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Temperature Uncertainties for Bare-Bead and Aspirated Thermocouple Measurements in Fire Environments

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Abstract

Two common approaches for correcting thermocouple readings for radiative heat transfer are aspirated thermocouples and the use of multiple bare-bead thermocouples with varying diameters. In order to characterize the effectiveness of these approaches, two types of aspirated thermocouples and combinations of bare-bead thermocouples with different diameters were used to record temperatures at multiple locations during idealized enclosure fires, and the results were compared with measurements using typical bare-bead thermocouples.

The largest uncertainties were found for thermocouples located in relatively cool regions subject to high radiative fluxes. The aspirated thermocouples measured significantly lower temperatures in the cool regions than the bare-bead thermocouples, but the errors were only reduced by 80–90 %. A simple model for heat transfer processes in bare-bead and aspirated thermocouples successfully predicts the experimental trends.

The multiple bare-bead thermocouples could not be used for temperature correction because significant temperature fluctuations were present with time scales comparable to the response times of the thermocouples.

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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 fire studies uncertainties for temperature measurements are not estimated or reported.

The work summarized here has been undertaken to characterize the errors in temperature measurements that 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 these errors.

Thermocouple Response Equations

Thermocouples are made by joining two dissimilar metal wires to form a junction. When a thermocouple junction is at a different temperature than the opposite ends of the two wires, a potential voltage difference develops across the open ends. If the open 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 that is usually the quantity of interest. This point is discussed extensively in the literature. (e.g., see [*2*] and [*3*]) For steady-state conditions, differences between the junction and local surroundings temperatures can result from 1) radiative heating or cooling of the junction, 2) heat conduction along the wires connected to the junction, 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 all of the heat transfer processes adding energy to or removing energy from the junction. However, for analysis purposes it is typical to isolate those processes that are expected to be most dominant. Such an approach greatly simplifies the mathematical analysis. When considering the effects of radiative heat transfer on a thermocouple junction temperature it is typical to assume a steady state and only consider convective and radiative heat transfer processes. With these assumptions the difference between the gas temperature (T_g) and the junction temperature (T_j) can be approximated as

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

where h_c is the convective heat transfer coefficient between the gas and junction, ε is the probe emissivity, and Φ is the Stefan-Boltzmann constant. T_s is the effective temperature of the surroundings for the junction. Values of h_c are usually obtained from heat transfer correlations written in terms of the Nusselt number (Nu) defined as $h_c d/k$, where d is the wire diameter and k is the gas conductivity. Numerous correlations are available for Nu. A commonly used expression from Collis and Williams can be written as

$$Nu\left(\frac{T_m}{T_j}\right)^a = A + BRe^n = A + B\left(\frac{Ud}{\nu}\right)^n \qquad (2)$$

for small diameter wires. [*4*] T_m is the film temperature defined as the absolute value of $0.5(T_g\text{-}T_j)$, Re is the Reynolds number defined as indicated for local gas flow velocity, U, and kinematic viscosity,<, and a, A, B, and n are constants having values of -0.17, 0.24, 0.56, and 0.45, respectively.

Equation (2) is based on results for heat transfer to a cylinder in a cross flow. In the literature heat transfer correlations for spheres are sometimes used since practical thermocouple wires are typically joined at beads, with approximately spherical shapes, that are two to three times larger than the wires used to form the junction. However, it has been demonstrated that thermal conduction rapidly spreads heat along the wires such that the presence of the bead is a minor perturbation on the local temperature present at the junction. [*5,6*] The spherical approximation only becomes valid for much larger junction-to-wire diameter ratios. [*7*]

Substituting Eq. (2) into Eq. (1), neglecting the small temperature dependence in Eq. (2), and assuming that U is sufficiently large that A can be ignored allows Eq. (1) to be rewritten as

$$T_g - T_j \sim \frac{d^{0.55}}{U^{0.45}}\left(T_j^4 - T_s^4\right) \qquad (3)$$

which 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 (3) allows two common approaches for reducing the effects of radiation on thermocouple measurements of gas temperature to be understood. The first is the use of 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 the thermocouple from its surroundings. The shield is heated/cooled by radiation to a temperature that 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 (3) indicates that the absolute value of $(T_g\text{-}T_j)$ becomes smaller as the aspiration velocity is increased. In practice, pumping capability and/or aerodynamic heating limit the maximum velocities that can be employed for aspirated thermocouples. The second approach is to record temperatures with several thermocouples having different diameters and to extrapolate the results to zero diameter. Equation (3) shows that such an extrapolation should provide a good estimate for the actual gas temperature.

