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Temperature measurement techniques for spray foam applications

C.J. Banister *, T.V. Moore, D.W. Van Reenen

Construction Portfolio, National Research Council Canada, 1200 Montreal Road, Ottawa, ON K1K 4R7, Canada

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ABSTRACT

Experiments were conducted to investigate the accuracy of thermocouple configurations in measuring temperatures within spray foam insulation products during application. Measurements of this kind are important for assessing products from the standpoint of thermal performance and safety. The response times of heating and cooling in air were first analyzed for several thermocouple configurations. The second phase of the investigation consisted of instrumenting five 2″ × 6″ wood frame cavities sheathed with a 2′ by 2′ piece of oriented strand board.

A method is presented for instrumenting specimens in a way that is minimally thermally invasive, which leads to temperature results that can be trusted as highly accurate. The thermocouple type recommended for this application is insulated Type K 36 gauge, joined via welding. Larger wire gauges result in significantly underestimated temperatures, by as much as 30 °C. In combination with thermocouple types with higher thermal conductivity of wires, this underestimation can reach as much as 60 °C. The potential inaccuracies are particularly pronounced due to the low thermal mass and low thermal conductivity of spray foam insulation.

1. Introduction

This study was conducted to determine the appropriate thermocouple type and instrumentation technique for measuring peak temperatures of spray foam during application. The results of this study inform on and provide evidence for requirements regarding the maximum allowable temperatures in spray foam. Measuring temperature in spray foam during application is challenging because of non-uniformities, which arise due to such factors as: pattern of application, human input, chemical reaction, and the formation of small air pockets. The temperature reached by spray foam during application is important because it impacts thermal performance and excessive temperatures can cause auto-ignition of the material, leading to a building fire.

The Zeroth Law of Thermodynamics states that if two bodies are both in thermal equilibrium with a third body, then they are in equilibrium with each other [1]. This makes temperature measurement possible by enabling the creation of temperature scales, which can be used as a common reference for comparison. The Zeroth Law likewise enables the calibration of a thermocouple (TC) against a reference resistance temperature device (RTD). In order to accurately measure temperature at a location of a medium, one must have a calibrated temperature sensor and ensure thermal equilibrium is reached between the medium and the probe.

In addition, one must ensure that errors are not introduced due to unintended and undesirable heat transfer. Care must be taken to ensure appropriate temperature probe selection, preparation, and placement, along with radiation shielding for cases where radiative exchange with the probe would give an undesired reading. In many cases, heat transfer along the temperature sensing device can cause problems in accuracy [2]. Use of thermocouples to measure temperature accurately requires careful attention to how they are applied.

Errors in temperature measurement caused by heat transfer and other physical effects at the sensing, or probe, end of the system, have been observed and investigated plentifully. However, a majority of the work involves surface temperature measurements and does not take into account exothermic chemical reactions, or irregular temperature distributions throughout the solid aside from the areas disturbed by an invasive conductor.

An analytical approach was developed by Hennecke and Sparrow which addressed the general problem of a wire or cylindrical conductor attached to a semi-infinite solid cooled by convection [3]. In this work, it is noted that the dimensionless temperature distribution depends only on the Biot number, which is defined as:

$$Bi = \frac{hr_0}{k} \tag{1}$$

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* Corresponding author.
E-mail address: carsen.banister@nrc.ca (C.J. Banister).

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Nomenclature

Bi	Biot number
h	heat transfer coefficient
k	thermal conductivity
r_0	effective probe radius
t_{start}	the timestamp before the first change in temperature more significant than random fluctuations
T_{start}	the temperature recorded by the thermocouple at the time t_{start}
T_{final}	the maximum temperature measured by the thermocouple in the oven for heating, or minimum temperature measured by the thermocouple at room temperature for cooling

where h is the heat transfer coefficient away from the wire, r_0 is the effective radius of the probe, and k is the conductivity of the solid. The solution to the temperature field shows that for larger Biot number, the magnitude and distance of the disturbance is greater. In addition, the definition of the Biot number shows that the impact of the disturbance is increased for reduced thermal conductivity of the bulk solid, as insulation is intended to have a low conductivity by definition.

