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

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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

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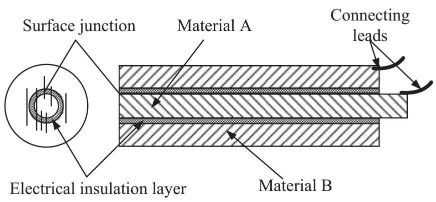


Fig. 1. Schematic diagram of coaxial surface thermocouple.

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]:

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

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

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.

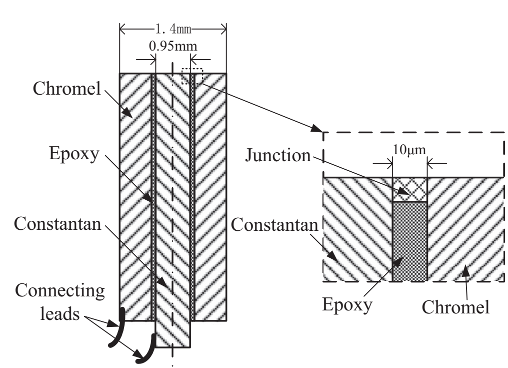


Fig. 2. Schematic diagrams of the thermocouple and the junction applied in numerical simulations.

Table 1
Physical properties of thermocouple materials.

	Constantan	Chromel	Epoxy
Thermal conductivity (W/m K)	21.17	19.25	0.20
Specific heat (J/kg K)	393.1	447.5	1960.0
Density (kg/m^3)	8920.0	8730.0	1060.0
Thermal diffusivity (m^2/s)	6.03×10^{-6}	4.93×10^{-6}	9.63×10^{-8}
Thermal effusivity (J/m^2 K s$^{0.5}$)	8616	8672	645

3. Numerical simulations

3.1. Numerical method and thermocouple model

It is preferred to create the surface junction by use of sandpaper, owing to not only the convenience of this method, but also its advantage of ensuring a smooth surface for the test model. As a result, the junction is bound to be located near the insulation layer, whereas its structure is uncertain and uncontrollable. The location of the junction means that in the vicinity of the junction, lateral heat conduction takes place inevitably when the thermocouple is heated on the top surface, because the thermal properties of the insulation layer differ significantly from those of the thermocouple materials, as Table 1 shows. To take this effect into account, a two-dimensional unsteady heat conduction equation is applied to model the heat conduction process inside the thermocouple:

$$\frac{\partial T(r,z,t)}{\partial t} = \frac{k_i}{\rho_i c_i}\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) \quad (i = 1,2,3,4), \tag{3}$$

where r and z are the radial and axial coordinates, respectively; the other quantities are the same as those in Eqs. (1) and (2), and the subscript 1, 2, 3 and 4 denote the constantan, chromel, insulation layer and junction, respectively. Inside the thermocouple, the temperature and heat flux satisfy the continuity condition at the interface between two different materials. With the boundary condition

$$\left(\frac{\partial T}{\partial z}\right)_{z=0} = \frac{\dot{q}}{k_i} \quad (i = 1,2,4);\ t > 0, \tag{4}$$

on the top surface, and the adiabatic condition on other surfaces, Eq. (3) is solved by the finite difference method for spatial discretization and the fourth order Runge–Kutta method for time integration [14].

The uncertainty and uncontrollability of the junction indicate that simplifying assumptions have to be made in numerical simulations. Here, the junction is assumed to be a circular ring with a rectangular cross section, just locating on the insulation layer, as shown in Fig. 2. Moreover, the thermal properties of the junction are assumed to be the average of the values of the chromel and constantan. Under these assumptions, the factors that may influence the response of a thermocouple are reduced to the junction depth and the insulation layer thickness. In addition, the influence of the thermal properties of the insulation layer is required to be investigated as well, because it is often made from different insulation material for different producers, whose thermal properties may range widely or may not be known precisely.

A grid of 160,000 cells was used to model the present thermocouple. To provide good resolution, the grid was clustered in the vicinity of the junction, such that there were at least 20 cells along the depth direction and 80 cells along the width direction within the junction.

