TEMPERATURE UNCERTAINTIES FOR BARE-BEAD AND ASPIRATED THERMOCOUPLE MEASUREMENTS IN FIRE ENVIRONMENTS

William M. Pitts, Emil Braun, Richard D. Peacock, Henri E. Mitler
Erik L. Johnsson, Paul A. Reneke, and Linda G. Blevins

Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8653

1. INTRODUCTION

Gas-phase temperature is the most ubiquitous measurement recorded in fire environments and plays a central role in understanding fire behavior. Generally, either bare-bead or sheathed thermocouples are employed. While it is recognized that such thermocouples are subject to significant systematic errors when used in fire environments, e.g., see [1], in most studies temperature uncertainties are not estimated or reported.

The work summarized here has been undertaken to characterize the uncertainties in temperature measurements which can occur when bare-bead thermocouples are used in fire environments and to assess the potential of two approaches--aspirated thermocouples and the use of multiple thermocouples having different diameters--to reduce the uncertainties.

2. THERMOCOUPLE RESPONSE EQUATIONS

Thermocouples are formed by joining two dissimilar metal wires. When a thermocouple junction is at a different temperature than the ends of the two wires, a potential voltage difference develops across the open ends. If the ends are held at a known temperature, the measured voltage can be related to the temperature of the junction. In general, the thermocouple junction temperature can be determined with a great deal of accuracy. The difficulty is that the junction temperature is not necessarily equal to the local surrounding gas temperature which is the quantity of interest. This point is discussed extensively in the literature. (e.g., [2] and [3]) For steady-state conditions, differences between the junction temperature and local surroundings can result from 1) radiative heating or cooling of the junction, 2) heat conduction along the wires, 3) catalytic heating of the junction due to radical recombination reactions at the surface, and 4) aerodynamic heating at high velocities. Radiative effects are particularly important in fire environments and will be the focus of much of what follows.

The final steady-state temperature achieved by a thermocouple junction in contact with a gas results from a balance between radiative and convective heat transfer to and from the junction. Using this balance, the difference between the absolute gas temperature (T_g) and the junction temperature (T_j) can be approximated as

$$T_g - T_j = \frac{\sigma\epsilon}{h_c}\left(T_j^4 - T_s^4\right), \tag{1}$$

where h_c is the convective heat transfer coefficient between the gas and junction, ϵ is the probe emissivity, σ is the Stefan-Boltzmann constant, and h_c is the convective heat transfer coefficient. T_s is the effective radiative temperature of the surroundings for the junction. Substitution of an appropriate heat transfer correlation (e.g., [4]) allows the following approximate equation to be written,

$$T_g - T_j \sim \frac{d^{0.55}}{U^{0.45}}\left(T_j^4 - T_s^4\right), \tag{2}$$

where d is the diameter of the thermocouple and U is the flow velocity over the probe. This expression demonstrates that the difference between a thermocouple reading and the actual gas temperature (i.e., the error in the gas temperature measurement) increases for larger diameter thermocouples, while it is reduced by increasing the gas flow velocity over the junction.

Equation (2) allows two common approaches for reducing the effects of radiation on thermocouple measurements of gas temperature to be understood. The first is to use an aspirated thermocouple in which the gas to be measured is pumped through a solid structure containing the thermocouple. The solid serves to radiatively shield

Joint Meeting. Combustion Institute. Proceedings. March 1999, Washington, DC, 508-511 pp, 1999 AND National Institute of Standards and Technology. Annual Conference on Fire Research: Book of Abstracts. November 2-5, 1998, Gaithersburg, MD, Beall, K. A., Editor, 15-16 pp, 1998, 1999.

the thermocouple from its surroundings. The shield is heated/cooled by radiation to a temperature which is intermediate between T_g and T_s and, due to the strong dependence of radiation on temperature, significantly reduces the effects of radiation at the junction. The gas flow over the shield and thermocouple increases convective heat transfer and brings both surfaces closer to the actual gas temperature. Equation (2) indicates the value of (T_g-T_j) becomes smaller as the aspiration velocity is increased. The second approach is to record temperatures with several thermocouples having different diameters and extrapolate the results to zero diameter.

