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A Thermocouple Homogeneity Scanner Based on an Open Pressure-Controlled Water Heatpipe

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Abstract This paper demonstrates a low-cost, high-performance thermocouple homogeneity scanner based on a pressure-controlled water heatpipe that is open to the atmosphere. With this arrangement, very much like a steam-point apparatus, the atmosphere provides the controlled pressure and the buffer gas for the heatpipe, and the isothermal zone is close to 100 °C. The thermocouple is inserted into the steam within the heatpipe through a plastic membrane so that the gradient is imposed over a spatial region determined primarily by heat flow within the thermocouple body, and can be as small as a few millimeters. The paper explains the construction of the scanner, and presents results of example scans demonstrating the uniformity and resolution of the scanner.

Keywords Calibration · Homogeneity · Scanner · Thermocouple · Uncertainty

1 Introduction

Thermocouples are by far the most widely used temperature sensor. However, their simple construction, a circuit of just two dissimilar wires, belies a hidden complexity due to the dependence of the thermoelectric voltage on the integral of all temperature gradients around the circuit multiplied by the Seebeck coefficient for the wire at the location of the gradient. Only if the Seebeck coefficient is homogeneous can the generated voltage be accurately related to the measured temperature. Because the Seebeck coefficient is susceptible to mechanical, chemical, thermal, and nuclear damage, thermoelectric inhomogeneity is the major source of uncertainty in the use and calibration of thermocouples.

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Homogeneity scanning of thermocouples was first suggested by White in 1910 [1], and has been more recently championed by Fenton [2] and Reed [3,4], amongst others. The principle is to pass the thermocouple slowly through a sharp temperature gradient into an isothermal zone. Because the voltage generated should ideally be constant, any variations in the Seebeck coefficient are betrayed by variations in the generated voltage. To date, such assessments have been carried out using, for example, furnaces [5], oil baths [6], heatpipes [7,8], fixed-points cells [9], and highly localized heating [10].

The two key attributes of a homogeneity-scanning system are the sharpness of the temperature gradient and uniformity of the isothermal zone, which, respectively, determine the spatial resolution and voltage resolution of the system. To date, oil baths are probably the best of the systems with millikelvin uniformity and the gradient distributed over 10 mm to 30 mm. Heatpipe and fixed-point systems also have a high uniformity but historically have not produced such sharp gradients.

A third important attribute is the operating temperature of the isothermal zone. Ideally, the temperature should be sufficient to ensure that the measured effects of the inhomogeneities are typical of those in use, while not so high that the scanning system itself induces changes in the wire. For platinum–rhodium [5] and platinum–palladium [10] thermocouples, the errors in the Seebeck coefficient observed at any temperature appear to be proportional to the output voltage at that temperature. That is, the inhomogeneities can be usefully expressed as a relative error, and the temperature at which the test is carried out is not so important. For base-metal thermocouples, especially, there may be an advantage with the use of a low test temperature (<150 °C) to avoid metallurgical phase transitions known to occur in some of the alloys [11].

This paper describes and demonstrates a low-cost, high-performance homogeneity scanner based on a pressure-controlled water heatpipe that is open to the atmosphere. By operating with the heatpipe open to the atmosphere, the atmosphere provides the controlled pressure and the buffer gas for the heatpipe, and the isothermal zone is held close to 100 °C. The heatpipe demonstrated here is manufactured from ordinary laboratory glassware with an operating length of close to 1 m. The thermocouple under test is inserted directly into the steam within the heatpipe through a plastic membrane so that the gradient is imposed over a spatial region determined primarily by heat flow within the thermocouple wire, and can be as small as a few millimeters. The design can be extended to cope with thermocouples of practically any length and diameter. The paper explains the construction of the scanner, and presents the results of example scans demonstrating the uniformity and resolution of the scanner.

