Experimental Thermal and Fluid Science 86 (2017) 141–148

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

On the response of coaxial surface thermocouples for transient aerodynamic heating measurements

Jinping Li [a], Hong Chen [a,b,*], Shizhong Zhang [a,b], Xiaoyuan Zhang [a], Hongru Yu [a,b]

[a] State Key Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
[b] School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 24 August 2016
Received in revised form 1 March 2017
Accepted 8 April 2017
Available online 9 April 2017

Keywords:
Heat flux measurement
Thermocouple
Response characteristics
Shock tube

ABSTRACT

Surface thermocouples are widely used in transient aerodynamic heating measurements, but their response often exhibits uncertainty and unpredictability, resulting in poor accuracy of measurement. To address this issue and provide reference information on their fabrication, the response of coaxial surface thermocouples was investigated numerically and experimentally. From the numerical simulations, it was observed that the heat blocking effect of the insulation layer can change the response of a thermocouple which strongly depends on the structure of the junction at short test times. Nevertheless, with increasing time, the response tends to be independent of the junction and be consistent with the prediction of the commonly used one-dimensional heat conduction model. Owing to the difficulty in controlling the junction, these observations not only account for the uncertainty and unpredictability of the response, but also suggest that for ensuring accurate measurements, a sufficiently long test time is necessary. The simulation also shows that the response of a thermocouple is insensitive to the properties of the insulation layer and that the duration of an uncertain response decreases dramatically with the thickness of the layer. To improve the performance of a surface thermocouple, additional effort should be directed at reducing the thickness of the insulation layer rather than enhancing its thermal properties. The shock tube experiments confirmed the achieved numerical results, and demonstrated a practical calibration technique for heat transfer gauges.

1. Introduction

The accurate prediction of aerodynamic heating is important in design and development of hypersonic flight vehicles, and it often remains difficult for modern computational fluid dynamics. Experimental measurements still play an indispensable role in addressing this problem. Because of the high-power requirements, these measurements are often carried out in impulse facilities, such as shock tunnels and shock tubes, in which the test time available is very short, usually no more than several milliseconds, and sometimes the flow environment is very hostile. There are only a few qualified gauges that are capable of the measurement of the aerodynamic heating under such rigorous conditions. A surface thermocouple is one of them; it has been widely used for many decades [1–3].

A surface thermocouple is often assembled coaxially, as shown in Fig. 1. The inner wire and the outer annulus, composed of two different thermocouple materials, are electrically insulated from each other except at the top surface, where they are bridged by small junctions created usually by using a scalpel or sandpaper [4]. The temperature of the junction is then sensed through the thermoelectric electromotive force in term of the Seebeck effect. Because the junction size is very small and the bond is strong, the surface junction thermocouple provides a measurement of the surface temperature and it is characterized by fast response and good durability. Surface thermocouples are widely used in many other applications, such as gun barrel studies [5], internal combustion engine heat-transfer measurements [6], and boiling research [7].

The surface temperature itself is, however, of minor interest to aerodynamic heating experiments, because within a short test time it cannot reach the high levels that occur in a real vehicle during flight. In contrast, the surface heat flux is a more meaningful quantity, owing to its easy simulation and its constancy during the test time in impulse facilities. To derive the heat flux from a measured surface temperature, a mathematical relation

* Corresponding author at: State Key Laboratory of High Temperature Gas Dynamics, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China.
E-mail address: hongchen@imech.ac.cn (H. Chen).

http://dx.doi.org/10.1016/j.expthermflusci.2017.04.011
0894-1777/

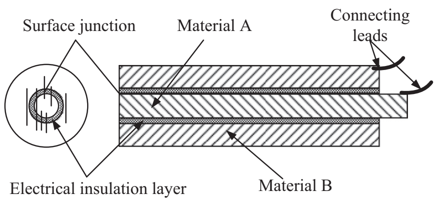

Fig. 1. Schematic diagram of coaxial surface thermocouple.

connecting the two quantities is required. Commonly, it is assumed that the heat conduction inside a surface thermocouple is one-dimensional conduction inside a homogeneous semi-infinite solid; thus, two straightforward solutions are obtained [1]:

$$T(t) = \frac{1}{\sqrt{\pi}\sqrt{\rho ck}} \int_0^t \frac{\dot{q}(\tau)}{\sqrt{t-\tau}} d\tau, \quad (1)$$

$$\dot{q}(t) = \frac{\sqrt{\rho ck}}{\sqrt{\pi}} \int_0^t \frac{dT}{d\tau} \frac{1}{\sqrt{t-\tau}} d\tau, \quad (2)$$

where $\dot{q}$ denotes the heat flux on the surface, ρ the density, c the specific heat, k the thermal conductivity of the solid, T the surface temperature, t the time, and τ the integration variable.

