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Engineering Notes

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Uncertainty Evaluation of Thermocouple Aeroheating Measurements for Hypersonic Wind-Tunnel Tests

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Introduction

FOR hypersonic wind-tunnel tests, thermocouples are widely used to measure aerodynamic heating on a model. In this approach, the heat flux is conventionally reduced from the time history of temperature by applying a method found in Ref. 1, which is based on the exact solution of the one-dimensional heat conduction problem. This is reasonable if the assumption of one-dimensional heat conduction is appropriate, but a series of uncertainties should be addressed to examine the accuracy of the data.

One common way to evaluate overall uncertainties of wind-tunnel tests is to estimate the error elements of each measurement process, (that is, calibration and data acquisition/reduction) for both the random and systematic (bias) components and to combine these errors in a root-sum-square fashion.[2,3] This hand calculation-type analysis is, however, not suitable for the heat flux measurements using a thermocouple because the process includes complicated numerical operations such as data smoothing, numerical integration, and time averaging. Hence, another method that can properly account for uncertainties generated in each data reduction step is required.

In the present study, a numerical method was developed to estimate the uncertainties in the aerodynamic heating measurements by using a Monte Carlo method. Under the assumption of constant heating, the temperature time history obtained from the exact solution of one-dimensional heat conduction problem was randomly varied by a specified level of uncertainty, and variance of the heating rate was iteratively evaluated. This is basically similar to the approach taken in Ref. 4, where a combined uncertainty was determined for the phosphor thermography method by applying a stochastic technique. The use of a Monte Carlo approach has an advantage that the numerical operations used in the actual data reduction process can be naturally taken into account. In what follows, the detail of the present methodology is described and the variation of measurement uncertainty is examined as a function of the level of heat flux. The estimated uncertainty is further examined by comparison with experimental data obtained from a hypersonic wind-tunnel test.

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Detail of Analysis

A time series of temperature data T_i, $i = 0, \ldots, n$, obtained from the thermocouple measurement is numerically integrated to reduce aerodynamic heating at time t_n by using the following formula[5]:

$$q(t_n) = 2\sqrt{\frac{\rho c k}{\pi}} \sum_{i=1}^{n} \frac{T'(t_i) - T'(t_{i-1})}{\sqrt{t_n - t_i} + \sqrt{t_n - t_{i-1}}} \tag{1}$$

where a dash denotes increment from the initial state, that is, $T'(t_i) = T(t_i) - T(t_0)$. Therefore, the accuracy of the computed heat flux is affected by uncertainties in the temperature measurement and in thermal properties of a material. Note that only the incremental values of temperature appear in Eq. (1) and no magnitude of measured value is necessary. This implies that a series of bias errors are expected to be offset and only random component of the temperature measurement error is to be considered. Hence, in the present study, a Monte Carlo method was newly developed to estimate properly the random uncertainty in the heating data coming from the temperature measurement noise. In this algorithm, the temperature data are randomly varied by a specified level of uncertainty, and the uncertainty in the time-averaging heat flux data is estimated by iteration. The procedure can be described as follows:

1) Set a constant value of the heat flux q_0.

2) Obtain a baseline temperature time history $T'_{0,i}$ by the following relation given from the exact solution of the one-dimensional heat conduction equation[5]

$$T'_{0,i} = 2q_0/\sqrt{\pi}\sqrt{t_i/\rho c k}, \qquad i = 0, \ldots, n \tag{2}$$

where the time series t_i is set to be consistent with the wind-tunnel data.

3) Initialize l as $l = 1$, where l is the number of iterations for steps 4–9.

4) Set the "noisy" temperature time history T'_i as

$$T'_i = T'_{0,i} + \Delta T(2U - 1) \tag{3}$$

where U is the random variable that takes a value between 0 and 1 and ΔT is the maximum level of uncertainty in the temperature measurement.

5) Smooth the temperature data by moving average, the same as in reducing heat flux from the actual measurement data.

6) Obtain heat flux time history from smoothed T'_i by using Eq. (1).

7) Compute time-averaging heat flux q^l_{av} from the heat flux time history.

8) Evaluate the variance σ^2 as

$$\sigma^2 = \sum_{i=1}^{l} \frac{\left(q^i_{av} - q_0\right)^2}{l} \tag{4}$$

9) Increment l as $l \rightarrow l + 1$.

