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A REVIEW OF ERROR ASSOCIATED WITH THERMOCOUPLE TEMPERATURE MEASUREMENT IN FIRE ENVIRONMENTS

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1. INTRODUCTION

Temperature has been used extensively to characterize wildland fire behavior, intensity, and effects. The thermocouple has become one of the most used instruments to measure this quantity. Although the devices are inexpensive, convenient and easy to use, there can be significant errors associated in temperature measurements when used in fire environments. If these errors are acknowledged and sensors are designed and used judiciously, the temperature measurement can be estimated with much greater accuracy. This paper briefly explains the physics behind thermocouples and some of the errors associated with their use.

2. HOW THERMOCOUPLES WORK

Thermocouples are a temperature measurement device that takes advantage of a phenomenon known as the Seebeck effect. An electrical potential is created when two ends of a wire are at different temperatures. This potential is characterized by a coefficient known as the Seebeck coefficient with units of microvolts per Kelvin. Contrary to popular belief, the emf is not created at the junction of the two wires; it is a product of the two single thermoelements or wires.

When two wires of different composition are welded or joined at two ends and the properties of the two metals are known (namely the Seebeck coefficients), the temperature can be derived from the voltage traveling through the circuit. Metals or alloys with Seebeck coefficients that differ greatly and are opposite in "direction" (one positive, one negative) make good thermocouples. For example, a type K thermocouple is composed of a positive Chromel[1] (Nickel-Chromium alloy) thermoelement and a negative Alumel[1] (Nickel-Aluminum and Silicon alloy) thermoelement which have a Seebeck coefficient of 21.8 μVK^{-1} and –17.7 μVK^{-1} at 0°C, respectively. Thus the thermocouple has a net Seebeck coefficient of 39.5 μVK^{-1} (Bentley 1998). This coefficient is not constant with temperature and can vary significantly depending on the type of thermocouple. The potential created is a function of the temperature at both ends of the wire(s). Although the signal is very small in magnitude, it can be measured with a good potentiometer. Applying a calibration to the signal gives the temperature of the sensor. Standard thermocouple calibrations assume that the second junction or cold junction is kept at 0°C. If the temperature of the cold junction is not 0°C but it is known, the signal can be compensated to correct for this error.

3. ERRORS

Most errors associated with the use of thermocouples are due to the fact that the temperature of the sensor may not be the temperature of the surrounding medium. Energy can be transferred to and from the bead of the thermocouple by radiation, convection and conduction. Unfortunately, when placed in the high intensity environments characteristic of fires, thermocouples can produce sensed temperatures significantly different than the actual temperature of the medium of interest (Jones, 1995, Shaddix 1998). These errors can be attributed to variations in the rate of energy transfer to and from the TC bead, temperature variations along the lead wires, and catalytic reactions between the metals comprising the bead at the surrounding gases-however for fires burning in woody fuels this is generally negligible for type K and R thermocouples.

When measuring rapidly fluctuating air temperatures the thermocouple will lag with respect to the changes in the air temperature. This lag is due to the time required to transfer energy to the center of the thermocouple bead when being heated and from the center to the outside surface of the bead when being cooled. The effect is that the thermocouple smoothes the fluctuations in the air temperature. The greater the mass of the thermocouple the greater the lag time between the thermocouple and actual fluid temperature.

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[1] Trademark of the Hoskins Manufacturing Company

When it is necessary to accurately measure the fluctuations in temperature, methods must be used that compensate for the time lag between the thermocouple and medium of interest. While not simple, electronic compensating circuits have been presented to address this issue (Ballantyne and Moss 1977; Lenz and Gunther 1980; Son 1988).

A second factor affecting the accuracy of thermocouple measurements is the relative magnitude of radiational heating or cooling versus convective heating of the bead surface. Knowledge of these mechanisms is not new, but their existence is often overlooked or assumed negligible. The result can be large errors in gas temperature measurements made in or near flames.

A simple method of accounting for the measurement error due to both thermal lag and radiational heating involves the use of progressively smaller diameter thermocouples (Walker and Stocks 1968). Using this method it is possible to deduce the true gas temperature by extrapolating simultaneous measurements from progressively smaller beads to an infinitely small bead. This method can provide a relatively accurate measurement of the air temperature; however, it requires that all temperature locations be sampled simultaneously with an array of thermocouples of decreasing size. Others have used radiation shields to reduce radiational heating or cooling. This method consists of placing the thermocouple bead inside a set of cylindrical annuli and then subjecting one end of the shield to a vacuum to increase convective energy transfer between the bead and gas.