2 Water Heatpipe

A schematic drawing of the water heatpipe, with close-up photographs, is shown in Fig. 1. The system operates as a pressure-controlled gravity thermosyphon [12] so that the water vapor from the evaporator circulates up the main tube where the thermocouple is immersed, then down the secondary tube to the condenser. The cool condensate flows back into the evaporator and ensures that there is little evaporation from the water surface below the secondary tube. The system operates as a conventional pressure-controlled heatpipe with the flowing vapor acting like a diffusion pump to

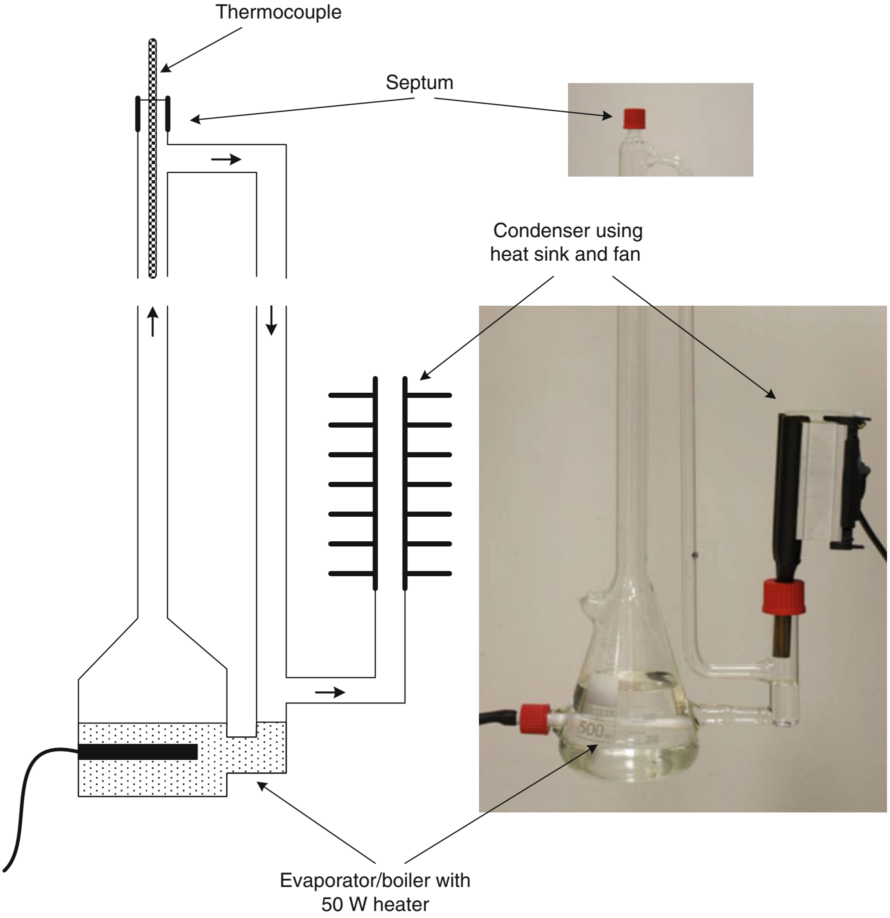

Fig. 1 Schematic diagram of the water heatpipe with close-up photographs of the septum, condenser, and evaporator

purge atmospheric gases from the system, and the open connection to the atmosphere at the condenser maintaining the internal pressure close to the current atmospheric pressure. The long secondary tube further helps to isolate the atmosphere from the active part of the heatpipe. Note that the water level in the boiler must be high enough to ensure that the only vapor path is via the full length of both tubes. The working length of the system is a little more than 900 mm.

Most of the heatpipe, as shown in the photographs, was manufactured from standard laboratory glassware, including the tubing, the conical flask used as the evaporator, and the threaded sections where the septum (containing the membrane) and the condenser are mounted. The heater is a 50 W cartridge heater controlled by a light dimmer to provide sufficient heat for the boiler to simmer gently. The condenser is manufactured from copper tubing glued to a section of aluminum heatsink by epoxy adhesive. The heatsink is cooled using a small fan of the type used to cool the processors in desktop computers. Although not shown in the diagram, the thermocouple is driven into the septum by a capstan and pinch-wheel arrangement driven by a clock motor. Air is also ducted onto the thermocouple immediately above the septum to help maintain a constant temperature in that region and to minimize the spatial region where the gradient is generated. In use, the glassware is housed in a fully insulated box to minimize thermal losses.

