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# Uncertainty Evaluation Program of Specific Heat Measurement Data

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## 1. Introduction

Most of the nuclear fuel design requirements - such as core temperature, cladding internal pressure, cladding deformation rate, and oxidation layer thickness - are functions of the temperatures of the nuclear fuel and the cladding. To determine the temperature gradient in the nuclear fuel and cladding, thermal physical properties such as thermal diffusivity, density, specific heat, etc., are needed. Ensuring the reliability of thermal property data necessitates evaluating the uncertainty in measured data [1]. We developed the uncertainty evaluation procedure of specific heat measurement data using DSC (Differential Scanning Calorimeter) [2]. Moreover, a program that can automatically calculate uncertainties based on measurement data is required as well.

In this study, we made a program that can automatically calculate uncertainties in specific heat measurements. Using this program, the uncertainties of specific heat measurement data for Zircaloy-4 cladding material were evaluated, and the results were compared with those obtained through manual calculation.

## 2. Uncertainty of Specific Heat Measurement Data

*2.1 Measurement model*

A heat capacity is be defined as the change in heat required for a unit change in temperature and a specific heat capacity is defined as the heat capacity per unit mass as follows:

$$c_p = \frac{1}{m} C(T) \times f_{cal}(T) \qquad (1)$$

where $c_p$ is the specific heat capacity, m is a specimen mass, C(T) is the heat capacity, and $f_{cal}$ is the correction factor. The correction factor is defined as follow:

$$f_{cal}(\mathrm{T}) = \frac{c_{p-ref-c}(T)}{c_{p-ref-m}(T)} \qquad (2)$$

where $c_{p\text{-ref-c}}$(T) is the specific heat of standard reference material in certificate and $c_{p\text{-ref-m}}$(T) is the measured specific heat of standard reference material using DSC.

*2.2. Factors affected on the uncertainty*

The contributing factors to the uncertainty from equation (1) are uncertainties of the specimen mass, u(m), heat capacity, u(c), and calibration of DSC, u($f_{cal}$).

*2.3. Determination of the combined standard uncertainty, $u_c$*

Combined standard uncertainty was calculated using the previously evaluated standard uncertainty, as follows:

$$u_c = \sqrt{a_m^2 u^2(m) + a_C^2\, u^2(C) + c_{fcal}^2 u^2(f_{cal})} \qquad (3)$$

where

$$a_m = \frac{\partial}{\partial m}\left(\frac{C}{m} f_{cal}\right) = -\frac{1}{m^2} C \times f_{cal}$$

$$a_C = \frac{\partial}{\partial C}\left(\frac{C}{m} f_{cal}\right) = \frac{1}{m} \times f_{cal}$$

$$a_{fcal} = \frac{\partial}{\partial C}\left(\frac{C}{m} f_{cal}\right) = \frac{C}{m}$$

*2.4. Calculation of expanded uncertainty, U*

The expanded uncertainty *U* is obtained by multiplying the combined standard uncertainty $u_c$ by a *coverage factor k*:

$$U = k\, u_c \qquad (4)$$

If the effective degrees of freedom (DOF) $\nu_{eff}$ is significantly high, the following can be carried out:

- Adopt $k$ = 2 and assume that U = 2$u_c$ defines an interval with a confidence level of approximately 95%.

Otherwise, for more critical applications:

- Adopt $k$ = 3 and assume that U = 3$u_c$ defines an interval with a confidence level of approximately 99%.

## 3. Program for Evaluation of Uncertainty Factors

A program has been constructed to calculate the standard uncertainty, sensitivity coefficients, composite uncertainty, and expanded uncertainty for each factor based on the given input data. The configuration is composed of five main calculations and seven modules.

The input data includes measured values of specific heat capacity (dd01.txt), standard sample temperature coefficient values (cc01.txt), certification values (cc02.txt), mass weight measurements (tt01.txt), and t-values based on freedom (tt02.txt) in text files. Other inputs such as the number of temperatures, number of measurement data at each temperature, number of mass measurement data, average mass measurement value, resolution of electronic balance, uncertainty of electronic balance certificate, and degree of freedom are provided in a basic input file (input.txt).

The main program calculates the uncertainties of mass, repetition measurement of specific heat capacity, sensitivity coefficients, combined uncertainty, coverage factors, and expanded uncertainty based on the above input data and outputs the results to a text file (output.txt). The program consists of seven modules and five main calculations. Fig. 1 represents the configuration of a program for calculating uncertainty of specific heat measurement data using DSC.