Obviously, an actual surface thermocouple does not meet the above assumption fully, because there are at least three different materials with different thermal properties (two thermocouple materials and one insulation material). To account for this effect, an effective thermal effusivity $(\sqrt{\rho ck})_e$ is often introduced. The effective thermal effusivity is usually determined through calibration experiments and considered as an inherent, invariant property of a certain thermocouple. Many calibration methods have been developed, such as fluid bath plunging [8], water dropping [9], and radiative heating techniques [4,10]. A calibration experiment is regarded as a reliable means to ensure the measured accuracy of a surface thermocouple.

However, in practical applications, a surface thermocouple often exhibits more complex response characteristics than predicted by the one-dimensional heat conduction model, and it does not always perform as reliably as expected, even after calibration. Buttsworth, through a series of careful calibration experiments, found that the response of a surface junction thermocouple is dependent on the time scale of interest, the location, and the size of the junction [9]. If the effective thermal effusivity is used to account for these effects, it is no longer a constant, but can be approximately 30% smaller on microsecond time scales than millisecond time scales, and could differ by 20% when the junction is located on the different thermocouple material. Buttsworth attributed qualitatively the phenomena to the lateral heat conduction inside the thermocouple which is caused by the differences in thermal properties between the thermocouple materials, as well as the insulation layer. Similar phenomena were also observed by Marineau et al. from numerical simulations. They also found the response is sensitive to the geometry of the junction which sits on the insulation layer [11]. Their study, however, focused on a specially designed thermocouple, in which the junction is not as created by a scalpel or sandpaper, as usual, but results from the interference between the tapered center electrode and the sharp-edged outer conductor. This design improved the robustness of the thermocouple [2].

Since a surface thermocouple is often fabricated in-house by a variety of techniques and it is applied to a wide range of conditions, it is helpful for users and producers to understand in a general sense the key factors and mechanism that affect the response characteristics of a surface junction thermocouple. In addition, most of available calibration methods are designed in a compromising way. They are either based on the one-dimensional heat conduction model, which has been demonstrated to be inadequate for describing the heat conduction process inside a thermocouple [8,9], or are susceptible to difficulty in providing the matching time for practical experiments and determining precisely heat absorptivity of the surface, such as found with radiative heating techniques [4,10]. Therefore, calibrations may not ensure an accurate determination of the heat flux in subsequent practical experiments. It is necessary to develop a calibration method for surface thermocouples that is more reasonable and closer to practical measurements.

In order to provide reference information on the fabrication of surface thermocouples and improve the accuracy of transient aerodynamic heating measurements taken with them, the response of coaxial surface thermocouples is investigated by numerical simulations and experiments in the present study. For the numerical simulation, a two-dimensional heat conduction equation is applied to model the heat conduction inside the coaxial surface thermocouple, and several factors that may influence the response characteristics, such as depth of junction and thickness of insulation layer, are discussed. For the experiments, a shock tube is employed to produce a uniform supersonic flow that is responsible for heating the thermocouples mounted on the stagnation region of a test model, so as to allow the thermocouples to experience the same heating process as encountered in practical experiments.

2. Configuration of coaxial surface thermocouples

There are many types of thermocouple, such as type E (chromel–constantan), K (chromel–alumel), and T (copper–constantan). The type E thermocouple, considered in the present study, is the preferred one, because the close thermal properties of the chromel and constantan minimize detrimental lateral heat conduction between the two materials. The present coaxial thermocouple, as shown in Fig. 2, provided by the State Key Laboratory of High Temperature Gas Dynamics (LHD), Institute of Mechanics, consists of an inner constantan wire of 0.95 mm diameter and a chromel annulus of 1.4 mm outer diameter, which are electrically insulated by epoxy along the axial direction. The thermal properties of the three materials are listed in Table 1 [12,13]. The gap between the two thermocouple materials, also the thickness of the epoxy, is approximate 10 μm. The sensitivity of the thermocouple in the range of temperature from 293 to 313 K, which is typically experienced in the present experiments, was found to be 60.3 μV/K based on the static calibration experiments.

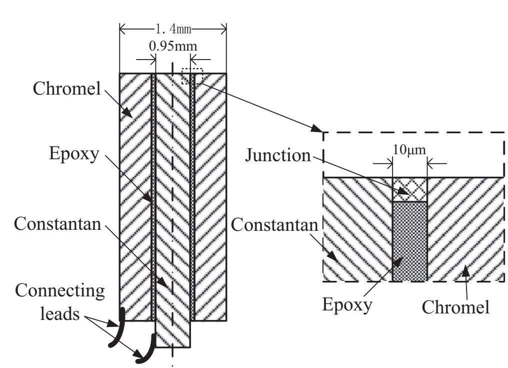

Fig. 2. Schematic diagrams of the thermocouple and the junction applied in numerical simulations.