3 Performance of the Heatpipe

3.1 Theoretical Limitations

Ideally, the whole of the main tube where the thermocouple is immersed is at the same temperature. In practice, there are two significant effects that induce a temperature gradient. Firstly, for a heatpipe operating vertically, as shown in Fig. 1, there is a theoretical limit imposed by the hydrostatic pressure of the water vapor. The limit is [13]

$$\frac{\mathrm{d}T}{\mathrm{d}h} = \frac{TMg}{\Delta H_{\mathrm{f}}}, \tag{1}$$

where T is the temperature, h is the vertical elevation, g is the acceleration due to gravity, M is the molar mass of water, and ΔH_{f} is the molar heat of fusion. In a water heatpipe at 100 °C, the hydrostatic contribution to the temperature gradient is about $1.6\,\mathrm{mK{\cdot}m^{-1}}$. This contribution would be zero if the heatpipe was operated horizontally.

The second contribution to the temperature gradient is due to the pressure gradient required to move the water vapor through the two tubes. Note that some vapor movement is required to heat all internal surfaces and compensate for losses to ambient, and to ensure that there is sufficient pumping action to purge the system of atmospheric gases diffusing from the condenser and leaking through the septum. The magnitude of the effect is approximately [12]

$$\frac{\mathrm{d}T}{\mathrm{d}l} = \frac{1}{P}\frac{RT^2}{\Delta H_{\mathrm{f}}}\frac{8\mu v}{a^2}, \tag{2}$$

where l is the length of the tube of radius a, R is the universal gas constant, μ is the viscosity of the water vapor, and v is the average velocity of the gas. For a 20 mm diameter tube with water vapor traveling at $1\,\mathrm{m \cdot s^{-1}}$ and at an ambient pressure of 101.325 kPa, the contribution to the gradient is estimated to be about $1\,\mathrm{mK \cdot m^{-1}}$.

Ideally, to provide the maximum spatial resolution of variations in the Seebeck coefficient, the temperature gradient imposed on the thermocouple at the septum should be close to a step function: the practical limit is determined by the finite thermal conductivity of the thermocouple wire.

A second contribution to the spatial resolution is due to the ingress of atmospheric gases through the septum into the primary tube of the heatpipe. Since the total pressure is more or less constant throughout the system, any contaminant gases in the vapor will lower the partial pressure of the water vapor and hence the temperature at which condensation forms on the adjacent surfaces. This effect is minimized by ensuring that the septum has a close fit to the thermocouple, and that there is a reasonable gas flow through the tubing. The temperature error due to the contaminating gas is

$$\Delta T = \frac{\Delta P}{P}\frac{RT^2}{\Delta H_\mathrm{f}}, \tag{3}$$

where ΔP is the partial pressure of the contaminant gas. The effect is apparent as a weak exponential tail on the immersion characteristic of a fine thermometer as it is immersed into the heatpipe.

The open heatpipe is also very sensitive to changes in the ambient pressure. Such changes may be due to the air-conditioning system, the effect of wind outside the laboratory, and the opening and closing of doors. The pressure sensitivity, according to Eq. 3, is about $0.28\,\mathrm{mK}\cdot\mathrm{Pa}^{-1}$.

3.2 Experimental Evaluation

Figure 2 shows the uniformity of the isothermal zone within the heatpipe as measured using a 4 mm diameter stainless steel sheated $100\,\Omega$ industrial platinum resistance thermometer. The resistance bridge has a resolution of about $250\,\mu\mathrm{K}$. This particular measurement was taken on a still day with the laboratory doors and windows open to minimize ambient pressure fluctuations: in normal use ambient pressure fluctuations cause variations of 1 mK to 2 mK rms in the heatpipe temperature. The uniformity measurement was carried out by withdrawing the thermometer from the heatpipe to reduce the immersion errors in the vicinity of the septum. The section of Fig. 2 from about 100 mm onwards shows the gradual increase in temperature with immersion, as expected according to Eq. 1. The 1 mK to 2 mK plateau at the beginning of the immersion characteristic appears to be a real effect, probably caused by the local increase in pressure

