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

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ABSTRACT

Temperature measurements have been made for natural-gas and heptane fires in a reduced-scale enclosure using a variety of bare-bead and aspirated thermocouples in order to characterize the uncertainties. The focus is the role of radiative heat transfer and the effects of finite time response on the measurements. The findings show that significant errors are possible for all thermocouples considered. Aspirated thermocouples reduce, but do not eliminate, such uncertainties. An alternate approach, use of several bare-bead thermocouples with extrapolation to zero diameter, is not easily implemented in the time-varying temperature environments characteristic of fires.

1. INTRODUCTION

Gas-phase temperature is the most ubiquitous measurement recorded in fire environments and plays a central role in understanding of 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 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 to form a junction. 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 generally 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 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 radiative and convective heat transfer to and from the junction. Using this balance, the difference between the 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 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 Williamson can be written as

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

for small diameter wires. [4] T_m is the film temperature defined as the absolute value of $0.5(T_g - T_j)$, Re is the Reynolds number defined as indicated for local gas flow velocity U and viscosity ν, and a, A, B, and n are constants having values of -0.17, 0.24, 0.56, and 0.45, respectively. Substituting Eq. (2) in 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

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

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.

Eq. (3) 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 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 (3) indicates the absolute value of (T_g-T_j) becomes smaller as the aspiration velocity is increased. In practice, pumping capability and/or aerodynamic heating limit the maximum velocities which can be employed for aspirated thermocouples. The second approach is to record temperatures with several thermocouples having different diameters and extrapolate the results to zero diameter. Eq. (3) shows that such an extrapolation should provide 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 due to the finite heat transfer rate between a gas and thermocouple junction. In this case it is necessary to consider the time constant, τ, for the response of the thermocouple which is written as

$$\tau = \frac{\rho_j C_j d}{4h_c} , \tag{4}$$

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

$$T_g - T_j = \tau \frac{dT_j}{dt} , \tag{5}$$

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

3. 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 typically 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 compared. Note that a drawback of this approach is that the actual temperature being measured can never be known with certainty.

The tests were performed in a 40%-reduced-scale enclosure (0.97 m × 0.97 m × 1.46 m) of a standard ASME enclosure used for fire testing. The enclosure includes a single doorway (0.48 m wide × 0.81 m high) which was sized using ventilation scaling. The enclosure has been described in detail elsewhere. [5] 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. 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 underventilated 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-I.D. 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 700-800 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"). [6] These probes were configured such that gas was aspirated over 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.

Combinations of bare-bead thermocouples, which were located close together, were also tested. These included three commercial thermocouples formed from wire having diameters of 0.127, 0.254, and 0.381 mm as well as two designs (bead and cross) of thermocouples which were made in-house at NIST by welding 0.254-mm-diameter alumel and chromel wires.

Comparisons of the response for the above three types of thermocouples (two aspirated and combination of bare-bead thermocouples) were made by repeating nominally identical fire tests while recording temperature measurements at ten locations using a given type of probe. Reproducibility was assessed by repeating each combination. Measurement locations included 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 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. [7] This is the most widely used type of aspirated thermocouple for fire testing and is recommended for standard fire testing, for which it is claimed that temperature measurement errors are negligible. [8] The second was a combination of commercial bare-bead thermocouples formed from wires having diameters of 0.025, 0.051, and 0.127 mm. These probes were only tested at the two locations in the rear of the enclosure for the three heat-release rates of 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 radiation flux by a Schmidt-Boelter probe positioned to look upwards at a location at the floor in the center of the doorway. For the vast majority of fire tests, 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. In experiments where the smallest variable-diameter thermocouples were used a separate PC-based data acquisition system allowed data to be recorded at either 7 Hz or 1000 Hz.

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-shield aspirated thermocouples with the results for a

NIST bare-bead thermocouple. The radiative flux measured by the floor-mounted radiometer is also shown. The measurement position is in the lower layer of the doorway where the bidirectional probe indicates that air is flowing into the enclosure with a velocity on the order of 1 m/s. The actual temperature at the measurement point is unknown, but is expected to be on the order of room temperature or ≈ 22 °C.