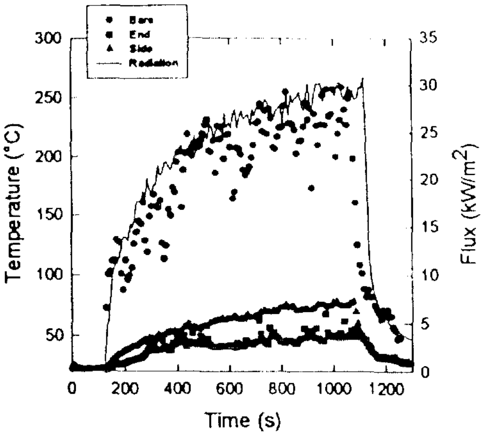

Figure 1. Temperatures measured in the lower layer of the enclosure doorway with end- and side- aspirated thermocouples and a 0.254 mm bare-bead thermocouple are shown for 400 kW natural-gas fires. Radiative flux was measured at the floor.

3. EXPERIMENTAL

Measurements using bare-bead thermocouples typical of those employed at NIST for fire tests, several types of aspirated thermocouples, and combinations of thermocouples having different diameters have been recorded at multiple locations in idealized enclosure fires, and the results have been compared. The tests were performed in a 40%-reduced-scale model (0.97 m × 0.97 m × 1.46 m) of a standard ASTM enclosure used for fire testing. [5] For the majority of fires, natural gas was burned on a 15.2-cm-diameter gas burner positioned at the center of the room near the floor. Nominal heat-release rates were chosen to generate conditions of fully ventilated burning (100 kW), near-stoichiometric burning (200 kW), and strongly underventilated burning (400 kW).

Two types of double-shielded aspirated probes based on a design described by Glawe et al. (designated as their "Probe 9") were constructed. [6] The outer shield had an inner diameter of 0.77 cm while the inner-shield diameter was 0.56 cm. A type K (alumel/chromel) bead thermocouple constructed from 0.51-mm-diameter wire was placed along the centerline within the inner shield. The difference between the two probes was the location of the opening (either on the end or side) through which the gas was aspirated. Pumps were used to draw gases through 0.32 cm^2 openings into the probes at volume flow rates of 18.9 L/min, based on room-temperature pumping. Aspirated gases were filtered and dried before passing through the pumps.

Limited measurements were made using an additional single-shielded aspirated thermocouple based on the design of Newman and Croce. [7] This is the most widely used type of aspirated thermocouple for fire measurements and is recommended for standard fire testing, for which it is claimed that temperature measurement errors are negligible. [8] Combinations of closely spaced bare-bead thermocouples having diameters of 0.127, 0.254, and 0.381 mm were also tested.

The response of various thermocouples were compared by repeating nominally identical fire tests while recording temperature measurements at ten locations including six heights (7.6, 22.9, 38.1, 53.3, 68.6, and 78.7 cm) above the floor along the centerline of the doorway and two heights (20 and 80 cm) above the floor in the front and rear of the enclosure (20 cm from end and side walls). Additional measurements included heat-release-rate by oxygen calorimetry and radiation flux by a Schmidt-Boelter probe positioned to look upwards from a location at the floor in the center of the doorway. Measurements were acquired with a computer-controlled data acquisition system which averaged the readings over a line cycle (1/60 s) and recorded data for a single sensor every 8 s. Times for individual fire tests varied from 900 to 1500 s.

4. RESULTS

Figure 1 compares temperature time records for 400 kW fires, recorded 22 cm above the floor in the doorway, for the two types of double-shielded aspirated thermocouples with the results for a 0.254-mm-diameter NIST bare-bead thermocouple. The radiative heat flux measured by the floor-mounted radiometer is also shown. The measurement position is in the lower layer of the doorway. The actual temperature at the measurement point is unknown, but is expected to be on the order of room temperature or ≈ 22 °C. Despite the low temperature, the radiative heat flux is relatively high due to the presence of hot gases and soot as well as heated walls in the upper regions of the enclosure. During the test, the bare-bead thermocouple recorded temperatures approaching a maximum of 250 °C and had a time dependence very similar to that for the radiant flux. For long times the error in the bare-bead temperature measurement due to radiation is on the order of 225 °C or roughly 70% in terms of absolute temperature.

The two aspirated thermocouples measured significantly reduced temperatures, but the temperature still increased with radiant flux. The two probes gave different results with the end-opening configuration approaching a maximum of 50 °C and the side-opening probe 75 °C, i.e. 25 °C and 50 °C above ambient, respectively. It is concluded that the use of the double-shielded aspirated thermocouples has reduced the error due to radiation by 80%-90% as compared to the bare-bead thermocouple. Evidently, aspirated-thermocouple effectiveness depends on the position of the aspiration opening.