3.2. Influence of junction depth

The influence of the junction depth on the response of the thermocouple was investigated by three cases, where an epoxy layer of 10 µm was taken as the insulation layer and the depth of the junction was 2, 5, or 10 µm. The initial temperature of the entire thermocouple was set to be 298 K and a constant heat flux of 1.0 MW/m^2 was applied on the top surface of the thermocouple.

Typical temperature distributions near the junction on the top surface of and inside the thermocouple, taken from Case 2 (junction depth = 5 µm), are presented in Fig. 3. *Fo* in the figures is the Fourier number, defined as $Fo = t\alpha_a/L^2$, where t and L are the time and the thickness of the insulation layer, respectively, and α_a is the average thermal diffusivity of the chrome and the constantan. As expected from the simulations, a more complicated heat conduction process inside the thermocouple is observed relative to the description of the one-dimensional heat conduction model. First, the temperatures on the top surfaces of the thermocouple are not consistent, except at the initial moment; they are higher in the vicinity of the junction than elsewhere, i.e., the lateral temperature gradient establishes and lateral heat conduction occurs around the junction, as shown in Fig. 3(a). Moreover, inside the thermocouple, the heat conduction depths for the three materials at the same time are different, as shown in Fig. 3(b). The depth for the constantan is the deepest and for the epoxy the shallowest. The reasons for these phenomena are that the insulation layer with the low thermal conductivity prevents the heat absorbed by the junction from conducting along the depth direction, and the thermal diffusivity that determines the heat conduction speed is different for the three materials. The complex heat conduction process within the thermocouple certainly affects the temporal change of

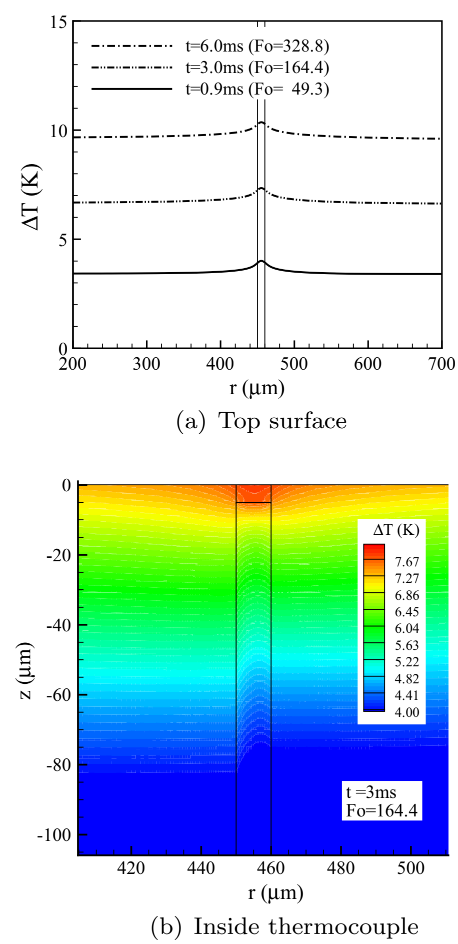


Fig. 3. Temperature distributions on top surface and inside the thermocouple for Case 2.

the junction temperature that is of interest to heat flux measurements.

Fig. 4 presents the junction temperature change with time and the Fourier number for the three cases, where the theoretical value calculated by Eq. (1) is plotted as well, with the $\sqrt{\rho ck}$ being the average value of the constantan and chromel (8644 J/m^2 K s$^{0.5}$). From the figure, it can be found directly that the heat blocking effect of the insulation layer causes the junction temperature to gradually deviate from the theoretical value with increasing time, and the shallower the junction, the greater the deviation. However, further inspection shows that the deviation does not continue to increase, but tends to remain constant for each case. This implies that although the junction temperature is different for different junction depths, its rate of change should be independent on the junction depth and be asymptotic to the theoretical value over time. Eq. (2) signifies that the inferred heat flux is directly dependent on the rate of change of the temperature between the integration interval [0, t], not on the temperature itself, so that this characteristics of the rate of change of the junction temperature is worth examining further.