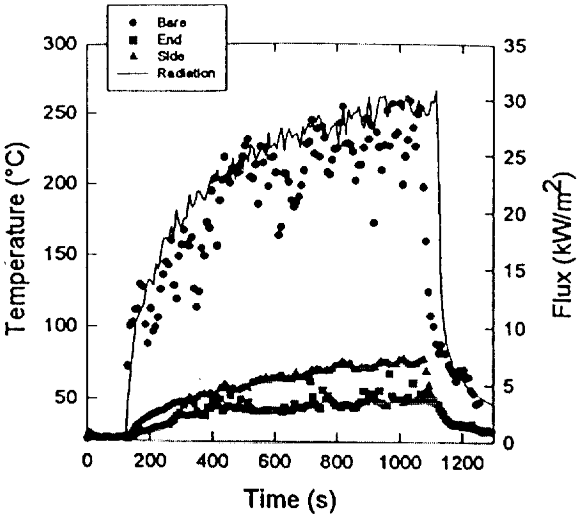

Figure 1. Temperatures measured in the lower layer of the enclosure doorway with end- and side-aspirated thermocouples and a 0.254 mm bare-bead thermocouple are shown for 400 kW natural-gas fires. Radiative flux was measured at the floor.

Burning was observed along the interface between the upper layer as well as in the plume exiting the doorway which explains the temporally increasing radiative flux. Thus the measurement location is a relatively cool location subject to a significant radiative flux. 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. 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%-90% as compared to the bare-bead thermocouple. It is evident that the effectiveness of the aspirated-thermocouple depends on the location of the opening.

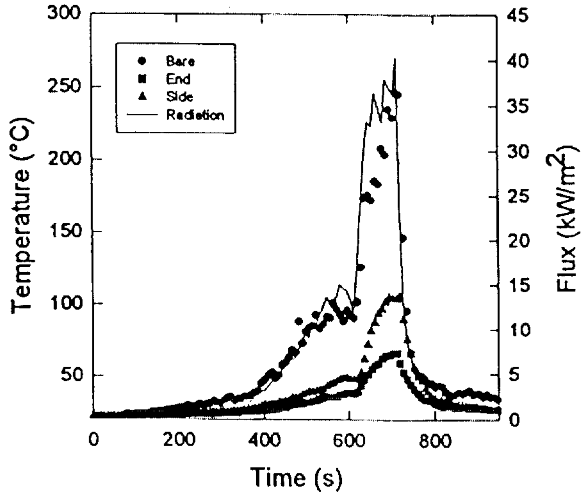

Figure 2. Temperatures measured in the lower layer of the enclosure doorway with end- and side-aspirated thermocouples and a 0.254 mm bare-bead thermocouple are shown for heptane fires. Radiative flux was measured at the floor.

Figure 2 shows the corresponding results for heptane 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 behavior of the aspirated thermocouples are consistent with those found when natural gas was the fuel.

Figure 3 compares the response of the two types of double-shield aspirated and the bare 0.25-mm-diameter thermocouples in the doorway 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 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. These findings indicate that the bare thermocouple is reading at least 90 °C low due to the effects of radiation losses.

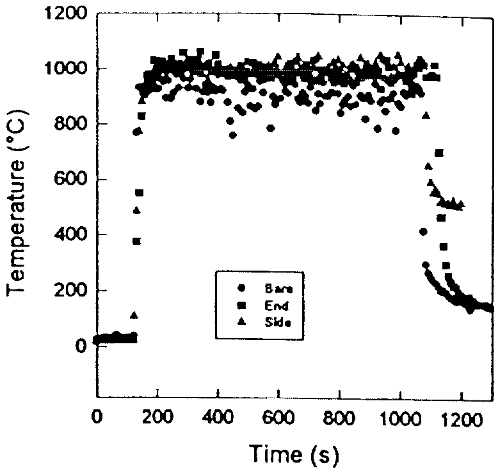

Figure 3. Temperatures recorded in the lower layer of the doorway with end- and side-aspirated thermocouples and a 0.254 mm bare-bead thermocouple are shown for 400 kW natural-gas fires.

An example of results using multi-diameter 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 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.

