Experimental Thermal and Fluid Science 65 (2015) 82–89

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Optimized thermoelectric sensitivity measurement for differential thermometry with thermopiles

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ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form 30 January 2015
Accepted 31 January 2015
Available online 12 March 2015

Keywords:
Thermopile calibration
Thermoelectric sensitivity measurement
Seebeck coefficient measurement
Seebeck effect
Differential thermometer
Calibration uncertainty analysis
High-precision heat flux modulation measurement

ABSTRACT

A novel approach to calibrate the sensitivity of a differential thermometer, consisting of several thermocouples connected in series (thermopile), has been developed. The goal of this method is to increase the accuracy of small temperature difference measurements ($\Delta T \leqslant 1$ K), without invoking higher sensor complexity. To this end, a method to determine the optimal temperature difference employed during the differential measurement of thermoelectric sensitivities has been developed. This calibration temperature difference is found at the minimum of combined measurement and linearization error for a given mean temperature. The developed procedure is demonstrated in an illustrative example calibration of a nine-junction thermopile. For mean temperatures between -10 °C and +15 °C, the thermoelectric sensitivity was measured with an uncertainty of less than ±2%. Subsequently, temperature differences as low as 0.01 K can be resolved, while the thermometer used for the example calibration was accurate only to ± 0.3 K. This and higher degrees of accuracy are required in certain research applications, for example to detect heat flux modulations in bifurcating fluidic systems.

1. Introduction

In 1826 A.C., made the first recorded proposal to employ the Seebeck effect in thermometers and by 1902 thermocouples were commercially available [1]. Today, they are in widespread use due to their low cost, robustness, small size, simplicity, speed of response and large temperature range [2]. This thermoelectric effect was discovered in the early 1820s by T. Seebeck [3–5], whereby an electric potential is induced due to a temperature gradient in a thermopair [6–8]. It is often utilized in specialized devices, such as thermometry near absolute zero [9,10] or in nanoscale devices [11].

While the absolute temperature is of interest in many applications, in others, such as monitoring nuclear reactors [12], temperature difference measurements are required. For example, in the 1970s thermocouples were calibrated to measure temperature differences in aircraft engine oil as low as 2.5 K over an absolute temperature range of hundreds of Kelvin [13].

Thermocouples can be employed to directly determine a temperature difference in a single measurement (and without reference junction compensation) [7,8]. This circumvents the error propagation that would otherwise be encountered when differencing two separate temperature measurements. To increase sensitivity, multiple thermocouples can be connected in series forming a thermopile. For precise measurements of differential temperatures above 1 K, [7] calibrated a thermopile with a high precision quartz thermometer ($T \pm 0.04$ K) and a specialized method of signal conversion. An accuracy of ± 0.07 K was achieved. When the calibrated thermopile is employed to measure differential temperatures, the mean temperature T_m is used to account for the non-linearity of the calibration curve. This method is limited by the accuracy of the calibration thermometer [14].

Differential temperature measurements are of particular interest for heat transfer investigations, as heat flux cannot be measured directly [15]. Nonetheless, differential thermometry can be used to relate the heat flux to the temperature gradient and the material properties (known heat resistance). Heat flux sensors based on this technique have been designed for a variety of applications ranging from industry to biological systems research, as well as radiometry for photo-voltaic and solar thermal energy studies [16–19]. Heat flux uncertainty of $\pm 4\%$ and $\pm 7\%$ are reported by [18,19], respectively.

In many heat transfer applications, the heat resistance between two thermal reservoirs is not known a priori. In these cases, the heat flux can be determined by measuring the heating (or cooling) power required to maintain quasi-isothermal reservoir boundaries.

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http://dx.doi.org/10.1016/j.expthermflusci.2015.01.018
0894-1777/

Nomenclature

$2h$	applied calibration temperature difference (K)
$2h_{opt}$	optimal temperature difference (K)
E_m	measurement uncertainty $(\frac{V}{K})$
E_{lin}	linearization error $(\frac{V}{K})$
E_S	uncertainty of TES $(\frac{V}{K})$
$E_{T,cal}$	temperature uncertainty of calibration thermometer (K)
S_A, S_B	TES of materials A, B $(\frac{V}{K})$
S_{AB}	TES of material pairing AB $(\frac{V}{K})$
S_{st}	TES from industry standard $(\frac{V}{K})$
$S_{st,K}$	standard K-type TES $(\frac{V}{K})$
$S(T)$	TES as a function of temperature $(\frac{V}{K})$
T	temperature (°C)
T_m	mean temperature (°C)
T_{ref}	reference temperature (°C)
ΔT	temperature difference (K)
$U(T, T_{ref})$	electric potential difference across thermopile (V)
$U(T_1, T_2)$	electric potential difference across thermopile (V)

For electric heat sources this is simply achieved by an electric-power measurement. For convectively cooled heat sink surfaces, on the other hand, this is typically accomplished by measuring the difference between the inlet and outlet temperature of the coolant in conjunction with its mass flux and material properties [20]. A high degree of temperature uniformity of the cooled plate is required in many studies. The pattern symmetry of surface tension gradient driven Bénard–Marangoni convection, for example, is highly sensitive towards temperature non-uniformities. Therefore, accurate differential temperature measurements are required to detect the heat flux modulation caused by bifurcations points, while at the same time maintaining a thermal gradient across the plate, which is as small as possible in order to maintain quasi-isothermal boundary conditions. To this end, a thermoelectric circuit has been developed by [20]; however, no uncertainty propagation analysis has been reported for the sensor calibration.

