effect of background radiation, the experiments to measure the emissivity were carried out with and without a stainless steel chamber. The measured emissivity with the chamber was higher than the measured emissivity without the chamber, as shown in Fig. 8. The additional radiation due to the chamber has a ratio of approximately 4~18 % with the temperature. This increasing trend is because the background radiation increases as the target temperature increases, and the quantity of radiation detected by the infrared thermometer thus also increases.

2.2 SNU-RCCS Experiments

The SNU-RCCS experimental facility was constructed at Seoul National University. As shown in Fig. 9, the facility consists of a reactor vessel, cavity, water pool, and an air cooling system. A sight tube was installed through the water tank and cavity in order to simplify the view factor and to facilitate the temperature measurements to calculate the radiation heat transfer. A corresponding window was installed in the separate emissivity measurement device.

The reactor vessel of SNU-RCCS was made from ASTM A36 steel and it was heated at 500 °C over 50 hours to allow for sufficient oxidization before the main experiments. The sight tube was made from 304 stainless steel and was heated at 150 °C for 10 hours.

Fig. 10 shows the process used to measure and calculate the emissivity. First, the absorption effect of the window and atmosphere were compensated for by their transmittance. The effect of background radiation was removed by solving a simultaneous equation. The result was compared with the emissivity of the same material with the reactor vessel of the SNU-RCCS. This measurement was made without any surrounding surface in the separate emissivity measurement device. In this study, this emissivity is referred to as the "true-emissivity" of the reactor vessel. In order to improve the accuracy of the true-emissivity result, calibration was performed using black paint and the absorption effect of the atmosphere was compensated.

2.2.1 Measurement of Emissivity in SNU-RCCS

Fig. 11 shows the measured emissivity at the middle height of the vessel surface with the sight tube in the SNU-RCCS. For the separate emissivity measurement device, the compensated emissivity was found considering the transmittance of the window and atmosphere.

The measured emissivity showed an increasing trend with temperature. The increase in emissivity with temperature was due to both the inherent dependency of the emissivity on temperature and the background radiation by other surfaces. Therefore, the effect of background radiation must be removed from the analysis in order to find the true-emissivity as well as the temperature dependence of the emissivity.

2.2.2 Estimation of the True-Emissivity

The measured emissivity in the SNU-RCCS corresponds with the emissivity including background radiation. However, the true-emissivity, which excludes the background radiation, is required to analyze the SNU-RCCS. Therefore, in order to remove the effect of background radiation on the measured emissivity, an analysis was carried out with a simplified geometry furnished by the sight tube, as shown in Fig. 12. The total number of divided surfaces was 8 and temperature was measured at each surface.

First, the compensated emissivity was found as outlined in section 2.2.1, and then the calculation was carried out by solving a simultaneous equation, as shown in equation (1). In this equation, i and j are indicial notation of surfaces: the target surface, the sight tube surface from 1 to 6, and the detector surface.

$$\frac{E_{B,i}-J_i}{(1-\varepsilon_i)/\varepsilon_i A_i} = \sum_j^N A_i F_{i-j}(J_i - J_j) \qquad (i \neq j) \tag{1}$$

The equation set consists of 8 equations and 8 unknowns: J_D, J_{s1}, J_{s2}, J_{s3}, J_{s4}, J_{s5}, J_{s6}, $\boldsymbol{\varepsilon}_T$,

In these equations, the radiosity of the target material was obtained with the measured emissivity using equation (2)

$$J_i = E_i + \rho_i G = \varepsilon_i E_{Bi} + (1-\varepsilon_i)G_i = \varepsilon_{mi} E_{Bi} \tag{2}$$

The view factors were calculated using a commercial code, NEVADA (Net Energy Verification and Determination Analyzer) (TAC Technologies, 2000).

The emissivity of the sight tube ($\boldsymbol{\varepsilon}_{s1}$, $\boldsymbol{\varepsilon}_{s2}$, $\boldsymbol{\varepsilon}_{s3}$, $\boldsymbol{\varepsilon}_{s4}$, $\boldsymbol{\varepsilon}_{s5}$, $\boldsymbol{\varepsilon}_{s6}$) was substituted by the constant emissivity of stainless steel, which is the material of the sight tube. This is done because the emissivity of stainless steel is not significantly affected by the oxidation level at the temperature range employed in these experiments (Aleksander, 1986). The emissivity and reflectivity of the infrared thermometer were assumed as those of ZnS (Zinc Sulfide), which is the lens material of the infrared thermometer. In other cases, the reflectivity was substituted by 1-$\boldsymbol{\varepsilon}$, because the sum of the emissivity and reflectivity is the unit for an opaque material.

