Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 10-11, 2007

Uncertainty Analysis of a Two-Color Pyrometry Applied to TROI Experiments

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1. Introduction

TROI experiments on the interaction of molten corium and water are performed to quantify the risk of a potential steam explosion in a nuclear reactor [1]. In the experiments, a cold crucible technique was used to generate the molten corium. The temperature of a molten corium is one of key parameters which have a strong effect on the behavior of the molten corium and water interaction. As the molten corium has a very high temperature of 2830~3200K, its temperature measurement is very difficult. Generally thermocouples are only used up to 2600K. So an optical pyrometry should be applied to measure the temperature of the molten corium. In the TROI experiment, optical two-color pyrometers are used to measure the corium temperatures. One of the pyrometer is to measure the melt temperature during the melt delivery to the water pool. The melt temperature by the pyrometer has uncertainties due to a spectral transmittance of the view port, and a transient response of the two-color pyrometer.

In this paper, uncertainty factors of the optical pyrometry in the TROI experiment, such as a spectral transmittance of a view port, and a time response were discussed.

2. Spectral Transmittance of View Port

In the TROI experiment, a pyrometer is to measure the corium temperature during the melt delivery to the water pool. The melt temperature by the pyrometer has uncertainties due to a spectral transmittance of a view port. In the early stage of the TROI experiments, a glass window has been used by the view port. Unfortunately, the spectral transmittances of the glass window vary with the wavelengths, so the temperature measured by the two-color pyrometer must be corrected.

The pyrometer is IRCON MODLINE3 Infrared Thermometer (3R-35C15-0001). This two-color pyrometer includes two optical sensors, one is a 0.7-1.08μm wide band sensor, and the other is a 1.08μm narrow band sensor. The intensities by the wide band and narrow band sensors are expressed by Eq.(1) and Eq.(2), respectively, by assuming Planck's equation and Wien's approximation.

$$E_{\lambda 1-\lambda 2} \approx \int_{\lambda 1}^{\lambda 2} \frac{\varepsilon_{\lambda}\, 2\pi C_1}{\lambda^5 \exp\left(C_2/\lambda T\right)} d\lambda \tag{1}$$

$$E_{\lambda 2} \approx \frac{\varepsilon_{\lambda 2}\, 2\pi C_1}{\lambda_2^5 \exp\left(C_2/\lambda_2 T\right)} \tag{2}$$

If a spectral emissivity varies linearly between wavelength λ_1 and λ_2, then the emissivity slope k can be defined by Eq.(3). If k is one, it means a graybody emission.

$$\varepsilon_{\lambda} = \varepsilon_{\lambda 2}\left[1+(k-1)\frac{\lambda-\lambda_2}{\lambda_1-\lambda_2}\right] \tag{3}$$

Using Eq.(1)-(3), the intensity ratio can be converted to an optical temperature by Eq.(4).

$$\frac{E_{\lambda 1-\lambda 2}}{E_{\lambda 2}} = \int_{\lambda 1}^{\lambda 2}\left(\frac{\lambda_2}{\lambda}\right)^5 \exp\left[\frac{C_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda}\right)\right] \times\left[1+(k-1)\frac{\lambda-\lambda_2}{\lambda_1-\lambda_2}\right] d\lambda \tag{4}$$

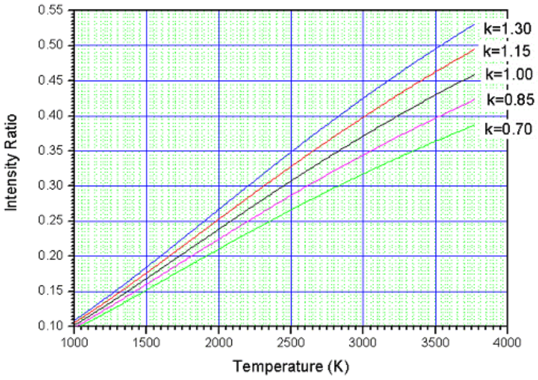

Fig.1 Intensity ratio along with temperature and emissivity slope (k)

Fig.1 shows the intensity ratio along with the temperature and emissivity slope obtained by solving Eq.(4). Using the Fig.1, a given intensity slope (a signal from the pyrometer) can be calibrated to a temperature value corresponding to a different emissivity slope. For example, it supposes that an emissivity slope is set as 1.0, and a measured temperature by the pyrometer is 2500K. If the emissivity slope is changed to 1.15 for the same target, then the measured value by the pyrometer may be estimated as 2300K by Fig.1.