The thermoelectric sensitivity (TES) is employed in the above mentioned heat flux studies [16,17,20]. It is commonly measured with the differential method (described in [8]) [17,21–25]. The uncertainty of the achieved TES measurement is dependent on the chosen temperature difference. To avoid non-linear effects and errors, it has in the past been recommended to choose a temperature difference on the order of a few percent of the mean temperature T_m ($\Delta T/T_m \ll 1$) [8,25]. However, until now, there has been no report of any systematic study of the selection of the temperature difference employed during TES measurement. This shortcoming is addressed in this study.

While international standards for the calibration of thermocouples as thermometers exist, customized calibration techniques have been developed for specialized applications [7,26]. For example, calorimetric and radiometric calibrations of thermoelectric heat flux sensors and radiometers have been developed [26,27]. For precise measurements of small differential temperatures, a method of calibration and signal conversion has been proposed for measurements with thermopiles [7]. In this study we address the calibration of even smaller temperature differences, and propose a novel approach.

Subsequently, the above mentioned technique proposed by Huang [7] is further extended to measure temperature differences below 1 K. In addition to the mean temperature of the differential temperature measurement (taken into account by Huang [7]), the mean temperature during the calibration process is considered as well. Instead of the calibration of the voltage-temperature correlation $U(T)$, the inverse of the TES is used as the calibration coefficient, and it is measured with the differential method described in Martin et al. [8]. An analysis of the maximum uncertainty of this method is performed and a procedure to optimize the accuracy of the differential technique is developed. The novel method is employed over a range of temperatures (−10 °C to 15 °C) in an illustrative example and compared to the aforementioned technique. A higher differential temperature resolution is achieved, although a significantly less accurate calibration thermometer ($T \pm 0.3$ K) was used. Finally, the steps of this method from calibration to small differential temperature measurement with high accuracy are summarized.

2. Fundamentals of thermocouples and thermopiles

The TES or Seebeck coefficient $S_A(T)$ is a physical property of material A and is dependent on the local temperature T [7,8]. As expressed by the Thomson relations (which essentially express microscopic reversibility), the Seebeck effect itself is a manifestation of the cross-correlation between thermal transport due to a gradient in electric potential on the one hand and charge separation induced by temperature differences on the other. Hence, when the material is exposed to an infinitesimal temperature difference dT, an electric potential difference dU is induced:

$$dU = S_A(T)dT. \tag{1}$$

The TES of a thermocouple is the difference between the sensitivities of materials A and B ($S_{AB} = S_A - S_B$). Thus, for a thermocouple ($N = 1$) exposed to a finite temperature difference $T_2 - T_1$, an electric potential difference

$$U(T_1, T_2) = N \cdot \int_{T_1}^{T_2} S_{AB}(T)dT, \tag{2}$$

is induced [8,28]. In order to improve the signal-to-noise ratio, the potential difference can be augmented by aligning multiple ($N > 1$) thermocouples in series. This assembly is typically referred to as a thermopile [7] and is shown schematically in Fig. 1.

In accordance with technical standards (EN 60584-1 [29], EURAMET cg-8 [30]) thermopiles are commonly calibrated by comparison with a calibration thermometer. For later reference, we refer to this type of calibration as absolute calibration. One set of junctions is held at a constant reference temperature T_{ref}, while

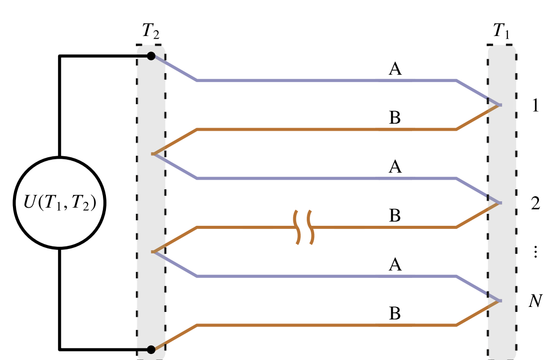

Fig. 1. Schematic representation of a thermopile, composed of N thermopairs of materials A and B. The temperature difference between T_1 and T_2 leads to the electrical potential difference $U(T_1, T_2)$.