The rates of change of the junction temperature (dT/dt) are presented for the three cases in Fig. 5, where $(dT/dt)_t$ is the theoretical value and the time axis is logarithmic to highlight the differences at short times. This figure manifests the above statement: whatever the junction depth, the rate of change of the junction approaches asymptotically the theoretical value at long times. It also reveals that at short times the rate of change of the junction temperature is very sensitive to the junction depth. For example, at t = 1 ms ($Fo = 54.8$) the computed rate of change of the junction temperature is 4% greater than the theoretical prediction for all cases, while at t = 0.01 ms ($Fo = 0.55$) the discrepancy is 94, 48, and 6% for Cases 1, 2, and 3, respectively.

In view of the role the rate of change of the junction temperature plays in determining the inferred heat flux, the reasons behind these phenomena are analyzed and discussed as follows: (1) Except in the immediately vicinity of the junction, the temperatures of the top surface layers of the thermocouple materials are litter affected by the heat blocking effect of the insulation layer, still changing in conformity with the one-dimensional conduction model, because the insulation layer is very thin relative to the thermocouple materials (see Fig. 3a). (2) There is a feedback between the rate of change of the junction temperature and the lateral temperature gradient around it that determines the change of the junction temperature. More specifically, the rate of change of the junction temperature decreases with an increase of the lateral temperature gradient, and vice versa. This feedback and the thin insulation layer ensure that, no matter how deep the junction, the rate of change of its temperature tends to that of the surface layers of the thermocouple materials with increasing time, until reaches to a balanced condition, in which the temperatures of the entire surface layers of the thermocouple vary at the same rate. (3) For different depths of the junction, the lateral temperature gradient required for the balanced condition is different, that is, the deeper the junction, the less the lateral temperature gradient, which leads to the difference in the rate of change of the junction temperature at short times.

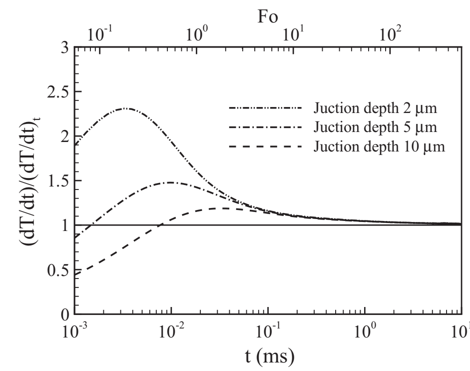


Fig. 5. Evolution of the rate of change of the junction temperature.

Based on the junction temperature histories, the heat fluxes $\dot{q}_i$ for the three cases were inferred from Eq. (2), as shown in Fig. 6, where $\dot{q}_a$ is the applied value. Apparently, all of the inferred heat fluxes deviate from the applied value. Owing to their close correlation mentioned above, the heat flux displays features similar to the rate of change of the junction temperature, i.e., at short times the heat flux diverges significantly for different junction depths. Even for the same depth, it may vary dramatically, although at long times it is less affected and converges asymptotically to a stable value. However, further comparison with the rate of temperature change shows that the heat flux takes a longer time to converge, and the stable values achieved within the considered time still deviate slightly for different junction depths. For example, at t = 1.0 ms ($Fo = 54.8$), the heat flux is 1.16, 1.09, and 1.05 for Cases 1, 2, and 3 respectively, in contrast to the same value of 1.04 for the rate of change of the junction temperature for all cases. This difference accrues because the heat flux at a moment t is inferred from an integration of the rate of change of the junction temperature between 0 and t, to which the instantaneous rate of change of the junction temperature within the entire integration interval contributes.

It should be noted that although the responses of the thermocouple were exhibited by simplified junctions, for more complicated junction structures the response should be the same

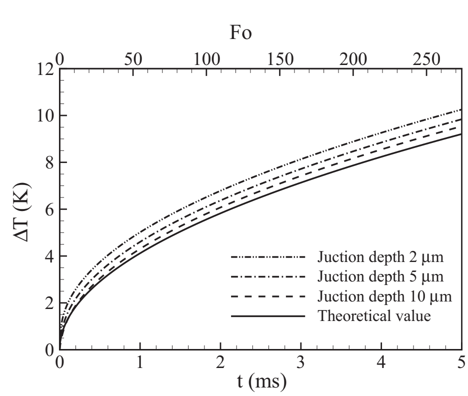


Fig. 4. Temporal evolution of the junction temperature.