In the initial stage of the TROI experiment, the corium temperatures during the delivery to the water pool have been measured by a pyrometer set of the emissivity slope as 1.0 through the glass window. If the corium emits a graybody radiation, the emissivity slope is decided by the spectral transmittance of the view port. Therefore, the pyrometer is calibrated with a blackbody furnace through the glass window. Fig.2 shows the calibration results of the pyrometer along with the emissivity slope 1.0 and 1.15. According to the set values of the emissivity slopes, the measured temperature values are different although the same temperature target is used. Using the measured temperature value set of the emissivity slope as 1.0, the temperature which is recalculated from the Fig.6 by assuming that the emissivity slope is set, is 1.15. Fig.2 also shows the recalculated and measured temperature values for the condition of the emissivity slope as 1.15. The recalculated temperature agrees with experimental one, qualitatively, but, not quantitatively. This is why Eq.(4) may not include the spectral sensitivities of the detectors.

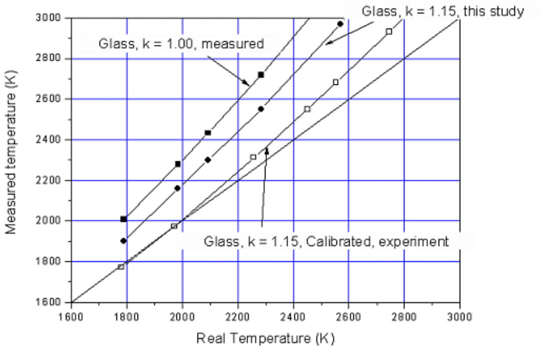

Fig.2 Experimental and theoretical temperature calibration results along with emissivity slope

3. Time Transient of Pyrometer

The melt temperature by the pyrometer has uncertainties due to a transient response of a two-color pyrometer. The pyrometer signal is maintained for a very short term in the TROI experiment, because the melt delivery time is very short. For evaluating visualization of the melt delivery process by a high speed camera, the effective melt delivery time is estimated at about 740msec. Erik Spjut [2] has evaluated the time response of a two-color optical pyrometry. He modeled the detector system as a first-order system, which is characterized by a unit step response, 1-exp(-t/τ), where t is the time and τ is the characteristic response time of the first-order system. He suggested a equation to evaluate the time response of the two-color optical pyrometry.

As shown in Fig.3, a true temperature profile in the TROI experiment is assumed as a step function. That is, the minimum temperature is assumed as 1800K, and the maximum is 3700K. The melt delivery time is also assumed to be from 140 to 880msec. The measured wavelengths of the optical pyrometer are assumed that λ_1 is 0.85μm, and λ_2 is 1.08μm. Fig.3 shows the transient response of the two-color pyrometry according to the characteristic response time of the pyrometer. The optical pyrometer responds much more rapidly for a temperature increase but much more slowly for a temperature decrease. In the TROI experiment, the time response setting value of the pyrometer is 0.01 second. So, the measured temperature decrease includes a larger error than the temperature increase.

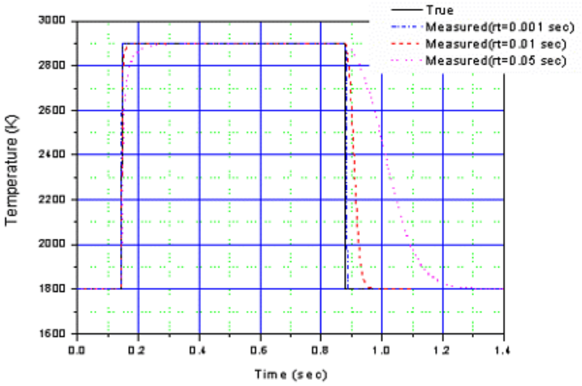

Fig.3 Transient response of pyrometer along with characteristic response time

4. Conclusion

Uncertainty factors of the optical pyrometry in the TROI experiment, such as a spectral transmittance of a view port, and a time response were discussed. The melt temperature by the pyrometer due to a spectral transmittance of a view port was theoretically evaluated and experimentally calibrated. And the time response analysis of the two-color optical pyrometry suggested by Erik Spjut [2] was applied to evaluate the time response error. So, it was confirmed that the measured temperature decrease includes a larger error than the temperature increase.

Acknowledgments

This study has been performed under the Long-and-Mid-Term Nuclear R&D Program supported by Ministry of Science and Technology, Republic of Korea

NOMENCLATURE

C1	first radiation constant, 0.59544×10^8μm^4/m^2
C2	second radiation constant,14388 μm·K
E_λ	spectral radiant intensity, W/m^2·μm
k	emissivity slope
T	temperature, K, t time, sec
ε_λ	spectral emissivity
λ	wavelength, μm
τ	characteristic response time, sec

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