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Research paper

Effects of thermocouple electrical insulation on the measurement of surface temperature

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HIGHLIGHTS

- Investigating the impact of thermocouple insulation on temperature measurement.
- Regardless of the insulation, a large diameter thermocouple has the greatest impact.
- Measurement using an 80 μm thermocouple is unaffected by insulation even above 800 °C.
- Insulation has an impact above 250 °C for 200 μm diameter wires.
- There is no specific critical diameter of thermocouple wire(s).

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ABSTRACT

Analytical, numerical and experimental analyses have been performed to investigate the effects of thermocouple wire electrical insulation on the temperature measurement of a reference surface. Two diameters of type K thermocouple, 80 μm and 200 μm, with different exposed wire lengths (0 mm, 5 mm, 10 mm, 15 mm and 20 mm) were used to measure various surface temperatures (4 °C, 8 °C, 15 °C, 25 °C and 35 °C). Measurements were made with the thermocouple in direct contact with the surface, with wires extending vertically and exposed to natural convection. Analytical results of the thermocouple wire with insulation confirm that there is no specific value for the critical radius and the rate of heat flux around the thermocouple wire continuously increases with the wire diameter even when this is larger than the critical radius. Numerical simulation using COMSOL Multiphysics software also confirms that there is negligible thermal effect from the electrical insulation. Moreover, the experimental results agree well with those obtained by both the analytical and numerical methods and further confirm that the diameter of the thermocouple has an impact on the temperature measurement.

1. Introduction

When thermocouple wires are exposed to an environment with a temperature different to that of the object being measured, heat transfer occurs through the wires, which disturbs the system, alters the thermocouple junction temperature and causes an error in the temperature measurement.

Boelter and Lockhart [1] carried out experimental work to measure the temperature of a thick stainless steel plate. The plate was kept at constant temperature(s) by heating one side and cooling other side by hot and cold air flow respectively. Two types of thermocouple were tested (iron-constantan and Chromel–Alumel) with different wire sizes and thermocouples were attached to the cold air side during the measurement process. Moreover, they investigated the influence of vertical and horizontal thermocouple attachment methods on the surface temperature measurement. They suggested that using an inter-thermocouple wire inside a plate or extending the wires along the surface being measured for a length more than 50 times the wire diameter can potentially minimise any measurement error. Tarnopolsky and Seginer [2] performed experimental analysis to study the effects of wire diameter and electrical insulation on conduction error during temperature measurement of vegetable leaves. Small wire(s) size

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(AWG40) type T thermocouples were placed parallel to the surface while the probe was attached using special glue. Different surface contact lengths of insulated and uninsulated thermocouple wires were tested. They verified that a length of bare thermocouple wire glued to a surface requires only half of the contact length of an insulated wire to achieve a uniform temperature between its junction and the measured surface. He et al. [3] conducted a CFD (Computational Fluid Dynamics) analysis and compared results between the effects of vertical and parallel positions of thermocouples on surface temperature measurement. Thermocouple(s) were attached to the uniform heat generating surface exposed to air flow rate with different speeds. They showed that placing thermocouple wires parallel to the surface can reduce measurement error by half as compared with a vertical position.

Various thermocouple arrangements inside low conductivity materials exposed to high heat transfer were examined experimentally by Brewer [4] and Dow [5]. They proved that relatively high error was produced when thermocouple wires passed through a low conductivity material parallel to the heat flow. Therefore, they recommended placing the wires at the same isothermal surface of the junction for several diameters to minimize the error. Singh and Dybbs [6] measured temperature variation inside the body by inserting thermocouples at different depths parallel as well as normal to temperature variation through the body. They advised that the thermocouple wires and the junction should be at the same isothermal plane in order to reduce error. Consequently, if the experiment conditions don't allow, then the temperature reading should be corrected. However, correction is not appropriate if the measurement error of the thermocouple is larger than the error due to conduction.