Thus far, the discussion has been in terms of steady-state heat transfer. The behavior is more complicated if the local gas temperature is changing since the convective heat transfer rate between a gas and thermocouple junction is finite. Most analyses of thermocouple time response only consider convective heat transfer and the thermal inertia of the thermocouple material. Other heat transfer processes such as radiation and conduction are assumed to be second order effects. With these and other assumptions, the time constant, ϑ, for the response of a thermocouple, can be written as

$$\tau = \frac{\rho_j C_j d}{4h_c}, \qquad (4)$$

where Δ_j is the density of the thermocouple material and C_j is the heat capacity. Using Eq. (2), it can be shown that ϑ should increase as $d^{1.55}$ and decrease with increasing gas velocity as $U^{0.45}$. The transient response of the thermocouple is written as

$$T_g - T_j = \tau \frac{dT_j}{dt}, \qquad (5)$$

where t is time. Significant instantaneous errors can occur when large gas temperature fluctuations occur on time scales less than or comparable to ϑ. Note that if values of ϑ are known, Eq. (5) offers a means to correct measured values of T_j for finite thermocouple time response.

Experimental

A practical approach for characterizing the errors associated with the use of thermocouples for gas measurements in fire environments has been adopted. 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 were recorded at multiple locations in a set of controlled and repeatable enclosure fires and the results compared. Note that a drawback of this approach is that the actual gas temperature can never be known with certainty.

The tests were performed in a 40 %-scale model (0.97 m × 0.97 m × 1.46 m) of a proposed standard ASTM enclosure for fire testing [*8*] , which is very similar to the ISO Fire Tests - Full-Scale Room Test for Surface Products (ISO 9705). The enclosure includes a single doorway (0.48 m wide × 0.81 m high) that was sized using ventilation scaling. [*9*] The enclosure includes a false floor, and, as a result, the base of the doorway is raised approximately 42 cm above the laboratory floor. The enclosure has been described in detail elsewhere. [*10*] Two fuels were employed. For the majority of fires natural gas was burned using a 15.2 cm diameter gas burner positioned at the center of the room near the floor. Nominal heat-release rates (based on fuel-flow rates) were chosen to generate conditions of fully ventilated burning (100 kW), near-stoichiometric burning (200 kW), and strongly under ventilated burning (400 kW). Natural gas burns fairly cleanly with little soot production. A heavily sooting fuel, liquid heptane, was also burned to assess the effects of varying soot levels on thermocouple measurements. The heptane fires grew naturally on a 21.7 cm diameter pool burner located near the floor at the center of the enclosure. Eventually they achieved flashover, reaching maximum heat-release rates on the order of 700 kW to 800 kW.

Temperature measurements for several types of thermocouples were compared. These included two types of double-shield aspirated probes based on a design described by Glawe et al. (designated as their "Probe 9"). [*11*] These probes were configured such that gas was aspirated over inside surfaces of both shields and the thermocouple. 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 through which the gas was aspirated. For the first, the opening was at the end of the outer shield, while in the second it was on the side. Pumps equipped with water and particle traps 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.

A group (referred to as Combination I) of bare-bead Type K thermocouples with different diameters, which were located close together (within 2 cm), were also tested. Commercial thermocouples formed from wires having diameters of 0.127 mm, 0.254 mm, and 0.381 mm with bead sizes two to three times the wire diameter were used. The length-to-diameter ratios for these thermocouples ranged from approximately 20 to 65. For mounting and connection purposes, the commercial thermocouples were spot welded to the appropriate 0.25 mm diameter leads of Type K commercial glass-insulated thermocouple wire. The exposed lengths of the 0.25 mm diameter wire were each approximately 4 mm. Two additional types of thermocouples, typical of those used during routine full-scale testing at NIST, were tested. These were formed by welding exposed 5 mm lengths of the 0.25 mm diameter alumel and chromel wires to form a bead (current practice, referred to as "NIST typical") or a cross (earlier practice).

