Correction of Thermocouple Conduction Error and its Sensitivity to Thermal Property Selection

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Introduction

The presence of a thermocouple in a low conductivity solid alters the heat flow through the solid and, as a result, the very temperature it is intended to sense is also disturbed. This disturbance is a well-established source of temperature measurement error. In previous works, the authors have developed correction techniques which incorporate error estimates from high fidelity computational thermocouple models. The techniques have previously been applied to the real world problem of metal casting/mold interfacial heat transfer analysis. In these previous works, computational models were used with constant thermal properties to generate the error estimates. In the current work, we evaluate the sensitivity of the corrected temperature histories to the thermal properties chosen for the computational model. A numerical experiment is presented here which yields a comparison between the actual metal/mold interfacial heat flux and the heat flux estimated with the combination of an inverse solver and the correction technique.

Correction Procedure

A technique for determining the undisturbed transient temperature is used to develop a kernel function which can be readily implemented into an inverse algorithm. This technique is based on methods originally reported by Beck[2] in which a mathematical formulation yields a correction equation:

$$T_{p\infty}(t) - T_p(t) = \int_0^t H(\lambda)\frac{\partial T_p(t-\lambda)}{\partial t}d\lambda$$

In this equation, T_p is the measured temperature, $T_{p\infty}$ is the undisturbed temperature, t is time, λ is a dummy time variable, and H is the correction equation. Using a computational thermocouple model with a constant heat flux, values for the correction equation can be determined by substituting the simulated measured and undisturbed temperatures and then inverting the equation to find H. These H values can then be used to estimate the error for any temperature measurements obtained from a system with a similar geometry.

Overview of Numerical Experiment

The experiment begins with a three-dimensional, high fidelity computational model of a thermocouple embedded in an aluminum sand casting mold. First, a simulation was performed using temperature dependent thermal properties for each component of the model and a prescribed heat flux. Simulated measured and undisturbed temperature histories were obtained from this simulation. Then two sets of values for the correction function were estimated using two sets of constant thermal properties, one set from a low temperature range and one from a high range. Both correction functions were used to correct the simulated measured temperature. These corrected temperatures were used to estimate the surface heat flux.

Computational Models

The computational model represents a thermocouple oriented perpendicular to a surface subjected to a heat flux. The system represented (Figure 1) here is a sand mold exposed to a heat flux from solidifying aluminum. The temperature is measured by Type K (chromel/alumel) thermocouples insulated by alumina oxide sheaths. The thermal properties for each component are shown in Figure 2 and Figure 3.

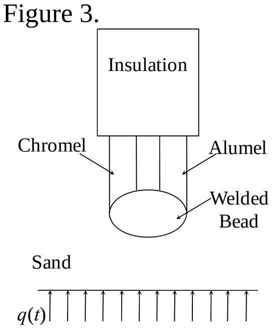

Figure 1. Model geometry.

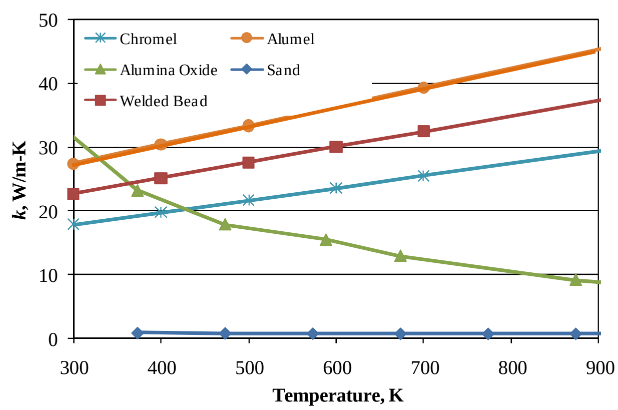

Figure 2. Temperature dependent conductivity values used in the computations.

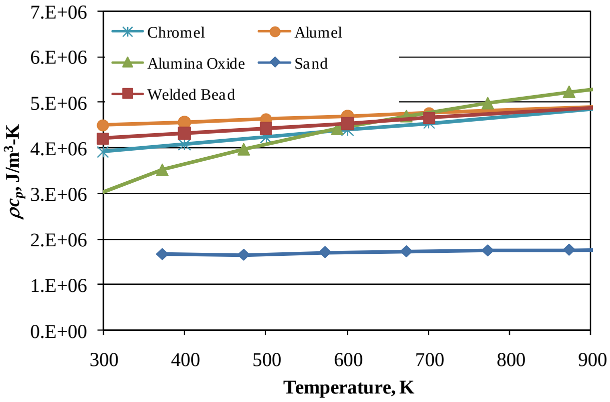

Figure 3. Temperature dependent ρc_p values used in the computations.