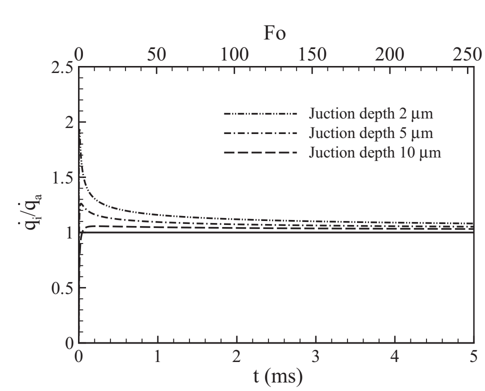


Fig. 6. Variation of the inferred heat fluxes with time for different junction depths.

essentially only if the insulation layer is sufficient thin relative to the thermocouple materials. Whatever the structure of the junction, the same feedback between the rate of change of the junction temperature and the lateral temperature gradient around it remains, which ensures the consistency in the response of the thermocouple at long times. Similarly, for a different structure of the junction the lateral temperature gradient for the balance condition may be different, leading to differences in the response of the thermocouple at short times. Hence, it can be recognized that, for a surface thermocouple, when the junction is formed by sandpaper, its response should be uncertain and unpredictable at short times because of the unknown and uncontrollable junction. It is only after a long enough time, when the response depends little on the junction, that it can be approximated by the one-dimensional heat conduction theory.

An effective thermal effusivity is introduced to correct the inferred heat flux for the present cases:

$$\left(\sqrt{\rho ck}\right)_e = \frac{\dot{q}_a}{\dot{q}_i}\left(\sqrt{\rho ck}\right)_a, \tag{5}$$

where $\dot{q}_a$ and $\dot{q}_i$ are the applied and the inferred heat flux, respectively, and $\left(\sqrt{\rho ck}\right)_a$ is the average of the constantan and the chromel. In terms of this equation and the achieved results, it can be concluded that the effective thermal effusivity is not an inherent, invariant property of a surface thermocouple, but rather is connected with the junction and the time. Especially at short times, it may vary dramatically. This conclusion suggests that the time experienced by a thermocouple in calibrations should be consistent with that in practical experiments, and also indicates that the effective thermal effusivity derived from a calibration for long times is more reliable than that for short times, because it is closer to a constant at long times.

3.3. Influence of insulation layer thickness

The thickness of the insulation layer may be different for different fabrication processes. Values of 10–18 μm have been reported in the literature [8,15]. The thicker the insulation layer, the rougher the sandpaper required to bridge the thermocouple materials on the top surface. This means the junction depth is approximately proportional to the thickness of the insulation layer. It is therefore reasonable to take the thickness of the insulation layer as the characteristic size of the junction. The Fourier number $Fo = t\alpha_a/L$, defined in Section 3.1 based on the thickness of the insulation layer, compares the characteristic size of the junction with the heat penetration depth, so that if the evolution of the heat conduction inside the thermocouple is measured by the Fourier number Fo instead of the time t, the achieved results are comparable for cases with different thickness of insulation layer.

The achieved results demonstrate that there is an initial period in which the response of a thermocouple is strongly dependent on the details of the junction. For different thicknesses of the insulation layer, the duration of this period is certainly different, but the corresponding Fourier number is the same. From the definition of the Fourier number Fo, it can be found that the duration of the uncertain response of the thermocouple resulting from the junction is proportional to the square of the thickness of the insulation layer. For example, if the thickness of the insulation layer is twice as thick as that for the cases in Section 3.1, it will take the inferred heat flux four times as long to achieve the same level of response. Therefore, for improving the performance of a surface thermocouple, it is effective to reduce the thickness of the insulation layer between the two thermocouple materials. Although this approach cannot eliminate the uncertainty of the response at short times, the duration of the uncertainty will decrease dramatically.