Comparisons of the response for the above three types of thermocouples (two aspirated and Combination I) were made by repeating nominally identical fire tests while recording temperature measurements at ten locations using a given type. Reproducibility was assessed by repeated tests for each type. Measurement locations included six heights (7.6 cm, 22.9 cm, 38.1 cm, 53.3 cm, 68.6 cm, and 78.7 cm) above the floor along the centerline of the doorway and locations in the upper (80 cm above floor) and lower (24 cm above floor) layers in the front and rear of the enclosure (20 cm from end and side walls).

Limited measurements were also made using two additional temperature probes. The first was a single-shield aspirated thermocouple based on the design of Newman and Croce. [*12*] This is the most widely used type of aspirated thermocouple for fire testing and is recommended by the ASTM Standard Guide for Room Fire Experiments (E 603 – 98a). ASTM E 603 – 98a claims the approach allows "accurate temperature measurement based on the thermocouple voltage alone." The second was a group (referred to as Combination II) of commercial bare-bead thermocouples formed from wires having diameters of 0.025 mm, 0.051 mm, and 0.127 mm (length-to-diameter ratios ranging

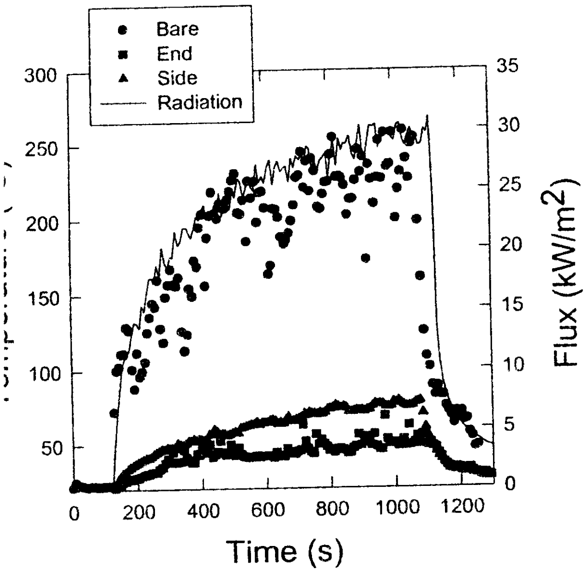

Fig. 1– *Temperatures measured in the lower layer of the enclosure doorway with end- and side-aspirated thermocouples and a 0.25 mm diameter bare-bead thermocouple are shown for 400 kW natural-gas fires. Radiative heat flux was measured at floor level.*

from 65 to 320) mounted like the Combination I probes. These probes were only tested at the two locations in the rear of the enclosure for the natural-gas fires.

Additional measurements made during the fire tests included heat-release-rate measurements by oxygen calorimetry, upper- and lower-layer doorway velocities (11 and 74 cm above the floor) by bidirectional probe, and radiative heat flux by a Schmidt-Boelter heat flux gauge positioned to look upwards at floor level in the center of the doorway. For the vast majority of fire tests, measurements were acquired with a computer-controlled data acquisition system that averaged the readings over a line cycle (1/60 s) and recorded data for a single sensor every 8 s. Total times for individual fire tests varied from 900 s to 1500 s. In experiments where the smallest ariable-diameter thermocouples were used, a separate PC-based data acquisition system llowed data to be recorded at either 7 Hz or 1000 Hz.

esults

Figure 1 compares temperature time records for 400 kW natural gas fires, ecorded 23 cm above the floor in the doorway, for the two types of double-shield aspi-ated thermocouples with the results for a NIST typical bare-bead thermocouple. The adiative heat flux measured by the floor-mounted radiometer is also shown. The emperature measurement position is in the lower layer of the doorway, where the bi-irectional probe indicates that air is flowing into the enclosure with a velocity on the rder of 1 m/s. The actual temperature at the measurement point is unknown, but is xpected to be on the order of room temperature or . 22 EC if the air entering the nclosure is not preheated before passing through the doorway. This temperature epresents a lower limit, but should be a good estimate since the air temperature rise ssociated with absorption of the imposed heat flux by water vapor, the only significant bsorber in ambient air, is estimated to be less than 1 EC [*13*], and the doorway is well removed from heated surfaces that could warm the incoming air.