The calculated emissivity was compared with the compensated emissivity and the true-emissivity, as shown in Fig. 13. The calculated emissivity was in good agreement with the true-emissivity and its trend. Therefore, it is believed that the effect of background radiation as accounted for the difference between the calculated and the measured emissivity. In addition, the background radiation was removed by the calculation. The calculated emissivity and true-emissivity increased gradually with increasing temperature at the low temperature range. Finally, both emissivities reached an almost constant value of 0.88 around 400 °C

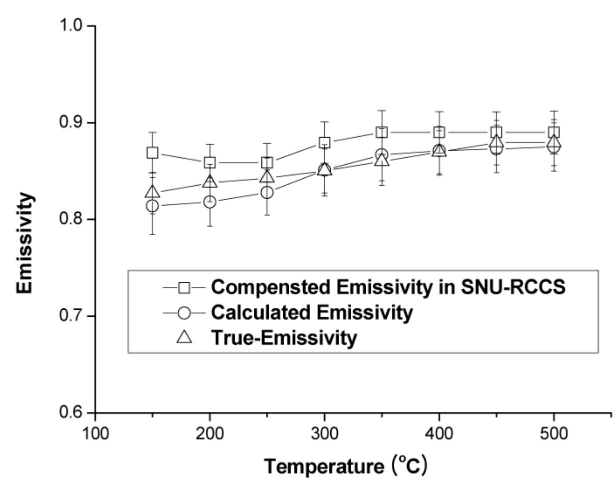

Fig. 13. Comparison of Calculated Emissivity with True-emissivity in SNU-RCCS

2.2.3 Verification of Calculation Method

In order to verify the method used to remove the effect of background radiation, additional experiments were performed with different material made from S45 steel in the separate emissivity measurement device. The emissivity was measured through the sight tube and without any surrounding surface, and then the compensation was performed using the identical method employed in section 2.2.2. Although the emissivity of S45 was different from that of ASTM A36 steel, it was shown that the calculation process properly estimated the effect of background radiation on the emissivity measurement in both cases, as shown in Figs. 13 and 14. It was found that the calculated emissivity was smaller than the true emissivity at low temperature due to the over-estimation of background radiation in both cases. This is caused by uncertainty of measurement as well as calculation for equation (1). The results of the uncertainty analysis illustrating this trend are shown in Fig. 17.

Fig. 15 shows the comparing result. The calculated emissivity shows good agreement with the true emissivity within 3 %. This means that the calculated process is proper to predict the effect of background radiation.

2.2.4 Sensitivity Analysis

In the estimation of the calculated emissivity, the emissivity of the sight tube was assumed to be constant at 0.60. This value was obtained by an experiment performed at 150 °C using stainless steel, the same material as the sight tube. Because the assumption did not consider the emissivity variation of stainless steel as a function of temperature, there might be some error in the calculations. The validity of this assumption was tested by carrying out a sensitivity analysis with various stainless steel emissivities using the same calculation process as that in the previous sections.

As shown in Fig. 16, the calculated emissivities yielded similar values even for different stainless steel emissivity, ranging from 0.4 to 0.8. The maximum difference in the calculated emissivity was 0.016 at 300 °C. Therefore, the error caused by the assumption of stainless steel emissivity had little effect on the analysis of the calculated emissivity.

Likewise, the emissivity and reflectivity of the detector also were presumed to be constant. The temperature of the detector was quite low compared with those of the other surfaces, and thus the emissivity variation of the detector had almost no influence on the calculation results.

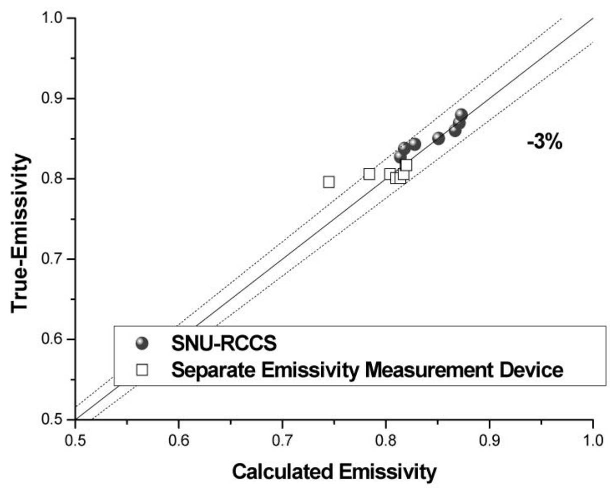

Fig. 15. Validation of the Calculated Emissivity

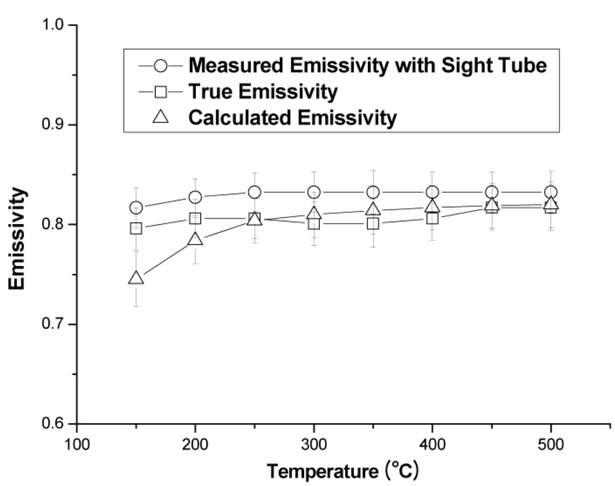

Fig. 14. Comparison of Calculated Emissivity with True-emissivity in Separate Emissivity Measurement Device

