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Performance of a thermocouple subjected to a variable current

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ABSTRACT

The aim of this study is to understand the various thermoelectrical phenomena by creating a 1D model that dynamically reacts like a thermocouple through which a current is passed. A new style of modelling is used in this study, which allows the characteristics transition between the two different alloys to be programmable. The main objective is to determine the best parameters that characterize the junction in terms of Seebeck coefficient and heat transfer coefficient in order to obtain a reliable model of the thermocouple. Experiments are performed on an E-type thermocouple of 80 µm in diameter. This thermocouple is subjected to three different types of variable currents. The 1D finite difference model results are compared with the experimental data acquired using an infrared camera. The development of an accurate dynamic model leads to a model exploration of the thermocouple response.

1. Introduction

A thermocouple is a sensor that is widely used in several domains. The principal use of a thermocouple is temperature measurement owing to the thermoelectric effects and more specificly the Seebeck effect. A potential difference is created when there is a temperature difference at the junction of two different materials [1]. Based on this thermoelectric effect, several sensors are used to measure pressures [2], fluid flows [3,4], and heat flux [5–7] by using the same principle (see Figs. 12 and 13).

However, there is another thermoelectrical effect that is less used in metrology applications: the Peltier effect. If an electric current flows across a junction of two dissimilar metals, the heat may either be absorbed (Peltier cooling) or given out (Peltier heating) in the junction volume, depending on the direction of the current. Then in the case of Peltier cooling, the junction absorbs heat from the surroundings and its temperature drops. Loffe [8] established the modern theory of thermoelectric conversion in 1949 and investigated the thermoelectric properties of semiconductors. Several years later, Goldsmid and Douglas demonstrated thermoelectric cooling below 0°C at room temperature environment [9]. Since then, the scientific community started to investigate the use of the Peltier effect as a cooling device [10,11].

However, its efficiency as a cooling device is low for commonly used materials [12]. Therefore, Peltier modules comprise structures with multiple junctions in order to increase the number of exchange surfaces and thus improve the impact of the current on the temperature drop [13]. Doped materials are also used in thermocouples to enhance their efficiency, and a large number of studies have been conducted to investigate the figures of merit [14].

Furthermore, some studies are focused on applications in which the Peltier effect is increasingly used for sensor applications such as [15] where the Peltier effect is used for anemometry [16], where it is used for the determination of fluid properties, and the work of [17–19] that concerns hygrometry measurement.

Following the study conducted by S. Amrane [20], the aim of this new research is to understand the behaviour of an E-type thermocouple subjected to a variable current using a transient numerical model and specific experiments.

A E-type of thermocouple (constantan/chromel) has been selected based on the electromotive force generated by it [1]. Therefore the choice of the materials (constatan and chromel) is driven by the selection of the highest Seebeck coefficient available. The drop in temperature caused by the Peltier effect is the parameter that is used for all sensor applications such as determining humidity parameters or water potential [21]; however, other thermal characteristics such as thermal conductivity [22] are also used. The aforementioned drop in temperature depends at first on the Seebeck coefficient value but also on several parameters such as the wire diameter and current injection as well as thermal effects such as conduction, convection, and radiation. The purpose of this study is to create a generalized thermoelectrical model of a thermocouple such that the position, length, wire diameter, material characteristics, and type of the junction are configurable. The results obtained with the model are then compared with a previous model prepared by Ref. [20] and also with the acquired experimental

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Nomenclature

Greek symbols

ε	Radiative emissivity [-]
ρ	Density [$kg \cdot m^{-3}$]
ρ_{elec}	Electrical resistivity [$\Omega \cdot m^{-1}$]
σ	Seebeck coefficient [$V \cdot K^{-1}$]
σ_B	Stefan Boltzmann coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
τ	Thomson coefficient [$V \cdot K^{-1}$]

Roman symbols

a	Junction length [m]
b	Temperature coefficient for electrical resistivity [K^{-1}]
c	Heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$]
d	Diameter [m]
Gr	Grashof number [−]
h	Convective heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
I	Current [A]
J	Current density [$A.\ m^{-2}$]
k	Thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]
L	Length [m]
Nu	Nusselt number [−]
Pr	Prandtl number [−]
R_i, R_j	Electrical resistance [Ω]
Ra	Rayleigh number [−]
S	Section [m^2]
T	Temperature [K]