Burning was observed along the interface between the upper and lower layers as well as in the plume exiting the doorway, which explains the temporally increasing radiative heat flux. Thus the measurement location is a relatively cool location subject to

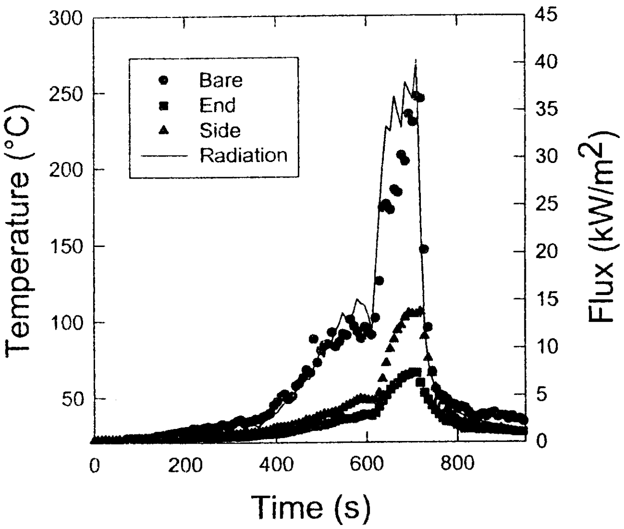

Fig. 2–*Temperatures recorded in the lower layer of the enclosure doorway with end- and side-aspirated and 0.254 mm bare-bead thermocouples are shown for heptane fires. Radiative heat flux was measured at floor level.*

a significant radiative heat flux. During the test, the bare-bead thermocouple recorded temperatures approaching a maximum of 250 EC 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 EC or roughly 75 % in terms of absolute temperature.

The two aspirated thermocouples measured significantly reduced temperatures as compared to the bare-bead thermocouple, but the temperature still increased with radiant heat flux. The two probes recorded different results, with the end-opening configuration approaching a maximum of 50 EC and the side-opening probe 75 EC, i.e. 25 EC and 50 EC above ambient, respectively. Assuming the air is actually at the ambient temperature, it is concluded that the use of the double-shield aspirated thermocouples has reduced the error due to radiation by 80 % to 90 % as compared to the bare-bead thermocouple. It is evident that the effectiveness of the aspirated thermocouples depends on the location of the opening, and the recorded temperatures cannot be error free. For this location the opening for the side-aspirated probe was facing into the doorway towards the fire and heated surfaces, while the end-aspirated probe faced the cool lower doorframe. This suggests that the different temperatures recorded by the two probes are due primarily to the limited view factors associated with the openings for the shielded thermocouples.

Figure 2 shows the corresponding results for heptane-fueled fires. The time bases have been shifted to match the heptane burnout times. Radiation fluxes are somewhat higher than for natural-gas fires due to the higher soot loading. The behaviors of the aspirated thermocouples are consistent with those found using natural gas.

Figure 3 compares the responses for the two types of double-shield aspirated and the bare 0.25 mm diameter thermocouples in the door way upper layer at a height of 68.6 cm above the floor for 400 kW natural-gas fires. At this location the probes should be immersed in hot gas and radiate to cooler surroundings. The figure indicates that the two aspirated probes measure similar temperatures that are somewhat higher than observed by the bare thermocouple. Averages taken over 400 s to 1000 s time periods yield 988 EC, 1003 EC, and 902 EC for the end-aspirated, side-aspirated, and bare thermocouples, respectively. These findings indicate that the bare thermocouple is reading at least 90 EC low due to the effects of radiative heat losses. This represents an absolute temperature error of approximately 7 %.