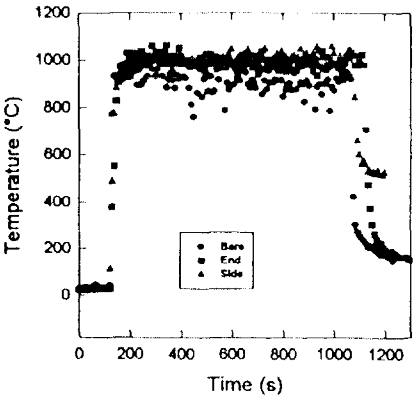

Figure 2. Temperatures recorded in the upper layer of the doorway with end- and side-aspirated thermocouples and a 0.254 mm bare-bead thermocouple are shown for 400 kW natural-gas fires.

Figure 2 compares responses for the two double-shielded aspirated and bare 0.25-mm-diameter thermocouples at a height of 68.6 cm above the floor in the doorway where the probes should be immersed in hot gas and radiate to cooler surroundings. It can be seen that the two aspirated probes measure similar temperatures which are somewhat higher than observed by the bare thermocouple. Averages taken over the 400 s - 1000 s time periods yield 988 °C, 1003 °C, and 902 °C for the end-aspirated, side-aspirated, and bare thermocouples, respectively, indicating that the bare thermocouple is reading at least 90 °C low due to the effects of radiation losses.

An example of results using multi-diameter bare-bead thermocouples is shown in Fig. 3 for measurements in the lower layer at the rear of the enclosure. For comparison purposes, temperatures recorded by an end-aspirated probe are also included. Several conclusions are immediately obvious. First, each of the bare-bead thermocouples is recording temperatures which are much higher (roughly 200 °C) than measured by the aspirated thermocouple. In this radiative environment it is expected that lower temperatures will be recorded by smaller diameter thermocouples. This trend is barely discernable in the data, being somewhat hidden by the time response of the thermocouples, which decreases with diameter.

5. DISCUSSION

The findings of this investigation demonstrate that instantaneous and time-averaged temperature measurements recorded in fire environments using bare-bead thermocouples can have significant systematic errors due to radiative heat transfer. In principle, it should be possible to correct for such uncertainties when sufficient knowledge of thermocouple properties and the environment are available. However, such properties as the local radiation environment, the local gas velocity and composition, and the thermocouple surface emissivity are difficult to measure, and, in practice, such correction does not appear to be currently feasible. Perhaps the best approach is for a researcher to estimate the various properties along with uncertainty ranges and use error propagation to derive the resulting uncertainty range for the measurement. It is the responsibility of the researcher to assess whether or not the resulting uncertainty limits meet the requirements of the experimental design.

The largest relative temperature errors are found for cool gases in the presence of strong radiation fields. Errors associated with measurements for a hot gas with the thermocouple radiating to cooler surroundings are significant, but relatively smaller.

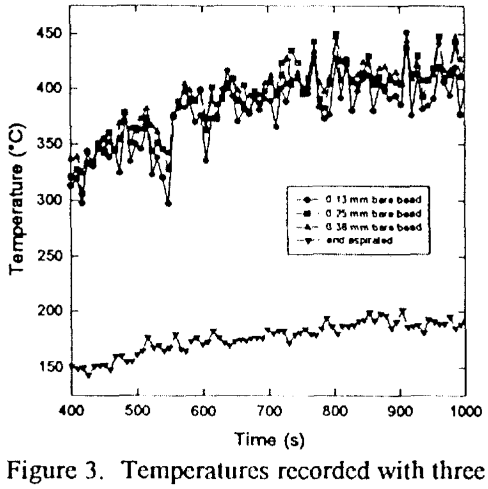

Figure 3. Temperatures recorded with three bare-bead thermocouples having indicated diameters and an end-aspirated probe are shown. The measurements are for the lower-layer location in the rear of the enclosure during 400 kW fires.