3.4. Influence of the properties of insulation layer

As discussed above, the properties of insulation layer may range widely for different thermocouples or may not be known precisely for a given one. To assess this effect, numerical simulations for other two cases were conducted, in which all parameters remained the same as those for Case 2, except that the thermal conductivity of the insulation was increased and decreased by a factor of 10. The corresponding results are presented in Fig. 7.

Fig. 7 shows that with the increase of the thermal conductivity of the insulation layer, the peak value of the heat flux decreases, and it approaches the steady value more quickly, namely, the performance of the thermocouple is improved. This result is expected because the higher the thermal conductivity of the insulation layer, the more heat is transferred. Somewhat unexpectedly, relative to the change magnitude of the thermal property of the insulation layer, the response of the thermocouple changes so little as to be negligible. The effect of other thermal properties, such as the specific heat and the density, is similar, because the heat conduction process inside the thermocouple is dependent on a combination of these parameters. Hence, it can be concluded that the response of the thermocouple is a little dependent on the thermal properties of the insulation layer. Therefore, to improve the performance of a thermocouple, changing the thermal properties of the insulation layer is not an effective means, unless they can be enhanced so significantly as to match those of the thermocouple materials.

4. Experiments with shock tube

In order to examine the response of the surface thermocouple in practical experiments and verify the obtained numerical results, heat-transfer experiments were performed within a shock tube. In these experiments, a uniform supersonic flow behind an incident shock wave was used to heat a thermocouple mounted at the stagnation point of a blunt body model. Because the heat flux in the stagnation region can be determined by the Fay-Riddell formula, and the flow field around the model is established in a very short time, these experiments allow a more or less stepwise heat flux loading with a known intensity to be experienced by the thermocouple, as was considered for the numerical simulations.

4.1. Detonation driven shock tube

The shock tube employed is a detonation driven shock tube, located at LHD, Institute of Mechanics, Beijing, China. This shock tube consists of a dump section, a driver section, a driven section, and a test section, as shown in Fig. 8. The dump, driver, and driven sections are 5, 10, and 13 m in length, respectively, and they share

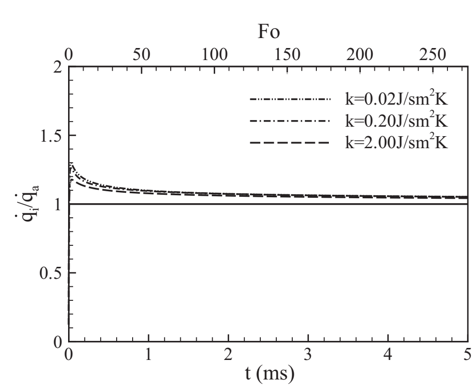


Fig. 7. Variation of the inferred heat fluxes with time for cases with different thermal conductivity of insulation.

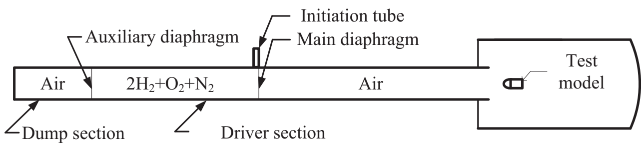


Fig. 8. Schematic diagram of the detonation driven shock tube at LHD.

the same inner diameter of 224 mm. The test section is 5 m long and 1 m in diameter. A mixture of $2H_2 + O_2 + N_2$ was used as the initial driver gas, and air as the initial test gas. As to the incident shock and the test gas behind it, the detonation driven shock tube has the same quality as a conventional one [16], but it consumes much less driver gas. It is therefore more suitable for large-scale facilities for providing long test times.

To identify the propagation of the incident shock wave, two pressure transducers were mounted flush with the inside wall of the driven tube, which were located 20 and 1500 mm upstream of the end of the driven tube. If the speed of the incident shock wave is known, the state of the gas behind the incident shock wave can be easily obtained from the moving shock relations [17].