10) Repeat steps 4–9 until the level of uncertainty (2σ for a 95% confidence limit) converges to a constant value.

Care was taken such that each of the uncertainty estimation process steps consistently follows the actual data reduction process. In the present study, the temperature random uncertainty ΔT was estimated from standard deviation of the measured temperature profile and was set to 0.2 deg.

On the other hand, because the term associated with the thermal properties appears as a constant in Eq. (1), its uncertainty can be treated as a bias component. Because the thermal conductivity k is normally reduced from the measurement value of thermal diffusivity α using the relation $k = \rho c \alpha$, the coefficient $\sqrt{(\rho c k)}$ is rewritten as $\rho c \sqrt{\alpha}$. From previous experience, the measurement uncertainty of ρ, c, and α was considered to be 1, 1, and 5%, respectively. Hence, the uncertainty in $\sqrt{(\rho c k)}$ was also evaluated using a Monte Carlo approach and was shown to be approximately 3.3%.

Finally, the total aeroheating uncertainty was evaluated as a root-sum-square combination of the random component concerning the temperature measurement noise and the bias component for the thermal properties.

Results and Discussion

The variation of predicted uncertainty as a function of the level of heat flux was examined by varying the heating rate from 1 to 100 kW/m^2 and is plotted in Fig. 1. It can be confirmed that, for the heating level of 1 kW/m^2, the total uncertainty reaches up to 40%. As expected, the effect of temperature uncertainty becomes dominant as the heat flux decreases, whereas it becomes negligible for high-heating cases. The data smoothing by moving average significantly reduces the level of uncertainty for low-heating cases. In fact, as much as 97% error was observed for the case of 1 kW/m^2 if the data were not smoothed. In this case, the temperature increase is around 0.3 deg at most, which is even comparable with the level of temperature measurement uncertainty. Hence, although the data are sufficiently smoothed, we cannot completely get rid of the effect of temperature noise. On the contrary, for the heat flux level of 100 kW/m^2, the temperature increase is shown to be up to 30 deg. In this case, the effect of the temperature noise becomes negligible, and we can obtain essentially identical results even though the data are not smoothed. Therefore, the total heat flux accuracy is essentially affected only by the bias uncertainty in the thermal properties.

Previously, aerodynamic heating measurement tests were conducted at the blowdown cold-type hypersonic wind tunnel at the Japan Aerospace Exploration Agency (JAXA) using a hypervelocity ballistic model HB-2 (Ref. 6). The schematic of the model is given in Fig. 2. A total of 21 chromel–constantan-type coaxial thermocouples were installed along the model surface in the axial direction. In an attempt to evaluate the data repeatability, a total of five repeat runs were conducted at the nominal reservoir pressure and temperature and Mach number of 2.5 MPa, 700C°, and 10, respectively. A detailed description of the wind-tunnel test is found in Ref. 7. Figure 3 shows the axial distribution of heat transfer coefficient for the five runs at zero angle of attack. The data are compared with respect not to the heat transfer rate but the heat transfer coefficient because the stagnation temperature of the tunnel slightly differs between each run. Note that the data are to a certain extent scattered in the low-heating region. Using these data, we can derive the random error (precision limit) for the heat transfer coefficient P as

$$P = tS \tag{5}$$

$$S^2 = \sum_{k=1}^{N} \frac{(h_k - \bar{h})^2}{(N-1)} \tag{6}$$

where t and $\bar{h}$ are the Student t value and mean value of h for a total of N data sets, respectively. The evaluated (measured) random error is then compared with values predicted from the present numerical analysis in Fig. 4. The predicted uncertainty in heat transfer coefficient was obtained from the heat flux random uncertainty curve in Fig. 1 by adding a component concerning the stagnation temperature uncertainty (approximately 0.75% in the present case). Considering that the predicted value indicates the maximum level of uncertainty with a 95% confidence limit, we can confirm that all of the measured values fall within the predicted range. Also the predicted value shows that more than 20% of uncertainty can be caused in the low-heating region and this is actually found in the experimental data. In other words, the present uncertainty analysis has verified that the data scattering observed in the wind-tunnel test is a type of expected measurement error.