The use of aspirated thermocouples can significantly reduce temperature measurement error as compared to bare-bead thermocouples. However, it has been found that aspirated thermocouples are not 100% effective, and that significant differences between actual and measured temperatures can still be present. This finding contradicts the suggestion of Newman and Croce [7] and the assertion by the ASTM [8] that such uncertainties are insignificantly small. It should be mentioned that many researchers, e.g., see [9], have recommended that aspirated thermocouples be operated with the highest aspiration velocities possible (on the order of 100 m/s) as opposed to values of less than 10 m/s commonly recommended for fire tests. It is clear that the use of higher velocities should reduce the errors associated with aspirated thermocouple measurements in fire environments. It should be remembered that there are potential penalties associated with aspirated thermocouple use including increased volume and temporal averaging as well as the environmental perturbations associated with the high pumping speeds and large probe size.

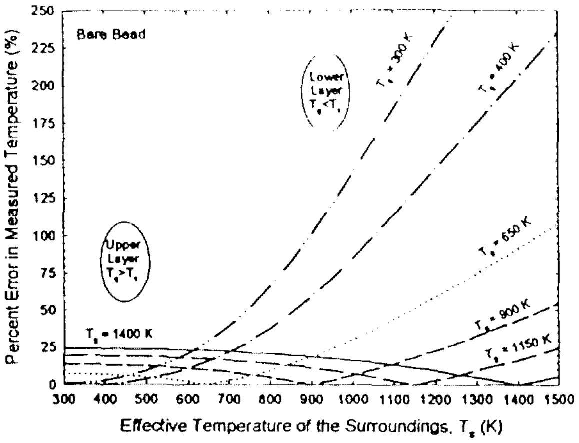

Figure 4. Calculated percentage errors in absolute temperature for an idealized 1.5-mm-diameter bare-bead thermocouple are shown as functions of gas temperature and effective surrounding temperature.

As part of this study, an idealized model of the relevant heat transfer processes for bare-bead and single- and double-shielded thermocouples in typical fire environments was developed. [10] Figure 5 shows calculated responses for a 1.5-mm-diameter bare-bead thermocouple. The behaviors are qualitatively similar to those observed experimentally with the largest relative errors predicted for cool gases in highly radiative environments. The calculations (results not shown here) show that for certain conditions aspirated-thermocouple measurements are subject to significant uncertainty and that double-shielded aspirated thermocouples are predicted to perform significantly better than single-shielded versions.

Based on the current results, it is concluded that extrapolation of temperature measurements to zero diameter for close groupings of bare-bead thermocouples having different diameters is not a viable approach for correcting thermocouple results in fire environments due to the strong temperature fluctuations present and the finite time response of the thermocouples. Techniques being developed for dynamic measurements of thermocouple time constants [11] combined with high speed data acquisition may allow future development of this approach.

The findings summarized briefly here are being prepared as a full internal report. [12]

6. REFERENCES

1. J. C. Jones, *J. Fire Sci.* **13** (1995) 261.
2. E. M. Moffatt, *Instruments* **22** (1949) 122.
3. R. J. Moffat, *Temperature: Its Measurement and Control in Science and Industry. Part 2.* (A. I. Dahl, ed.), Reinhold, New York (1962), pp. 553-571.
4. D. C. Collis and M. J. Williams, *J. Fluid Mech.* **6** (1959) 357.
5. N. P. Bryner, E. L. Johnsson, and W. M. Pitts, *Carbon Monoxide Production in Compartment Fire: Reduced-Scale Enclosure Facility*, **NISTIR-5568**, National Institute of Standards and Technology, 1994.
6. G. E. Glawe, F. S. Simmons, and T. M. Stickney, *Radiation and Recovery Corrections and Time Constants of Several Chromel-Alumel Thermocouple Probes in High-Temperature, High-Velocity Gas Streams*, **NACA-TN3766**, National Advisory Committee for Aeronautics, 1956.
7. J. S. Newman and P. A. Croce, *J. Fire Flamm.* **10** (1979) 326.
8. ASTM Standard E 603-95a, *1996 Annual Book of ASTM Standards*, **ASTM Publication Code 01-040796-10**, West Conshohocken, PA, 1995, p. 589.
9. T. Land and R. Barber, *Trans. Soc. Instru. Tech.* **6** (1954) 112.
10. Blevins, L. G., "Modeling of Thermocouple Behavior in Fires," *1998 Annual Conference on Fire Research*, Gaithersburg, MD, November, 1998.
11. M. Tagawa and Y. Ohta, *Combust. Flame* **109** (1997) 549.
12. W. M. Pitts, E. Braun, R. D. Peacock, H. E. Mitler, E. L. Johnsson, P. A. Reneke, and L. G. Blevins, *Thermocouple Measurement in a Fire Environment*, NIST Internal Report, to appear.