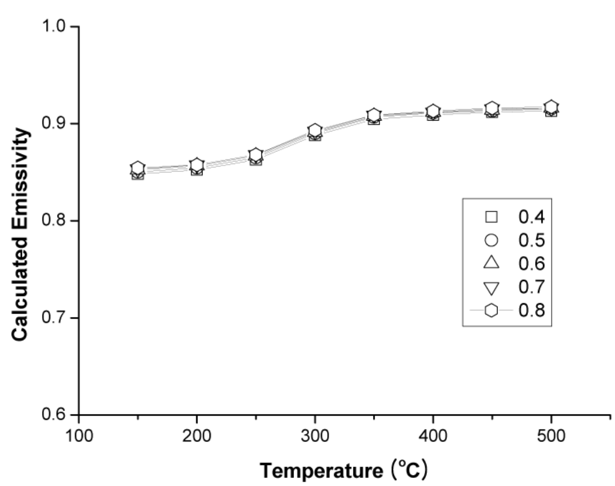

Fig. 16. Calculated Emissivity with the Emissivity of Various Stainless Steels

Table 2. Averaged Uncertainty

	SNU-RCCS	Separate emissivity measurement device
Measurement of true emissivity	2.6 %	2.7 %
Measurement of emissivity with sight tube	2.4 %	2.4 %
calculation of true emissivity	3.0 %	2.9 %

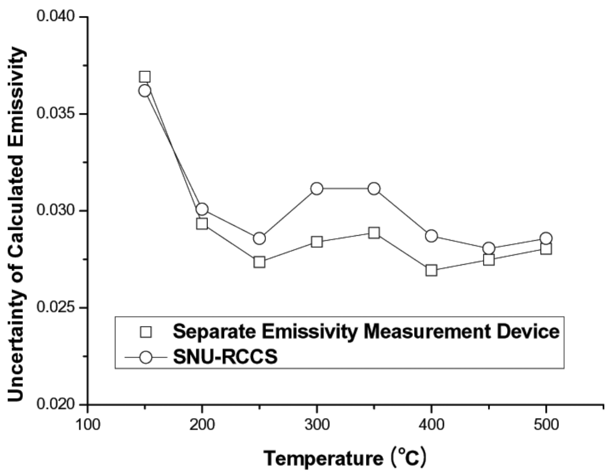

Fig. 17. Uncertainty of Calculated Emissivity

2.3 Uncertainty Analysis

Uncertainty in the emissivity measurement was assessed considering uncertainties of the thermocouple and an infrared thermometer. In addition, uncertainties due to the detecting angle and position of the infrared thermometer were also considered. Level of oxidation was considered constant after 50 hours heating at 500 °C because we confirmed that emissivity does not change after this amount of time. The effect of surface roughness was included in the uncertainty of position and oxidation level assessments.

K-Type thermocouples were calibrated using a calibration curve from 0 °C to 500 °C within a 0.5 °C error band. Although the accuracy of the infrared thermometer is given by the manufacturer as 1 %, we considered the accuracy of the thermometer to be 2 %, including the error in compensation of atmosphere transmittance. In addition, the sensitivity of emissivity measurement on the detecting angle and position was tested with a traversing system installed in the infrared thermometer. The uncertainties of the calculated emissivity at each temperature are shown in Fig. 17, and the averaged uncertainties are summarized in Table 2. These results were used to plot the error bar in Figs. 13 and 14.

3. CONCLUSIONS

The emissivity of a reactor vessel was measured using an infrared thermometer in order to estimate the true-emissivity for an analysis of the SNU-RCCS. From experiments in a separate emissivity measurement device, it was found that there was no significant change in emissivity with the concentration of air and helium in the wavelength range of the infrared thermometer used in this study. However, the steam had a large effect on the emissivity measurements due to the absorption and reflection of radiation.

The emissivity was then measured through the sight tube in SNU-RCCS. First, the attenuation effects of the window and filling gas were compensated. Then, the effect of background radiation was removed using a simultaneous equation, and the calculated emissivity showed good agreement with the true-emissivity. The calculated emissivity increased from 0.82 to 0.88 at temperatures below 350 °C, and showed an almost constant value of 0.88 over 400 °C.

In conclusion, the calculation method introduced in this study provides good estimation of the true-emissivity with temperature. For a precise analysis of radiation heat transfer in the VHTR, the emissivity, which is compensated for by factors such as temperature, background radiation, and attenuation by media, should be considered.

ACKNOWLEDGEMENTS

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NOMENCLATURE

ε	emissivity
E	emissive radiation
G	irradiation
J	radiosity
ρ	reflectivity
F	view factor

Subscripts

i,k	surface index
m	measured
B	blackbody
T	target
S1~S6	sight tube
D	detector

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