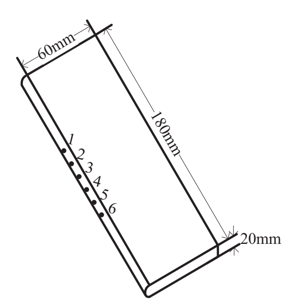
4.2. Test model and experimental arrangement

The test model for mounting the thermocouples was a cylindrically blunted flat plate, composed of stainless steel. The plate was 20 mm thick, and spanned 180 and 60 mm in the lateral and flow directions, as shown is Fig. 9(a). Along the lateral direction, six thermocouples were flush mounted at the stagnation points within the middle-third part of the test model, and the interval between each adjacent sensor was 10 mm. The test model was placed 50 mm downstream of the open end of the driven tube, to avoid disturbances caused by the interaction between the detached shock wave and the inside wall of the tube to the flow field around the test model, as shown in Fig. 9(b).

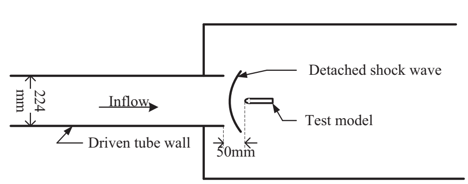
According to the Fay-Riddle formula, for the present model the heat flux at the stagnation point is [18]:

$$\dot{q} = 0.57Pr^{-0.6}(\rho_e\mu_e)^{0.4}(\rho_w\mu_w)^{0.1}\sqrt{(du/dx)_0}(h_e - h_w). \tag{6}$$

Here ρ, μ, and h are the gas density, viscosity and enthalpy, respectively, and Pr is the Prantl number. The subscripts w and e denote



(a) Test model



(b) Experimental arrangement

Fig. 9. Schematic diagrams of test model and experimental arrangement.

the conditions at the wall and the outer edge of the boundary layer, respectively. $(du/dx)_0$ is the velocity gradient at the outer edge of the boundary layer, given by [18]:

$$(du/dx)_0 = \frac{1}{R}\sqrt{\frac{2(P_e - P_2)}{\rho_e}}, \tag{7}$$

where R is the nose radius of the test model, P is the pressure of the gas, and the subscript 2 denotes the test gas behind the incident shock wave.

The thermocouple junction was formed by abrading the top surface of the thermocouple with 300-grit sandpaper. To convert the output of the thermocouple into the heat flux, an electrical analog circuit was used, where the thermal effusivity for all the thermocouples was set to the average value of the chromel and constantan. The effective thermal effusivity for each thermocouple was then determined by comparing this measured value with that predicted by the Fay-Riddle formula, as Eq. (5) indicates.

4.3. Experimental results and discussion

Seven runs, divided into two sets, were performed in the shock tube. For Set 1, including runs 1–3, the junction of the thermocouple remained unchanged after being formed by the sandpaper, with an aim of examining the repeatability of the thermocouple with the unchanged junction. For Set 2, including runs 4–7, the junction was renewed by the sandpaper before each run, in which the emphasis laid on the influence of the junction variation on the response. The initial state of the test gas and the measured Mach number of the incident shock, as well as the state behind the shock, are listed in Table 2.

Typical measured heat fluxes for the six thermocouples are presented in Fig. 10(a). On the whole, at first the arrival of the high-temperature gas behind the incident shock induced jumps in the heat flux, then the heat flux decreased gradually over approximately 0.7 ms, and finally remained almost constant for approximately 1.2 ms. The individual heat fluxes for the different thermocouples may, however, be very different before they approach to the steady value, as is more explicitly illustrated by Fig. 10(b). The repeated experiments prevent the results from being obtained by chance, as Fig. 11 shows. The experimental results are in good accordance with the numerical results. They support the conclusion that the response of a surface thermocouple with a junction formed by sandpaper is uncertain and unpredictable at short times, and with increasing time, the response depends less and less on the details of the junction and tends to be consistent. In addition, these experimental results indicate that a thermocouple with an insulation layer approximately 10 μm thick is sufficient for heat flux measurements on the order of milliseconds. For shorter time scales, it is better to reduce the thickness of the insulation layer further or to apply another means to improve the response characteristics of the thermocouple.