Subscripts

∞	Ambient [−]
c	Contact [−]
i	Wire number or discretization index [−]
j	Junction [−]
rad	Radiation [−]
ref	Reference [−]

data. The experimental set-up involves a constantan wire aligned with a chromel wire and arc welded [23,24]. The junction created with a linear weld (see section 2.1) will result in a cylindrical junction whereas a traditional arc weld will result in a spherical junction. The thermocouple is then subjected to a variable current produced by a programmable power supply and the temperature drop realized is then evaluated using an infrared (IR) camera.

2. Experimental set-up

In Ref. [20], a second thermocouple is glued on top of the junction that induces experimental issues. In contrast, the experimental set-up in the present study is designed to obtain temperature measurements while being as non-intrusive as possible. The device chosen to obtain the various data is an IR camera that facilitates data acquisition while remaining external to the system. For the model validation, an E-type thermocouple of 80 μm welded linearly is chosen (i.e. the two wires are welded end to end as shown on Fig. 2). To suspend the thermocouple horizontally, a metallic frame that is painted in black to reduce the radiance at the maximum is used. To insulate the system as well as possible, the latter is enclosed in black panels to reduce the radiation that it is exposed to.

Fig. 1 illustrates the experimental set-up, and the various devices used are as follows:

1. An IR camera FLIR SC7000 for the contactless temperature measurements. The camera is combined with a lens L0120 which has an aperture of F/2, a focal of 10.45 ± 0.50 mm and a spectral band of 3.5–5 ± 0.25 μm.
2. A temperature input module NI 9211 connected to a compactDAQ modular data acquisition system for performing temperature measurements using a microthermocouple. This device is used only for calibration purposes and is thus not shown in Fig. 1.
3. A PXI-4110 programmable power supply and PXI-1033 controller for generating the various voltage profiles.
4. The two software ALTAIR and LabVIEW Desktop.
5. E-type thermocouple (wires by Omega).

This section comprises three parts: the first part consists of the description of the thermocouple welding and the device used for its manufacturing, the second part concerns the thermocouple characterization according to the IR camera numerical levels, and the third part

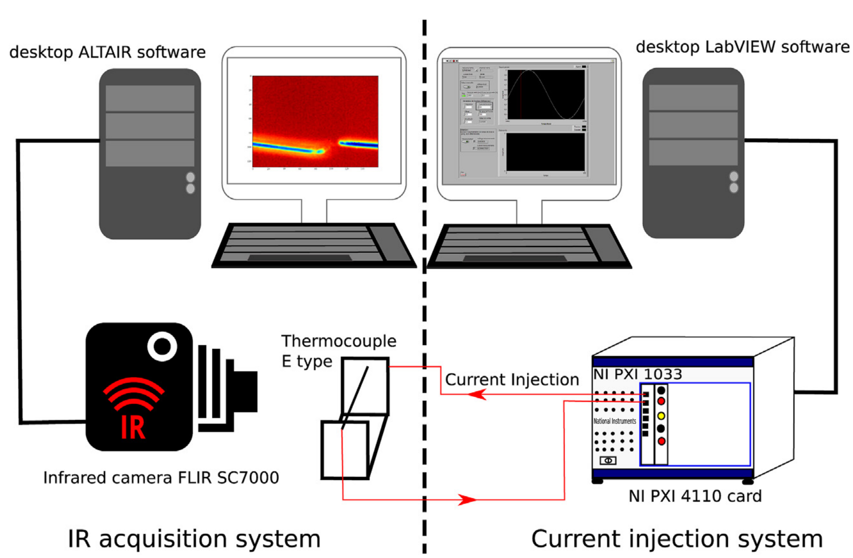

Fig. 1. Experimental set-up with the two different desktops and the experimental material. The IR camera and the thermocouple are shielded via black panels to prevent any parasite IR radiation.

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