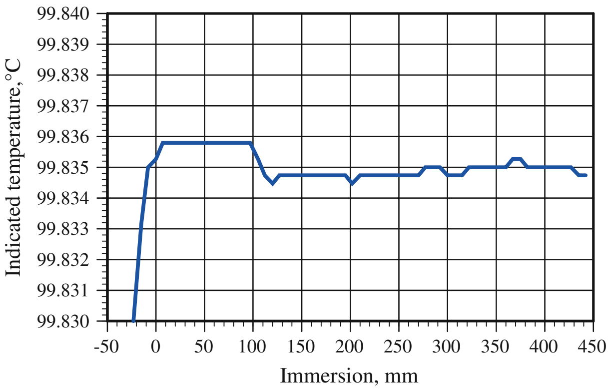

Fig. 2 Uniformity of the heatpipe measured using a 4 mm diameter industrial platinum resistance thermometer

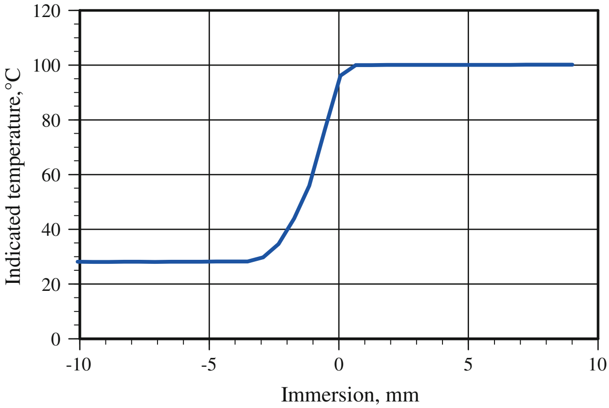

Fig. 3 Immersion characteristic of the heatpipe as measured by bare Type K thermocouple formed from 0.2 mm diameter wires

accompanying the change in direction in the gas flow near the elbow in the tubing below the septum.

Figure 3 shows the immersion profile of the heatpipe measured using 0.2 mm diameter Type K thermocouple wire. To maximize the spatial resolution in the measurement, it is necessary to minimize both the size of the junction, and the amount of damaged wire around the junction. For this measurement, one leg of the bare thermocouple was passed through a loop formed by the other leg, so the junction was formed simply by the point of contact between the two loops. The electrical connection was maintained by suspending a small weight on the wire within the heatpipe. Figure 3 shows that most of the gradient is contained within a 4 mm region.

Figure 4 shows the derivative of Fig. 3, which measures the gradient imposed on the wire in the vicinity of the septum. The curve is the kernel of the integral that relates the Seebeck coefficient to the total voltage generated by the thermocouple. The main features of the curve are the high gradient achieved despite the modest operating

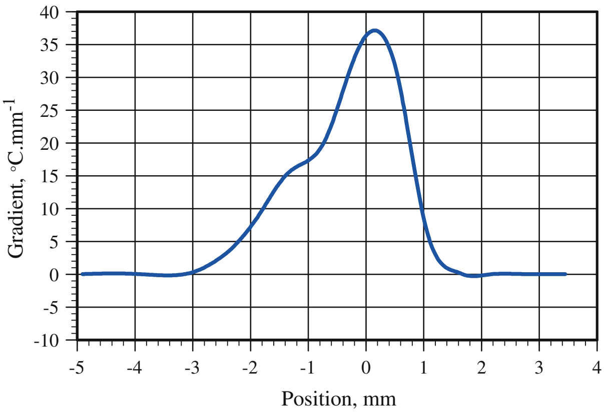

Fig. 4 Temperature gradients in the vicinity of the septum

temperature of the heatpipe, and the asymmetry in the curve. For most scans the peak gradient was in the range 30 °C · mm^{-1} to 35 °C · mm^{-1}. The right-hand side of the figure shows a sharper increase in temperature due to the higher effective thermal conductivity of the heatpipe compared to the atmosphere. The left-hand side shows a less rapid rise in the temperature due to the combination of the poorer thermal conductivity of the atmosphere and the finite thermal conductivity of the wire: the curve is several times wider when a Type T thermocouple (one copper leg) is scanned. Even for the Type K wire, which has a much lower thermal conductivity than copper, the ducted air at the top of the heatpipe was necessary to get the left-hand side of the curve as sharp as shown. Additionally, there was a small difference in the curves for insertion and withdrawal of the thermocouple (at 1.5 mm · s^{-1}).