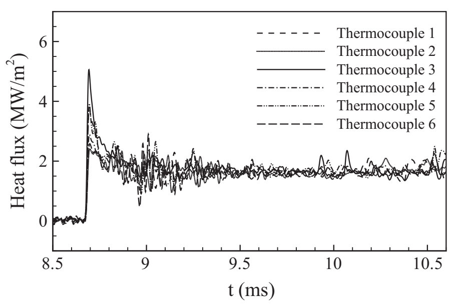
The numerical results show that, even at long times, it is necessary to introduce an effective thermal effusivity to correct the inferred heat flux. To determine from the experimental results the effective thermal effusivity for the present thermocouples at long times, the average heat flux between 0.7 ms and 1.2 ms after the jump is taken as the measured value, in which the thermal effusivity is assumed to be the average value of the constantan and the chromel (8644 $J/m^2\,K\,s^{0.5}$). The results are summarized in Table 3, along with the corresponding theoretical values calculated from Eq. (6).

From Table 3, it is found that for the experiments of Set 1 the repeatability of each thermocouple is significantly better than that for Set 2, but the scatter range of the different thermocouples in Set

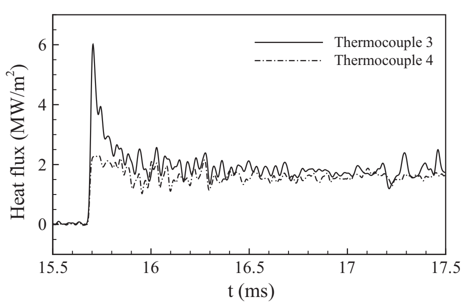
Table 2
Experimental conditions.

Set No.	Set 1			Set 2			
Run No.	1	2	3	4	5	6	7
Temperature T_1 (K)	297	297	297	297	297	296	296
Pressure P_1 (kPa)	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Shock Mach number	2.98	2.98	2.98	2.98	2.97	2.98	2.97
Temperature T_2 (K)	774	774	774	774	771	772	768
Pressure P_2 (kPa)	25.7	25.7	25.7	25.7	25.6	25.7	25.6
Gas speed u_2 (m/s)	769	769	769	769	767	768	765

Note: Subscript 1 denotes initial test gas; 2 test gas behind incident shock.

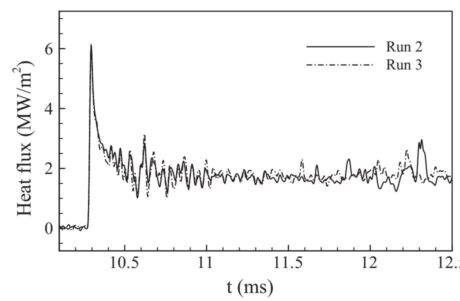


(a) Measured heat fluxes for six thermocouples for Run 4

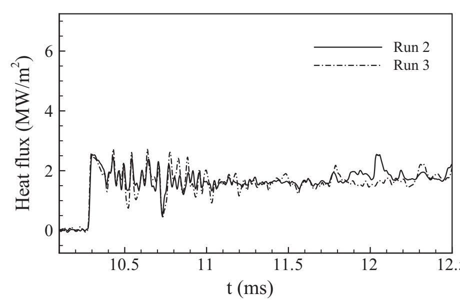


(b) Measured heat fluxes for two thermocouples for Run 1

Fig. 10. Typical heat fluxes measured by the thermocouples.



(a) Thermocouple 3



(b) Thermocouple 4

Fig. 11. Measured heat fluxes of repeated experiments for two thermocouples.

1 is approximately equivalent to the range from several runs for the same thermocouple in Set 2. These sets of data indicate it is acceptable to take the effective thermal effusivity obtained from appropriate calibrations as an invariable property of a thermocouple with an unchanged junction, whereas for a thermocouple with a junction that was renewed for subsequent measurements, the prior calibrations only provided a statistical average of the effective thermal effusivity.