The constant property/constant heat flux cases were simulated with properties from a low temperature range of 300 to 373 K and from a high range of 673 to 700 K. The prescribed heat flux was taken from an actual sand casting experiment and is presented in the results section.

Results

Using temperature dependent thermal properties and a prescribed heat flux, a simulation was performed to generate the measured temperature, $T_{Measured}$, and exact values for the undisturbed temperature, $T_{Undisturbed}$, which would occur if the sensor was not present to disturb the thermal field. These temperature histories are presented in Figure 4 with the temperatures corrected using the low temperature range simulations, $T_{Correct\text{-}Lo}$, and the high range simulations, $T_{Correct\text{-}Hi}$.

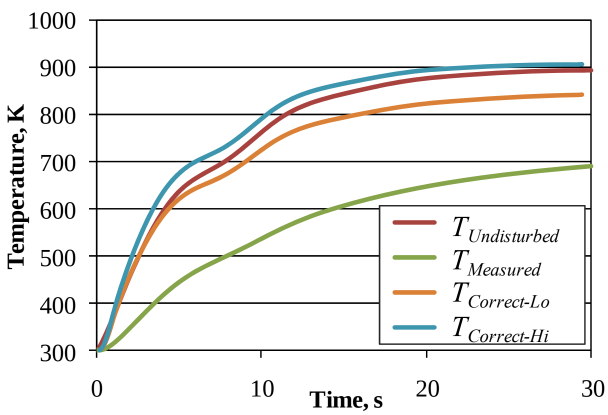

Figure 4. Undisturbed, measured and corrected temperatures.

The estimated heat fluxes were determined by Beck's sequential estimation procedure and are presented with the exact heat flux, q_{Exact}, in Figure 5. The heat fluxes are estimated using either a measured or corrected temperature history in combination with the estimated undisturbed temperature response from a constant heat flux simulation with either high or low range properties. The heat fluxes estimated from measured temperatures are denoted with a *Meas* subscript and those estimated from corrected temperatures are denoted by a *Cor* subscript. The heat fluxes estimated using the temperature response determined with high range properties are denoted with a *Hi* subscript while the *Lo* subscript denotes those determined with low range properties.

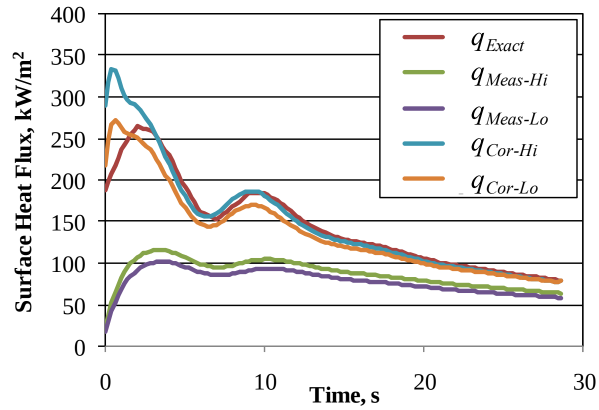

Figure 5. Exact and estimated surface heat fluxes.

Conclusions

This study demonstrates that enormous error can be present in heat fluxes estimated from thermocouple measurements. The correction method is shown to significantly mitigate the error which results from the heat flux estimates. However, it can be concluded that some improvement in the correction technique is necessary at early times/low temperatures to address the error which remains in the first three to five seconds. It can also be concluded that thermal properties should be chosen from an appropriate temperature range to yield the best results from the correction procedure.

Uncertainty in these error estimates should be included in a final analysis of the uncertainty and the uncertainty in the error estimate should be smaller than the estimated error itself. Estimating the heat fluxes from measured temperatures yielded a maximum percent error of approximately 90% while the heat fluxes estimated from the corrected values yielded a maximum percent error of around 60% for the high range properties and of less than 30% for the low range properties. The high range properties yielded much better results after the first three seconds, with the maximum percent error staying less than 6% for the remainder of the time domain considered.

References

[1] J.V. Beck, "Determination of Undisturbed Temperatures from Thermocouple Measurements using Correction Kernels", *Nuclear Engineering and Design*, vol. 7, 1968, pp. 9-12.