

Uncertainty Evaluation of the Thermal Expansion of $Gd_2O_3-ZrO_2$ with a System Calibration Factor

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1. Introduction

Both gadolinia (Gd_2O_3) and zirconia (ZrO_2) are widely used in the nuclear industry, including a burnable absorber and additives in the fabrication of a simulated fuel. Thermal expansions of a mixture of gadolinia (Gd_2O_3) 20 mol% and zirconia (ZrO_2) 80 mol% were measured by using a dilatometer (DIL402C)[1] from room temperature to 1500 oC. Uncertainties in the measurement should be quantified based on statistics. Referring to the ISO (International Organization for Standardization) guide,[2,3] the uncertainties of the thermal expansion were quantified for three parts - the initial length, the length variation, and the system calibration factor.[4,5] The whole system, the dilatometer, is composed of many complex sub-systems and in fact it is difficult to consider all the uncertainties of the sub-systems. Thus, the system calibration factor was introduced with a standard material for the uncertainty evaluation. In this study, a new system calibration factor was formulated in a multiplicative way. Further, the effect of calibration factor with random deviation was investigated for the uncertainty evaluation of a thermal expansion.

2. Method and results

Thermal expansion is defined as a variation of the length with a temperature change, which is expressed as follows,

$$\Delta l / l_0 = (l_f - l_0) / l_0 = \alpha_l (T_f - T_0) \quad (1)$$

where

l_0, l_f : length at temperatures T_0 and T_f , respectively,

α_l : linear coefficient of a thermal expansion.

The approach for an uncertainty of the thermal expansions of a uranium oxide fuel starts from the following formulation based on the ISO guide[2,3],

$$f_E(T) = (l(T) - l_0) / l_0 \times f_{cal} \quad (2)$$

where

$f_E(T)$: thermal expansion, or output of experiments,

l_0 : sample length at the room temperature (mm),

$l(T)$: sample length at T °C (mm),

f_{cal} : ratio due to system calibration.

The factor of f_{cal} has a unit value and its uncertainty comes from a system calibration test with a reference material.[4,5] If the results of the system calibration lie

within a proper criterion, the system (DIL 402C) is thought to be a normal state and no other calibration is not performed. This contains two kinds of uncertainties: the first one is an iterative experiment uncertainty with a reference material (type A) and the second one is a reference material uncertainty from a report (type B).

However, if we consider a system calibration as a non-unit value of f_{cal} , the following multiplicative correction can be derived.

$$f_E^M(T) = (l(T) - l_0) / l_0 \times M(T) \quad (3)$$

and $M(T)$ is a multiplicative scaling factor which is defined as

$$M(T) = f_E^{CRM}(T) / f^{CRM}(T) \quad (4)$$

where, $f^{CRM}(T)$ is the thermal expansion of the CRM (certified reference material) at temperature T in the CRM report and $f_E^{CRM}(T)$ is a measured thermal expansion of the CRM during a system calibration. In this study, alumina (Al_2O_3) was used as the CRM for the thermal expansion measurement.

In Eq. (2), f_{cal} has a unit value, which means that no calibration was done. However, Eq. (4) performs a temperature dependent calibration in a multiplicative way. The procedure for the uncertainty evaluation is similar to the previous approach except for the sensitivity coefficient. The sensitivity coefficients with a multiplicative calibration factor are also easily derived as follows.

$$C_{M(T)} = \partial f_E^M / \partial M(T) = (l(T) - l_0) / l_0 \quad (5)$$

$$C_{l_0} = \partial f_E^M / \partial l_0 = -M(T) \times ((l(T) - l_0) / l_0 + 1) / l_0 \quad (6)$$

$$C_{l(T)} = \partial f_E^M / \partial l(T) = M(T) / l_0 \quad (7)$$

Thermal expansion of the $Gd_2O_3-ZrO_2$ increases linearly as a function of the temperature as shown in Fig. 1. The calibrated data is nearly the same as the un-calibrated data. In this normal case, it was also found that the uncertainties of the multiplicative calibration are similar to that of the un-calibrated evaluation. Therefore, it is not necessary to calibrate the measurement data in this case because the uncertainty is already considered in the system calibration factor. In this work, it was assumed that the system deviates randomly by about 5% and 10% from the normal case to investigate the effect of the calibration. Thus, the thermal expansions of the CRM and the gadolinia and zirconia were set to have 5% and 10% low average distributions when compared with the normal state. The random data was obtained from the following equation.

$$f_E^{DS} = f_E \times (0.9 + 0.1 \times RAND) \quad (8)$$

$$f_E^{D10} = f_E \times (0.8 + 0.2 \times RAND), \quad (9)$$

where f_E^{D5} , f_E^{D10} , f_E are the 5% and 10% deviated and normal thermal expansions, respectively and $RAND$ is a random number between 0 and 1.