To evaluate the uncertainty estimation program for heat capacity measurement data of Zircaloy-4 using DSC, we used the measured heat capacity data, the certified values of standard materials, and the mass values of the specimens to assess the uncertainties. Table I is a measurement data of the sample mass, the heat capacity of Zircaloy-4, and the correction factors and the sensitivity factors. The standard uncertainties, the combined uncertainty, the coverage factors, and the expanded uncertainty values calculated using this program are also in Table I.

## 3. Conclusion

The uncertainty evaluation program is made in accordance with the GUM to improve the reliability of specific heat measurement data. The study can be summarized as follows:

(1) The contributing factors to the uncertainty are uncertainties of the specimen mass, heat capacity, and calibration of DSC.
(2) The program has been constructed to calculate the standard uncertainty, sensitivity coefficients, combined uncertainty, and expanded uncertainty for each factor based on the given input data
(3) The program consists of seven modules and five main calculations.

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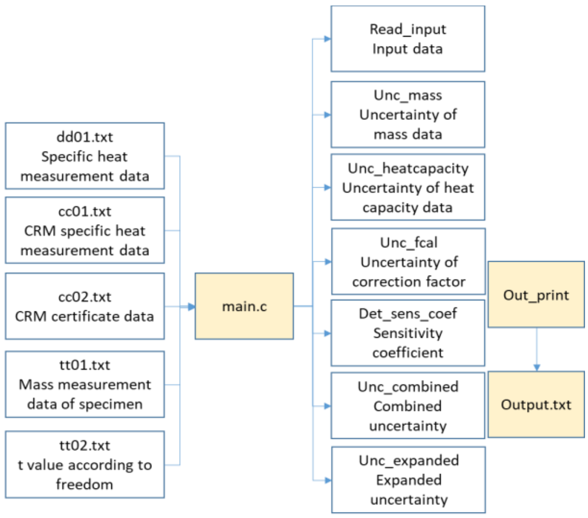


Fig. 1 The configuration of a program for calculating uncertainty of specific heat measurement data using DSC

Table I. The heat capacity value of Zircaloy-4 using DSC

| Temp. °C | *m*, *g* | *C* *J/K* | $f_{cal}$ | $a_m(T)$ $J/g^2 \cdot K$ | $a_C(T)$ $1/g$ | $a_{fcal}(T)$ $J/g \cdot K$ |
|---|---|---|---|---|---|---|
| 50 | 1.90E-01 | 5.62E-02 | 0.99 | -1.53 | 5.19 | 0.30 |
| 100 | 1.90E-01 | 5.73E-02 | 0.99 | -1.57 | 5.22 | 0.30 |
| 150 | 1.90E-01 | 5.83E-02 | 1.00 | -1.61 | 5.25 | 0.31 |
| 200 | 1.90E-01 | 5.91E-02 | 1.00 | -1.63 | 5.24 | 0.31 |
| 250 | 1.90E-01 | 5.98E-02 | 1.00 | -1.65 | 5.25 | 0.31 |
| 300 | 1.90E-01 | 6.05E-02 | 1.00 | -1.67 | 5.25 | 0.32 |
| 350 | 1.90E-01 | 6.09E-02 | 1.00 | -1.69 | 5.27 | 0.32 |
| 390 | 1.90E-01 | 6.11E-02 | 1.01 | -1.70 | 5.29 | 0.32 |
| *u(m)* *g* | *u(C)(T)* *J/K* | *u(fcal)(T)* | *uc(T)* *J/g·K* | *k* | *U(T)* *J/g·K* | % |
| 1.72E-05 | 7.93E-04 | 1.18E-02 | 5.40E-03 | 2.36 | 1.28E-02 | 4.32 |
| 1.72E-05 | 7.42E-04 | 1.09E-02 | 5.09E-03 | 2.36 | 1.20E-02 | 3.99 |
| 1.72E-05 | 7.23E-04 | 1.00E-02 | 4.88E-03 | 2.36 | 1.15E-02 | 3.76 |
| 1.72E-05 | 6.93E-04 | 8.02E-03 | 4.40E-03 | 2.36 | 1.04E-02 | 3.35 |
| 1.72E-05 | 5.73E-04 | 7.18E-03 | 3.76E-03 | 2.36 | 8.89E-03 | 2.83 |
| 1.72E-05 | 4.91E-04 | 6.90E-03 | 3.39E-03 | 2.36 | 8.01E-03 | 2.52 |
| 1.72E-05 | 4.08E-04 | 7.92E-03 | 3.32E-03 | 2.36 | 7.86E-03 | 2.46 |
| 1.72E-05 | 3.51E-04 | 9.05E-03 | 3.45E-03 | 2.36 | 8.15E-03 | 2.54 |