Another strategy was adopted by Li and Wells [7] to measure surface temperature by pushing a thermocouple through a hole opposite to the surface. Surface temperature was measured during quenching process by a type K thermocouple which was inserted into the hole near the surface. Experimental and numerical study confirmed that the effect of the hole and thermocouple should be considered during the temperature measurement. Furthermore, Li and Wells [7] proved that an increase in the hole diameter caused larger effect on the temperature measurement. Two dimensional analysis by Bartkus [8] predicted that most of the error in thermocouple measurement within the body comes from the increase in thermal resistance between the thermocouple insulation and the surrounding materials. Attia et al. [9] experimental and numerical results consolidated the conclusions of Li and Wells [7] and Bartkus [8]. Moreover, Attia et al. [9] studied the effects of different thermocouple materials properties (E, J and T) and the surrounding material on temperature measurement inside the body. They showed an increase in thermocouple thermal conductivity augmented heat transfer and thus underestimated the temperature reading. Further, the existence of a thermocouple hole altered the temperature field around the thermocouple and caused a reading error [9].

Tarnopolsky and Seginer [2] observed that a thermocouple with lower thermal conductivity (type-K) needs 60% less contact length than one with a higher conductivity (type-T). Dow [5] pointed out that because of its high thermal conductivity, alumina tubes produce higher error in comparison with resin-glass insulation when used as an insulation material for thermocouple wires. While numerical results of Kidd [10] for skin temperature measurement confirmed that paring chromel-constantan wires gave a lower conduction error in comparison to other materials used for thermocouple wires. Experimental results of Boelter and Lockhart [1] showed iron-constantan gives higher error in temperature measurement than Chromel–Alumel. Shaukatullah and Claassen [11] performed experimental results for the temperature measurement of a chip surface with different thermocouple sizes and attachment methods. They advised that using a small diameter of thermocouple with lower thermal conductivity can minimize thermocouple wires conduction error.

Boelter and Lockhart [1] confirmed that there is negligible effect from electrical insulation on temperature measurement when the thermocouple diameter (including the insulation) is less than the critical radius. Further, Mohun [12] discussed analytically the effect of electrical insulation for temperature measurement inside a solid wall. Mohun showed that the presence of electrical insulation over a critical length can only affect the thermocouple reading if the wires pass through a variable environment temperature. Tszeng and Zhou [13] used the finite element method to analyse conduction error through thermocouple wires when the probe was in direct contact with the surface. They showed that when the heat flux along thermocouple wires insulation surface is small and the thermocouple is fine, the effect of insulation on thermocouple probe temperature is negligible. Moreover, Tszeng and Zhou [13] recommended using bare wire with small diameter rather than a larger diameter thermocouple with insulation. Woolley [14] confirmed that alumina oxide Al_2O_3 insulation causes higher measurement error in comparison to glass braid insulation during temperature measurement at the interface between aluminium and sand during a metal casting process. These results have been demonstrated for different sizes of thermocouples and for very high temperature difference (~1500 K).

Experimental results presented by Perera et al. [15] studying the effect of different fixing methods of thermocouple on an LED lens for surface temperature measurement. They indicated that using thermal adhesive tape or silicone elastomer has an identical effect on measurement. Furthermore, fixing the thermocouple junction with a spot weld gave better results than soldering or condenser-discharge welding (Boelter and Lockhart [1]). Shaukatullah and Claassen [11] showed that using silver epoxy or silver epoxy with insulating epoxy to fix the thermocouple to the surface gave a good contact and consequently lower error in temperature measurement. Moreover, attaching the thermocouple to the surface with polyimide or aluminium tapes produced higher errors due to poor contact. He, Smith and Xiong [3] mentioned that an increase of the epoxy drop diameter from 2.5 mm to 7.5 led to reduced measurement error but this increased again for a diameter of 10 mm. Moreover, the results confirmed that the thermocouple error can be minimized when using high thermal conductivity silver filled epoxy instead of classic epoxy of low conductivity.

Another approach was followed by Robertson and Sterbutzel [16] who used two thermocouples and a heater which were attached to a probe. The first thermocouple is in direct contact with the surface, measured the disturbed temperature and the second, away from the surface measured the temperature of the probe itself. Both thermocouple outputs were fed into a power controller which supplied a heater current proportional to the temperature difference. Consequently, the heater reduced the temperature difference between the thermocouples. When both thermocouples are at the same temperature there is no heat flux along the thermocouple wires and the first thermocouple accurately records surface temperature.

In the present work heating and cooling impact of different stripped lengths of thermocouple electrical insulation and surface temperatures on the thermocouple reading was recorded. During the measurement process the thermocouple junction was in direct contact with surface without any fixing glue while the wires were extended vertically and exposed to free convection from the outside environment. Moreover, analytical and numerical analyses investigated in detail the effect of thermal contact resistance between the thermocouple probe and the surface on temperature