Often the temperature sensor on portable weather stations is of the shielded variety. Martin and others (1969) provide a brief problem analysis of the error due to radiative heating or cooling of a thermocouple bead. They compare measurements from shielded-aspirated thermocouples against those from non-shielded, non-aspirated thermocouples. Their measurements were made in a flame burning in a crib of white fir sticks. Their data show that the non-shielded, non-aspirated thermocouple measurements are approximately 300°C less than those from the shielded-aspirated thermocouples. A shielded aspirated thermocouple design was recommended. Newman and Croce (1979) present a simple, economical and effective design for a single wall shielded-aspirated thermocouple. Shielded-aspirated thermocouples can provide accurate temperature measurements, but the necessary pumps and piping make it difficult to use such instruments in field experiments. Nevertheless, others have reported success with shielded-aspirated thermocouples in wildland fires.

4. DISCUSSION

Due to its low cost, ruggedness and ease of use the thermocouple will continue to be used as a primary instrument for characterizing temperatures in fire environments. The application can be divided into two cases, 1) measurement of solid material temperatures (e.g. soil temperature); and 2) the measurement of gas temperatures.

For the first case, the sources of measurement error can be attributed to temperature variations along the TC leads. This measurement error can be reduced by taking care to place the leads along the expected natural isotherms within the system.

For the second case the sources of error are more varied but are most often due to radiational cooling or heating (Shaddix 1998). When the TC measures gas temperatures outside a flame, the sensor can be heated due to radiant energy transfer from a nearby flame. This will result in artificially high gas temperatures. In applications where the TC is in a flame, it may be subject to radiational cooling due to energy loss to cool surroundings if the flame is relatively thin. A mathematical model based on an energy balance on a thermocouple bead is shown below.

$$\{\varepsilon_{flame}\sigma T^4_{flame} - \varepsilon_{bead}\sigma T^4_{bead}\}F_{flame\text{-}bead} - \{\varepsilon_{bead}\sigma T^4_{bead} - \varepsilon_{\infty}\sigma T^4_{\infty}\}(1 - F_{bead}) = hA_{bead}(T_{air} - T_{bead})$$

where: ε is emissivity σ is the Stefan-Boltzman constant (~ 5.669 x 10^{-8} W-m^{-2} -K^{-4}), F is the view factor, h is the convective heat transfer coefficient (W-m^{-2}-K^{-1}), and T is temperature (K). Shaddix (1998) presents a solution of this equation and a procedure for estimating the error associated with a given measurement situation.

4.1 Radiation

Radiant heat transfer from the temperature sensor to it's surroundings can be a large source of error. The law governing radiation from an emitter is the Stefan-Boltzman law defined as:

$$q_{rad} = \varepsilon\sigma T^4$$

where ε is the emissivity of the object and σ is the Stefan-Boltzman constant (~ 5.669 x 10^{-8} W-m^{-2} -K^{-4}). Since radiation is proportional to T^4, it is obvious that at high temperatures a thermocouple bead could be radiating much more energy that it is receiving. This is especially true when the surrounding environment is at a much lower temperature and not emitting radiation to the bead, which is common in fire environments. To compound the problem, a large radiant energy source is present as well. When the flame is in close proximity to the sensor it radiates energy that may increase the temperature of the bead significantly over that of the gas surrounding the sensor.

4.2 Convection

Energy is transferred to the surface of the bead from the gas flowing around it by convection. This mode of heat transfer is more efficient when the fluid has a high velocity and is the basis for aspirated thermocouples. The relative contributions of radiant and convective energy transfer to the thermocouple measurement vary with the application.

4.3 Conduction

For bare-bead thermocouples, larger beads have a higher thermal inertia. This means more energy is required to heat the bead to the temperature of the gas. A time lag is introduced due to the thermal inertia and a larger bead has a larger time lag. Ballantyne and Moss (1977) address this error and provide a digital correction for the problem. Energy can also be conducted away from the bead down the leads of the thermocouple. A simple solution is to place the leads on an expected isotherm.

5. CONCLUSION

It can easily be shown that thermocouple temperature measurement in fire environments is fraught with many potential errors. However, the magnitude of these errors can be reduced by simply taking several relatively simple steps. 1) use as small a thermocouple bead as is possible. 2) use new shiny thermocouples whenever possible, the low emissivity will minimize radiational heating. Position thermocouple leads along isotherms whenever possible.

Measurements show that significant errors can occur when measuring temperatures in near or within wildland flames with thermocouples larger than 0.13 mm. While the use of a shielded-aspirated thermocouple reduces the error in the average trace, it prevents knowledge of the maximum temperatures. Highest accuracy is attained when using small diameter shielded-aspirated thermocouples. However given the difficulty of deploying the necessary equipment that accompanies aspirated thermocouples in the field, a significant increase in accuracy can be attained through the use of small diameter non-shielded, non-aspirated thermocouples. While errors in maximum temperature can be as high as 200°C, the error in an averaged temperature-time trace will be minimized.

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7. ACKNOWLEDGMENTS

This work was funded by the USDA Forest Service, Rocky Mountain Research Station, Fire Behavior Research Work Unit; USDA Forest Service in Missoula, Montana.