It is also observed that the measured heat fluxes are on balance slightly higher the theoretical values. Based on the experimental and theoretical heat fluxes and Eq. (5), the average of effective thermal effusivity $(\sqrt{\rho c k})_e$ for the 42 experimental results is found to be 7970 J/m^2 K s$^{0.5}$, which is approximately 8% lower than the average value of the chromel and the constantan and is basically consistent with the numerical predictions. The maximum deviation of the effective thermal effusivity from the average value is approximately 10%, which is higher than the deviation of approximately 5% available from fluid bath plunging experiments [11].

Although the experimental results agree well with the numerical simulations, it is still noted that there are some possible error sources pooled in the present experimental results. First, the cylindrical model was used with the purpose of mounting multiple thermocouples simultaneously. However, due to the finite width of such a model, a cross-flow may take place along the stagnation line. This leads to a thinner boundary layer as compared with the theoretical solution and therewith a little higher heat flux. The higher measured value should be partially attributed to this effect. Second, the stagnation line may not be homogeneous or may slightly deviate in its location along the cylinder because of the cross-flow, the asymmetry of the shock tube flow, etc. This unhomogeneity should to some extent increase the scatter of the experimental data. Third, in order to obtain a long test time, the Mach number of the incident shock was set to be a relative low value of approximately 3, and the corresponding flow velocity no more than 770 m/s. For this low velocity, the accuracy of the Fay and Riddell formula needs to be investigated further. For the present experiments, it is difficult to quantitatively analyze these possible error sources. But, these error sources are not inevitable for shock tube heat-transfer experiments; they can be reduced effectively by using a spherical model and enhancing the Mach number of the incident shock beyond 5. Therefore, and because the experiments reflect the actual and projected response of the thermocouple for subsequent practical experiments, it can be an optional calibration method to convectively heat the thermocouple by use of a shock tube.

Table 3
Theoretical and measured heat flux values.

Set No.		Set 1			Set 2			
Run No.		1	2	3	4	5	6	7
Theoretical heat flux (MW/m^2)		1.51	1.51	1.51	1.51	1.49	1.51	1.49
Measured heat flux (MW/m^2)	Thermocouple 1	1.75	1.68	1.78	1.61	1.58	1.54	1.60
	Thermocouple 2	1.60	1.63	1.65	1.56	1.50	1.65	1.50
	Thermocouple 3	1.80	1.77	1.79	1.66	1.65	1.74	1.78
	Thermocouple 4	1.61	1.64	1.63	1.54	1.64	1.71	1.53
	Thermocouple 5	1.73	1.62	1.71	1.53	1.49	1.52	1.65
	Thermocouple 6	1.50	1.54	1.58	1.53	1.50	1.78	1.62

5. Conclusions

The response of a coaxial surface thermocouple of Type E was investigated numerically and experimentally for transient heat flux conditions. The obtained results demonstrate that the actual heat conduction process near the junction deviates strongly from that described by the commonly used one-dimensional heat conduction theory, because of the heat blocking effect of the insulation layer. Accordingly, a thermocouple exhibits much more complex response characteristics. At short times, the response of a thermocouple depends strongly on the detailed structure of the junction, so that the response is uncertain and unpredictable at short times because of the unknown and uncontrollable aspects of the junction. It is only after a sufficiently long time, when the response depends little on the junction, that it can be approximated by the one-dimensional heat conduction model. For ensuring accurate measurements, not only a calibration for identifying the response characteristics of the applied thermocouple is necessary before measurements, the test time is required to match the response time of the thermocouple as closely as possible.

Reducing the thickness of the insulation between the two electrodes is an effective means to improve the performance of the thermocouple. Although reducing the thickness cannot eliminate the uncertainty of the measured heat flux at initial time, the duration of the uncertainty will decrease dramatically. Enhancing the thermal properties of the insulation is not an effective means, unless they can approach those of the thermal materials.

The calibration method applied in the present work takes advantage of a shock tube for producing uniform supersonic flow and the predictability of the heat flux at the stagnation point, which can also be used for calibrating other types of transient heat flux gauges. Compared with the commonly used methods, such as fluid bath plunging technique, this method is more complicated and requires more labor, but it yields the actual response of a heat flux gauge, especially for aerodynamic heating experiments, and thus reduces the possibility of inaccuracy in measurement caused by the responses of heat flux gauges.

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