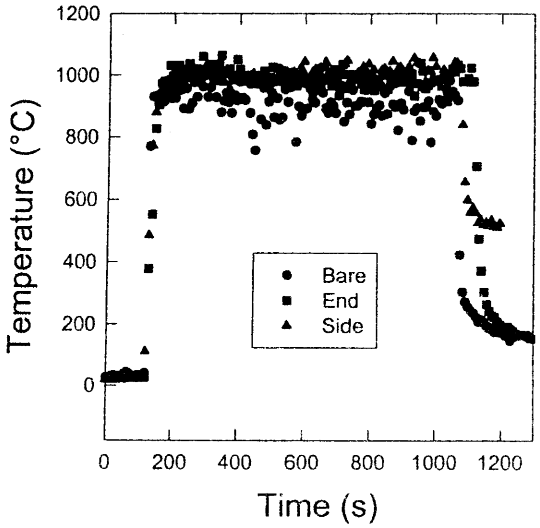

Fig. 3–*Temperatures recorded in the upper layer of the doorway with end- and side-aspirated thermocouples and a 0.254 mm bare-bead thermocouple are shown for 400 kW natural-gas fires.*

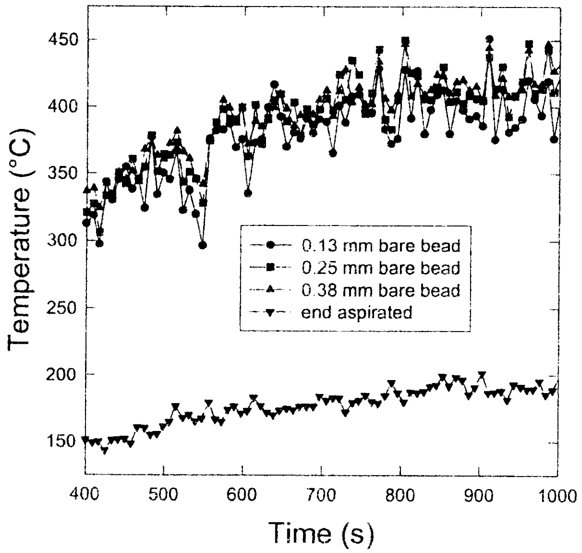

Fig. 4–*Temperatures recorded with three bare-bead thermocouples having the indicated diameters and an end-aspirated probe are shown. The measurements are for the lower-layer location in the rear of the enclosure during a 400 kW natural-gas fire.*

An example of results using the Combination I bare-bead thermocouples is shown in Fig. 4 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 that are much higher (roughly 200 EC) 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 differences in time responses for the thermocouples, which decrease with diameter, to temperature fluctuations.

Such convolution is more evident for data recorded with the set of smallest thermocouples. Figure 5 shows the results for data recorded at 8 Hz over a short time period in the rear of the upper layer for a 400 kW natural-gas fire. The temperature fluctuations are much larger than the variations in thermocouple response due to the use of different diameters and depend strongly on the thermocouple time constants. The presence of a diameter dependence for both the time response and radiation correction means that a simple correction for radiation is not feasible. It should be noted that the fluctuations evident in Fig. 5 are much larger than those measured with the larger thermocouples, indicating that the limited time response of thermocouples of a size typically used for fire testing can result in significant errors in instantaneous temperature.

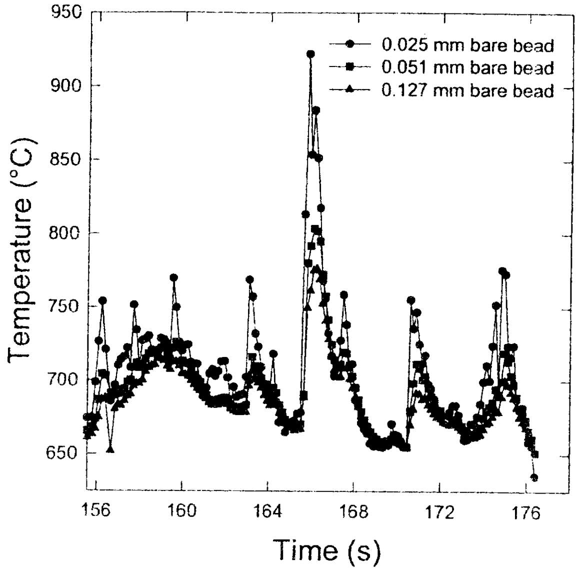

Fig. 5–*Simultaneous temperatures recorded in the rear of the upper layer of the enclosure using three small thermocouples are shown for a short period during a 400 kW natural-gas fire.*

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 both radiative heat transfer and finite time response. In principle, it should be possible to correct for such uncertainties when sufficient knowledge of thermocouple properties and the environment is available. However, such properties as the local radiative 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 feasible. Perhaps the best approach is for a researcher to estimate the various properties along with uncertainty ranges and use error propagation to estimate 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.

