International Journal of Heat and Mass Transfer 108 (2017) 2283–2292

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Development of a guard-heated thermistor probe for the accurate measurement of surface temperature

Takahiro Okabe[a,*], Junnosuke Okajima[b], Atsuki Komiya[b], Shigenao Maruyama[b]

[a] *Graduate School of Science and Engineering, Hirosaki University, 3 Bunkyo-cho, Hirosaki, Aomori 980-8577, Japan*
[b] *Institute of Fluid Science, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, Miyagi 980-8577, Japan*

ARTICLE INFO

Article history:
Received 21 September 2016
Received in revised form 10 January 2017
Accepted 19 January 2017

Keywords:
Temperature measurement
Surface temperature
Thermistor
Heat loss
Guard heater

ABSTRACT

It is difficult to accurately measure the absolute value of the surface temperature of a material through ordinary methods such as with a thermocouple or a thermistor. This is due to heat loss along the electrical lead wires of the component, which causes conduction error and can ultimately influence the results. In this paper, we propose a thermistor probe that utilizes a guard heater. The goal of this design is to obtain an accurate measurement of the surface temperature of a material at a higher temperature than the ambient temperature. The probe consists of two thermistors, each with a diameter of 0.43 mm. One thermistor was utilized for the temperature sensor, while the other was used with the guard heater to minimize heat loss, and inserted into a fluorinated ethylene propylene (FEP) tube. The guard heater was placed above a half-exposed thermistor, and operated as both a sensor and a heater in order to minimize the temperature difference between the two thermistors. To evaluate the minimization of heat loss along the thermistor's lead wires in a surface temperature measurement, experiments were conducted with the surface of an aluminum block heated to 35.00 °C in two scenarios. Measurements were taken using a guard-heated thermistor probe with and without guard heating. The experimental results showed that the surface temperature was measured as 34.98 °C in the scenario where guard heating was utilized, and 34.79 °C in the scenario where it was not utilized. Therefore, the results experimentally demonstrated that the guard heater allowed the thermistor probe to provide a more accurate measurement of the surface temperature, regardless of the contact method. In addition, a two-dimensional axisymmetric heat conduction analysis was also conducted. The purpose was to quantitatively evaluate the amount of heat that passes through the lead wires of a thermistor while it is measuring the surface temperature of a heated material. The calculation results confirmed that a guard heater successfully minimized heat loss through the lead wires. The minimized heat loss was −0.016 mW, which was one-sixth of the loss measured in the scenario without guard heating.

1. Introduction

Medical treatment that utilizes heat transfer phenomena has attracted a lot of attention among researchers and has been studied actively because it has the advantage of providing less invasive treatment options. This kind of treatment can be classified into two types. One type is a method that utilizes heating, such as the hyperthermia therapy [1], laser therapy [2], and thermal therapy [3,4]. The other type is a method that utilizes cooling, such as the hypothermia therapy [5] and cryosurgery [6,7]. In these treatments, failures related to temperature control cause unnecessary damage in a patient's healthy tissues due to overheating/cooling. Thus, monitoring the tissue temperature during treatment plays an important role in preventing the treatment from failing due to overheating/cooling.

Skin surface temperature is a reflection of the physiological state of the human body. In fact, it has been determined that the surface temperature of human skin is regulated by the individual's local metabolism, blood perfusion underneath the skin, and heat exchange between the body and ambient condition [8,9]. A change in any one of these parameters can induce a variation in the skin surface temperature. Therefore, many researchers have attempted to accurately measure skin surface temperature [10–12] and apply that information to medical techniques responsible for diagnosing a variety of diseases such as diabetes, fever, breast cancer, and skin cancer [13–18]. Most studies of medical diagnoses involving skin surface temperature have used a non-contact method, such as

---

[*] Corresponding author.
E-mail address: oka@hirosaki-u.ac.jp (T. Okabe).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.01.072
0017-9310/

Nomenclature

A	sectional area, m^2
c	specific heat, J/(kg·K)
k	thermal conductivity, W/(m·K)
K_P	proportional gain
$\dot{q}$	heat generation rate, W/m^3
Q	amount of heat, W
r	radius, m
t	time, s
T	temperature, °C
T_c	temperature of thermistor chip, °C
T_D	derivative time, s
T_g	temperature of guard heater
T_I	integral time, s
T_{lead}	temperature of lead wire
T_s	temperature of sensor
ΔT	temperature difference, °C
V	voltage, V
V_c	volume of thermistor chip, m^3
z	depth, m