Figures 5 and 6 plot the homogeneity scans for two 1.6 mm diameter mineral-insulated-metal-sheathed (Inconel 600®) Type N thermocouples. Each graph plots the percentage change in the Seebeck coefficient, *S*, calculated as

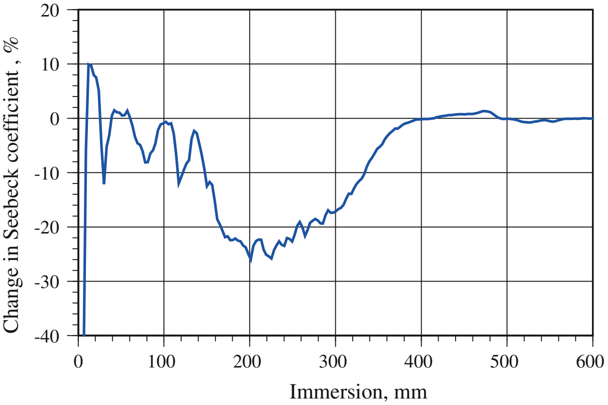

Fig. 5 Immersion characteristic for a 1.6 mm diameter mineral-insulated metal-sheathed Type N thermocouple damaged by prolonged exposure to temperatures near 1000 °C

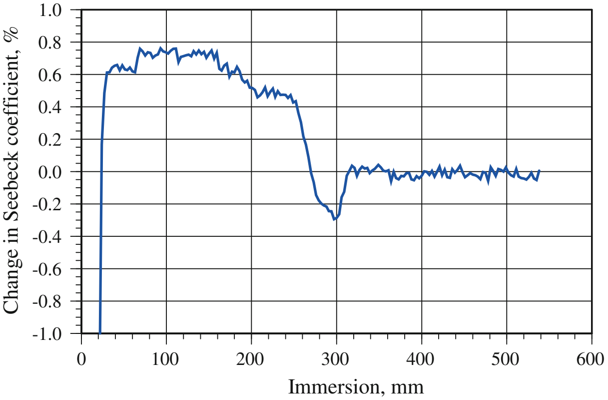

Fig. 6 Immersion characteristic for a 1.6 mm diameter mineral-insulated metal-sheathed Type N thermocouple damaged by short-term exposure (~1 h) at 1000 °C

$$\Delta S = \left(\frac{V_{\text{meas}} - V_{\text{ref\_high}}}{V_{\text{ref\_high}} - V_{\text{ref\_low}}} \right), \tag{4}$$

where V_{meas} is the voltage produced by the thermocouple during the scan, $V_{\text{ref\_low}}$ is the voltage derived from the thermocouple reference function for ambient temperature, and $V_{\text{ref\_high}}$ is the voltage derived from the reference function for the operating temperature of the heatpipe.

The first thermocouple (Fig. 5) was operated at approximately 1000 °C for a few months, and shows the extreme damage typical of long exposure and contamination from the sheath. The variations in Seebeck coefficient span a total of 30 %, with large excursions in both the positive and negative directions.

The second thermocouple, Fig. 6, is of the same type as the thermocouple of Fig. 5, but has been calibrated against a Type S thermocouple at about 1000 °C, with the exposure totaling about 1 h. This scan shows that changes of the order of ±0.5 % occur with minimal heat treatment of the wire.

4 Conclusions

A simple thermocouple homogeneity scanner based on a water heatpipe and manufactured from laboratory glassware, is described. The system operates near 100 °C, below the temperatures likely to cause changes in the Seebeck coefficient of the wire. The system has a sufficiently sharp transition between the ambient conditions and the inside of the heatpipe that the temperature gradients induced in the thermocouple are limited by the thermal conductivity of the wire and the air around the wire. Ducted air over the septum area is necessarily to obtain the sharpest temperature gradients. The uniformity of the heatpipe was found to be within 2 mK, which is as expected from theoretical considerations, and sufficient to ensure that the thermocouple inhomogeneity is measured with the highest practical voltage resolution.

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