The use of aspirated thermocouples can significantly reduce temperature measurement errors due to radiative effects as compared to bare-bead thermocouples. However, it has been found in this study, and elsewhere, 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 [*12*] and the assertion in ASTM E 603- 98a that such uncertainties can be considered to be insignificantly small. It should be mentioned that many researchers, e.g., see [*14*], 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 will further 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.

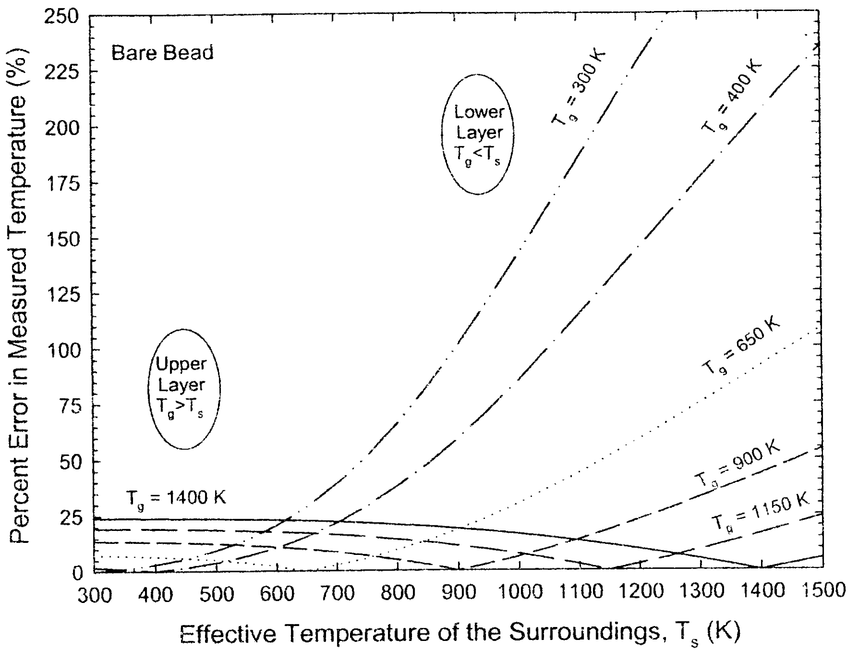

Fig. 6–*Calculated percentage errors for an idealized bare-bead thermocouple with 1.5 mm diameter bead are shown as functions of gas and effective surroundings temperatures.*

The lack of a strong dependence of thermocouple temperature on thermocouple wire diameter evident in Figs. 4 and 5 requires further comment. It is known that thermal conduction to the prongs supporting a thermocouple can change the temperature of the junction as well as its response time. Estimates of the required length-to-diameter ratio necessary to completely eliminate effects of conduction are generally on the order of 200. [*5,15*] For the small diameter Combination II thermocouples used for the data shown in Fig. 5, the length-to-diameter ratio ranges from 65 to 320. This suggest that while conduction may play some role, its effects on the both the time response and junction temperature should be relatively small. Thus the time variation of the relative ordering and magnitudes of the recorded temperatures for the different thermocouples shown in this figure must be due to a coupling of the different thermocouple time responses and the temporal temperature fluctuations present in the gas. Similar behaviors are evident for the larger diameter thermocouples shown in Fig. 4, but heat conduction to the 0.25 mm diameter wire supports may play a more complicated role since length-to-diameter ratios vary from 20 to 64 for the Combination I thermocouples. Such a coupling may partially explain the relatively small variations in measured temperature with thermocouple diameter. However, it is also clear that changes in time response are responsible for the temporal variations in relative temperature ordering for the three thermocouples.