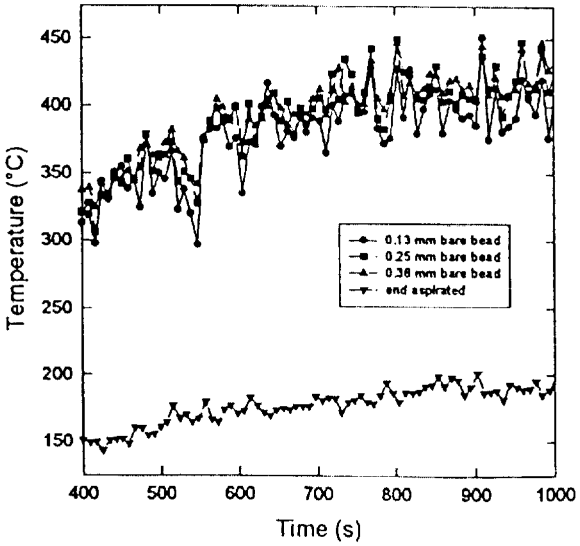

Figure 4. Temperatures recorded with three bare-bead thermocouples having indicated diameters and an end-aspirated probe are shown. The measurements are for the lower-layer location in the rear of the enclosure during a 400 kW fire.

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 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 multiple diameters and depend strongly on the time constants for the thermocouples. 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 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.

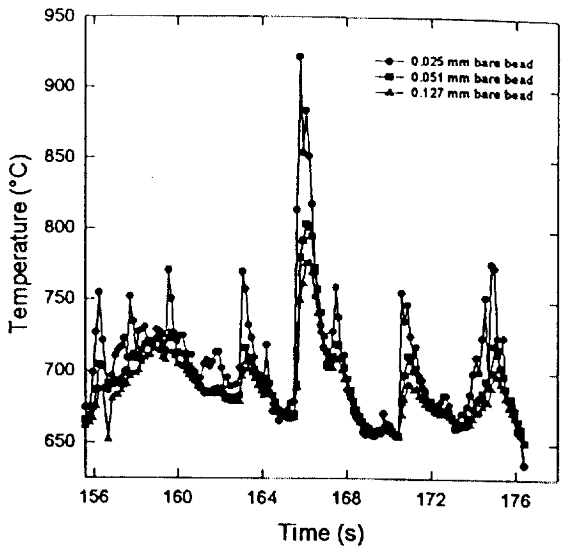

Figure 5. Temperatures recorded in the rear upper layer of the enclosure simultaneously using three small thermocouples are shown for a short period during a 400 kW natural-gas fire.

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 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 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 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 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.

As part of this study, an idealized model of the relevant heat transfer processes for bare-bead and single- and double-shield thermocouples in typical fire environments has been developed. Figure

6 shows calculated responses for a 1-mm-diameter bare-bead thermocouple. The calculated behaviors are qualitatively similar to those observed experimentally. The largest calculated relative errors occur 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-shield aspirated thermocouples are predicted to perform significantly better than single-shield versions.

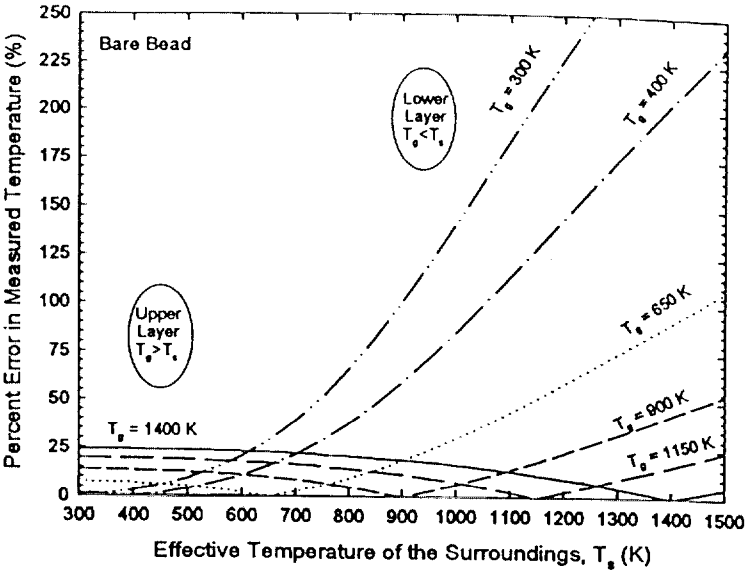

Figure 6. Calculated percentage errors for an idealized 1.5-mm-diameter bare-bead thermocouple are shown as functions of gas temperature and effective surrounding temperature.

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. It is possible that techniques being developed for dynamic measurements of thermocouple time constants [10] combined with high speed data acquisition might allow future development of this approach.

The findings summarized briefly here are being prepared as a full internal report. [11]

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