Greek symbols

ρ	density, kg/m^3

Subscripts

c	thermistor chip
D	derivative
g	guard heater
I	integral
lead	lead wire
loss	heat loss
mean	mean
P	proportional
s	sensor

infrared (IR) thermography, to measure radiation emitted from the surface of the skin. This method has great advantages, such as a non-invasive modality, and a large amount of data, meaning a temperature distribution over the entire visible surface is attainable. This is why IR thermography is widely used in the clinical applications mentioned above. However, it should be noted that the topical application of substances such as ultrasound gel to the skin in clinical situations, might influence the skin surface temperature by causing emissivity changes. According to Bernard et al., the changes in emissivity due to substances applied to the skin resulted in temperature errors of over 1 °C [19]. This means that if a skin temperature abnormality caused by an inflammation-induced high metabolic rate or blood perfusion in a lesion is of the order of 0.1 K or less, IR thermography may be inappropriate as a diagnostic tool to measure even a relative value. In addition, it is difficult for IR thermography to exactly measure the absolute value of skin surface temperature because of the following uncertainty factors: (1) the emissivity of skin is unknown and may vary in different conditions; (2) the emission may be directional; (3) there may be an incident component from the environment; (4) there may be light attenuation between the emission source and the detection element, depending on room humidity, air composition, etc. Thus, if one needs to accurately measure the skin surface temperature with an uncertainty of the order of 0.1 °C or less, another measuring technique may be preferable.

The contact method, for instance, is a more convenient technique for temperature measurement, and utilizes a thermocouple or a thermistor. It is well known that the contact method can achieve much higher accuracy than a non-contact method. However, when the surface temperature of a material is measured at a higher temperature than ambient temperature, heat losses along the sensor lead wires and adhesive tape due to the temperature difference can cause significant errors in temperature readings (please note that adhesive tape is used to secure sensor contact). This problem has been discussed in previous studies, and the majority of them have focused on the effect of lead wires on the reading using a thermocouple.

J. C. Chato conducted a simplified analysis to estimate the error caused by heat loss along T-type (copper – constantan) thermocouple's wires running perpendicular to the biological tissue surface [20]. According to their analysis [20], to keep the error within 10%, the diameter of the lead wires needed to be less than 5.72 μm, which is not a realistic value for manufacturing and practical use. Boelter and Lockhart experimentally investigated the effects of thermocouple type, thermocouple size, wire size, and electrical insulation on the surface measurement of a stainless-steel plate (0.94 mm thick) exposed to hot air at about 540 °C on one side and to cool air at about 38 °C on the other side of the plate [21]. They used two types of thermocouple (J type and K type) with different wire sizes (0.11–3.3 mm). Moreover, they studied the effect of thermocouple attachment methods (horizontal and vertical) on the temperature readings. Their experiment indicated that J-type (iron – constantan) thermocouple gives higher conduction error in the reading than K-type (chromel – alumel) thermocouple. Tarnopolsky and Seginer carried out experimental work to determine conduction error as a function of thermocouple type (T type and K type), wire diameter (0.075–0.50 mm), electrical insulation and length of contact between wire and sample during surface temperature measurement on plastic plate and vegetable leaves [22]. According to their experimental results, a K-type thermocouple needs only about 40% contact length of a T-type thermocouple for the same conduction error. In addition, the required contact length of an uninsulated thermocouple wire is only about half of that of an insulated wire. Kidd estimated the surface error caused by heat loss along the thermocouple wires by running two-dimensional numerical simulations under various conditions, including different sized thermocouples, material types, and several skin thicknesses [23]. The numerical result shows that thermocouple wire with diameters less than 0.076 mm cause smaller temperature error, and that E-type (chromel – constantan) thermocouple gives a lower conduction error than that in other types of thermocouple. Shaukatullah and Claassen conducted experiments using a T-type thermocouple on the surface temperature measurement of electric packages in order to investigate the effects of the wire sizes (0.08–0.51 mm) and the attachment methods (polyimide tape, aluminum tape, and silver plus insulating epoxy) [24]. The experiments indicated that smaller thermocouples with lower thermal conductivity wires can minimize heat loss through the wires. Moreover, they advised that use of tapes and non-thermally conductive epoxy to attach thermocouples results in larger errors. Al Waaly et al. conducted an experiment to investigate the effects of the lead wires of K-type thermocouple on the surface temperature of a heated or cooled Peltier module at 4–35 °C [25]. Their experimental results showed that the maximum temperature decrease due to heat loss was equal to 2 °C and 4 °C for 80 μm and 200 μm, respectively, when the surface temperature of the Peltier module was 35 °C.

As described above, most previous studies of the surface temperature measurement are evaluations of the effects of the heat loss along the lead wires. In summary, the conduction error in