As part of this study, idealized models for the relevant heat transfer processes for bare-bead and single- and double-shield thermocouples in typical fire environments have been developed as discussed in detail elsewhere. [*16,17*] Figure 6 shows calculated

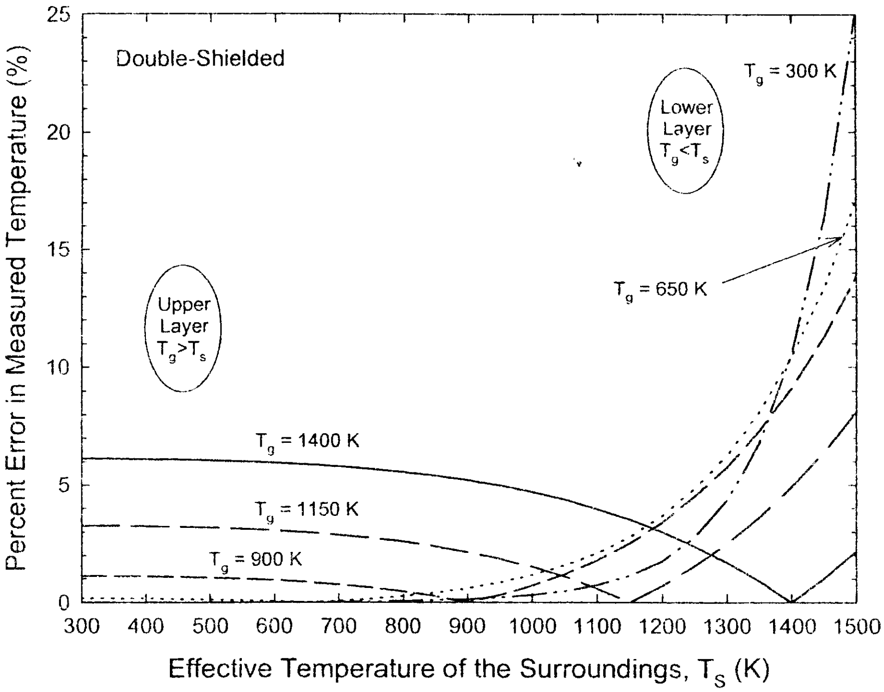

Fig. 7–*Calculated percentage errors for an idealized double-shield aspirated thermocouple are shown as functions of gas and effective surroundings temperatures.*

responses for a 1.5 mm diameter bare-bead thermocouple. The calculated behaviors are qualitatively similar to those observed experimentally. The largest relative errors occur for cool gases in highly radiative environments.

Similar results for a model of a double-shield aspirated thermocouple are shown in Fig. 7. Comparison with Fig. 6 indicates that for given gas and effective surroundings temperatures the calculated errors are reduced considerably for the aspirated probe. This is consistent with the current experimental results. Inspection of Fig. 7 also shows that the calculated percentage errors for the aspirated probe remain significant for conditions encountered in real fires. This conclusion is also consistent with current experimental findings.

Calculations were also carried out for a single-shield probe similar to that described by Newman and Croce. [*12*] The results of these calculations indicate that the double-shield probe is more effective at minimizing differences between actual and measured temperatures. These calculations provide additional evidence that contrary to the current recommendations of ASTM E 603 – 98a, significant temperature measurement errors may still be present for single-shield aspirated thermocouples.

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 temporal temperature fluctuations present and the variab finite time responses of the thermocouples. This conclusion is also at variance with the recommendations of ASTM E 603 – 98a. It is possible that techniques being developed for dynamic measurements of thermocouple time constants, e.g., see [*18*], combined with high-speed data acquisition might allow future development of this approach.

Summary

The current investigation has shown that, for conditions frequently present in enclosure fires, temperatures recorded with bare thermocouples have large errors due to the radiative environment. Errors in terms of absolute temperature as high as 75 % were observed in the lower layer and 7 % in the upper layer. The use of aspirated thermocouples reduces the error by 80 % to 90 %, but with the cost of increased complexity and reduced spatial and temporal resolution. The use of bare-bead thermocouples having different diameters as a means for correcting for radiative effects is not appropriate when implemented using typical fire measurement approaches. It is possible that this approach could be effectively used if more elaborate data acquisition and analysis approaches are employed.

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