Figs. 2 and 3 show the results of the calibrations for 5% and 10% deviations, respectively. It was found that the calibration results provide more accurate thermal expansion data than the un-calibrated data for small system. The maximum differences between the normal state and un-calibrated state are obtained $1.16E-03$ and $2.33E-03$ for the 5% and 10% deviations, respectively. However, the maximum differences between the normal state and calibrated state are reduced significantly by $4.56E-04$ and $9.15E-04$ for 5% and 10% deviations, respectively. Thus, it is strongly recommended to check the measurement system when an unexpected distribution happens in a standard calibration test with higher than a 10% deviation.

3. Conclusion

Thermal expansion was measured with a dilatometer for a mixed oxide (Gd_2O_3 and ZrO_2) and its uncertainty was evaluated with a system calibration with temperature changes in a multiplicative way. This approach was found to be useful for an application to the evaluation of an uncertainty for a system calibration. It is recommended that the measurement system should be kept at a reliable state and be calibrated with a reference material during a routine period to reduce an uncertainty related with a system calibration and to provide more reliable experiment data. As a conclusion, our approach for an uncertainty evaluation is expected to be applied easily to the measurement of other thermophysical properties and also would be helpful in providing a fundamental approach to produce more reliable measurement data for the thermophysical properties of a nuclear fuel.

Acknowledgements

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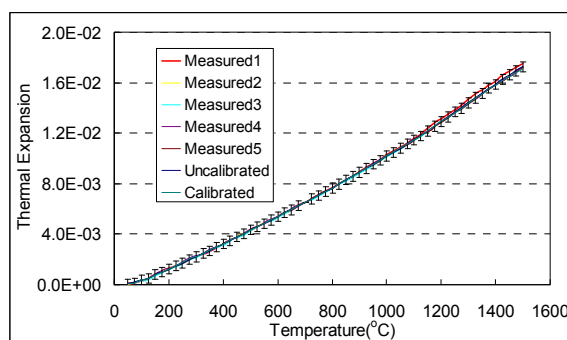


Fig. 1 Thermal expansion of Gd_2O_3 - ZrO_2 mixture as a function of temperature.

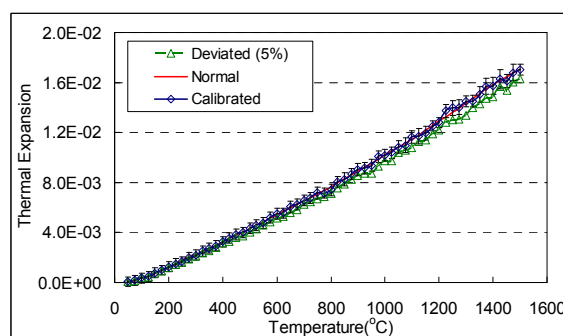


Fig. 2 Thermal expansion of Gd_2O_3 - ZrO_2 mixture as a function of temperature. (5% deviated)

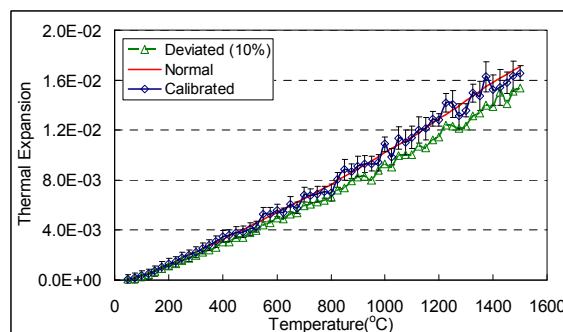


Fig. 3 Thermal expansion of Gd_2O_3 - ZrO_2 mixture as a function of temperature. (10% deviated)