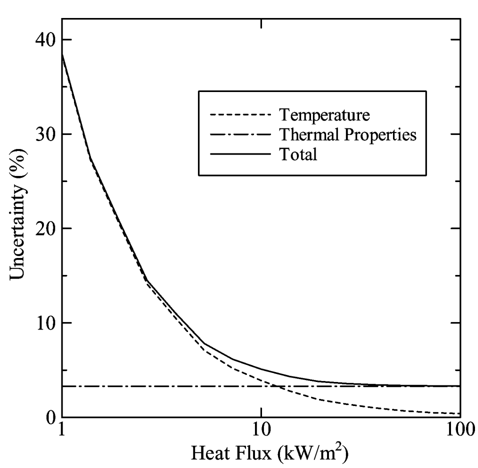

Fig. 1 Estimated heat flux errors vs heat flux level.

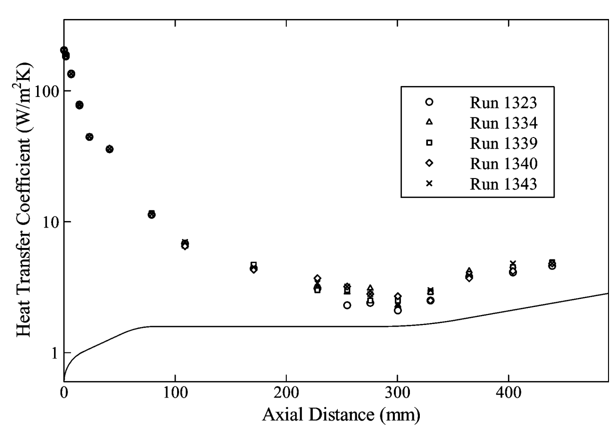

Fig. 3 Axial distribution of heat transfer coefficient obtained from JAXA 1.27-m hypersonic wind-tunnel test.

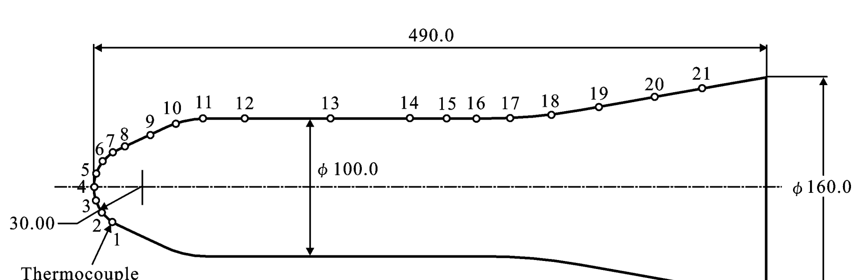

Fig. 2 HB-2-type standard model; dimensions in millimeters.

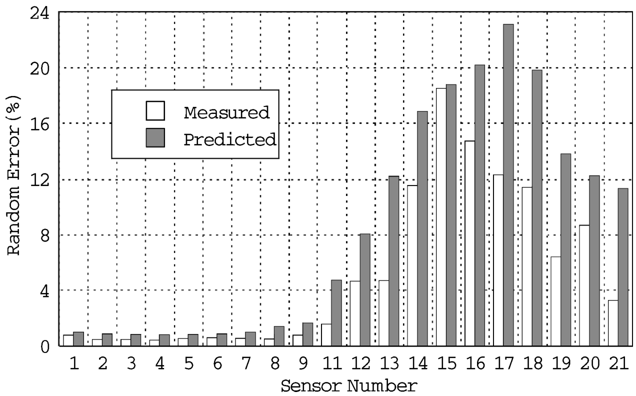

Fig. 4 Comparison of random error distribution evaluated from five repeat runs of wind-tunnel tests with predicted values.

Conclusions

An uncertainty analysis was performed for hypersonic aerodynamic heating measurements using a thermocouple. In the present approach, the random uncertainty derived from the temperature measurement noise was numerically evaluated by a Monte Carlo method and combined with the bias uncertainty associated with thermal properties of the thermocouple material to estimate the total uncertainty. The result indicated that up to 40% of uncertainty can occur due to the temperature measurement noise for the heating level of 1 kW/m^2, whereas the effect of uncertainty in thermal properties becomes dominant for the higher heating cases. The estimated random uncertainty was further compared with experimental data obtained from a hypersonic wind-tunnel test, showing that the stochastic technique reasonably predicts the level of uncertainty for a range of the surface heat flux. Thus, the present code is expected to serve as a numerical tool for pre/postevaluation of the accuracy of aerodynamic heating measurement tests using a thermocouple.

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