Thomas et al. demonstrated that the temperature measurement error increases with increasing absolute temperature of the medium being measured. For their case of a thin plate and a cylindrical rod taken to be a thermocouple wire, the solution shows that the error is proportional to the absolute temperature to the power of 5/2 [4].

Burnett investigated the effect of the error for transient surface temperature measurements of heated slabs and developed a method for estimating the error on the unheated side of the slab [5]. Beck also investigated the measurement error for a transient case, which considered a thermocouple embedded in a material of low thermal conductivity [6].

Xu and Gadala used finite element analysis to investigate the accuracy of thermocouple temperature measurements for the cooling of steel plates and found that modelled temperature measurements with a thermocouple introduced could be as much as 60 °C lower than the modelled case without a thermocouple [7].

The motivation for this work arose out of inconsistencies observed in initial temperature measurements of spray foam insulation during application, depending on type and configuration of thermocouple used. The thermocouple type, gauge, junction style, sheathing, and placement within the foam were studied in order to minimize thermal invasiveness and account for temperature variability throughout the foam. Due to suitable temperature ranges and availability, Type T and Type K thermocouples were considered in this study. The options investigated are listed in Table 1 below.

2. Materials and methods

This investigation consisted of evaluating thermocouple variations through two sets of tests. The first set of tests was conducted to give an indication of variation in thermocouple response time for several configurations of thermocouples. This was completed in an oven set to 200 °C, the maximum anticipated temperature to be measured during a spray foam application. The second method was used to evaluate the various thermocouple configurations in a conventional spray foam application. The thermocouple configurations were calibrated via comparison to an RTD in a glycol bath. Each thermocouple type was tested in a 200 °C oven to assess performance prior to use in a conventional spray foam application.

Table 1
Summary of thermocouple options investigated.

Variable	Options compared
Thermocouple type	Type T, Type K
Thermocouple gauge	24 AWG, 36 AWG
Thermocouple junction	Twisted, Soldered, Welded

The thermocouple variations considered in this evaluation are:

- insulated Type T 36 gauge, welded junction;
- insulated Type K 36 gauge, welded junction;
- insulated Type T 24 gauge, both welded and soldered junction;
- insulated Type K 24 gauge, welded junction;
- uninsulated (bare) Type T 24 gauge, welded junction; and
- uninsulated Type K 24 gauge, welded junction;

The accuracy of the thermocouples in measuring steady state temperatures was verified. All thermocouples were immersed in a bath at temperatures of nominally 10, 25, and 40 °C and the results were compared with a calibrated temperature sensor, a Guildline 9540 PRTD (platinum resistance temperature device) sensor. All of the thermocouples were shown to be within 0.5 °C of the calibrated RTD.

2.1. Thermocouple response comparison

The response time of various thermocouple configurations to a step change in air temperature was examined. This was a preliminary test to quantify the response of the thermocouples. Two different types, K and T, were tested in various configurations. These thermocouple types were selected because they are two of the most common types and Type K, in particular, has two metals of relatively low conductivity (compared to Type T), which are expected to reduce thermal invasiveness [2]. The impact of the following variables on response time was examined:

- Thermocouple Type (T and K).
- Thermocouple Gauge (24 AWG and 36 AWG).
- Thermocouple Junction Type – Soldered (for Type T), Twisted, and Welded.
- Thermocouple Insulation – Sheathed and Bare Wire.

The test consisted of inserting a thermocouple at room temperature into an oven at 200 °C and monitoring the response to the step temperature change. The step response of the thermocouple to the temperature change resulting from removal from the oven back into room temperature was also examined.

In order to determine the effects of the variables listed above, a series of tests was conducted. A list of the tests completed is shown in Table 2.

2.1.1. Test description

A data acquisition system was used to monitor and record the temperatures of the thermocouples at a frequency of 1 Hz. The data acquisition system that was used in the study was a Campbell Scientific CR 3000 Micrologger. It was used with two