International Communications in Heat and Mass Transfer 35 (2008) 853–859

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Design and fabrication of coaxial surface junction thermocouples for transient heat transfer measurements ☆

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ARTICLE INFO

Available online 28 April 2008

Keywords:
Design
Fabrication coaxial surface junction thermocouples
Type-K
Transient heat transfer
Shock tube facility

ABSTRACT

Low cost coaxial surface junction thermocouples (CSJTs') have been fabricated in-house and calibrated to measure the transient surface temperature rise within a UNITEN's shock tube wall facility, consisting of K-type coaxial thermocouple elements. The aim of this paper is to explain the design technique of the CSJTs' and the difficulties that have occurred during the fabrication process. The microstructural analysis and the chemical characterization for these types of thermocouples have also been carried out to verify the surface morphology and to qualitatively evaluate the CSJT materials composition. The preliminary testing was performed to demonstrate the performance of these thermocouples to be used for measuring the surface temperatures and heat transfer rates under transient conditions. The preliminary results from shock tube tests have shown that these thermocouples have a time response on the order of microseconds and were suitable for making heat transfer measurements in highly transient conditions. It was concluded that the current construction technique produced gauges that were reliable, reproducible, rugged and inexpensive.

1. Introduction

The need for an instrument to measure transient temperatures in a short time duration flow (few microseconds) arises in numerous heat transfer investigations particularly in internal combustion engine cylinder walls [1–5], aerodynamics facilities [6,7], gun barrels [8] and in boiling experiments [9–11].

Because of their simplicity and comparatively rapid response, fine-wire thermocouples usually are employed. However, in certain applications fine-wire thermocouples are unsatisfactory because of their lack of strength and difficulties in positioning the junction at the point of interest. Furthermore, the minimum size of the junction, which affects the rate of response, usually is limited to the wire diameter.

The coaxial thermocouple design originally proposed by Bendersky [12], which was made up of a small wire coated with very thin layer of aluminum oxide insulation. Other surface junction thermocouples have been fabricated using scratches from abrasive paper or a sharp implement [13] which causes small scale plastic deformation of the thermocouple material and bridges the insulation. In addition, the surface junction thermocouples have also been manufactured using two parallel thermocouples wires [14] or ribbon elements [1–4] that are insulated from each other except at the exposed surface where the insulation is again bridged by either metallic plating or small scale plastic deformation of the thermocouple material itself. Recent research has used various thin film thermocouple designs to measure the transient heat flux. However, a reliability and endurance problem encountered with those designs justifies further research in this area. So, one of the objectives of this work is to develop a reliable sensor that could be used in an extensive characterization of transient heat transfer measurements. Therefore, this paper describes the design, construction, and testing the performance of these sensors in a harsh environment (i.e. shock tube facility) with the objective of measuring the surface temperature history, and consequently calculating the transient heat flux rates.

In fact, there are many measuring devices to measure the surface temperature such as thin-film resistance thermometer which it should have its thin platinum film worn away or short circuited due to the abrasion and ionization of the flow. Another device which is the calorimeters would not be capable of measuring the temperature fluctuations within the time required due to it has longer response time and would also be more complex and expensive to manufacture. So, the CSJT is chosen in this work to perform the surface temperature measurement, because it is easy to build and it has low cost. Even though the surface junction thermocouples may be broken without being remade during the experiment, it is usually simple and inexpensive to refurbish the device using a sharp implement or some abrasive papers. Recent research has used various thin film thermocouple designs to measure the transient heat flux, even it is commercially available [15], however, due to high costs, it is necessary for the present research being conducted at UNITEN. Thus, the use of

☆ Communicated by W.J. Minkowycz.
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doi:10.1016/j.icheatmasstransfer.2008.03.009

Nomenclature

C	specific heat at constant pressure (J/kg °C)
L	axial distance between two pressure transducers (m)
M_s	shock Mach number
q_s	surface heat flux (W/m^2)
t	time from start of heating or cooling (s)
T	surface temperature measured by the thermocouple (°C)
T_i	initial temperature (°C)
T_s	surface temperature (°C)
u	shock wave speed (m/s)

Greek

κ	thermal conductivity (W/m°C)
β	thermal product ($\sqrt{\rho c \kappa}$)(J/m^2 K s$^{1/2}$)
ρ	density (kg/m^3)
τ	dummy variable wrt time (s)

Subscript

1	conditions at driven section
4	conditions at driver section

CSJTs' to measure transient heat transfer offers some important advantages: (1) sturdy design, (2) fast response time, (3) calibration stability, and (4) ability to be contoured to model surface.

2. Description of CSJTS' design and fabrication

2.1. CSJT substrate surface preparation

The fabrication of a small CSJT requires some precision work due to the small dimensions of the inner element coating and the wall thickness of the external tube. The basic steps in the fabrication process are as follows: preparation of the external element, preparation of the internal element, preparation of the sensing end of the assembly. The thermocouples are of the alumel/chromel elements (type-K). They consist of 1 mm wire of one element disposed symmetrically and coaxially into a hollow machined cylinder of the other element whose outside diameter is 3 mm. The two thermocouple elements are separated by a thin film of an electrical insulation with few micrometers thickness. The schematic diagram of the thermocouple assembly is shown in Fig. 1. The thermocouple junctions are formed by gently sanding the end surface of the thermocouple to be exposed to the flow using abrasive papers with different grit sizes.

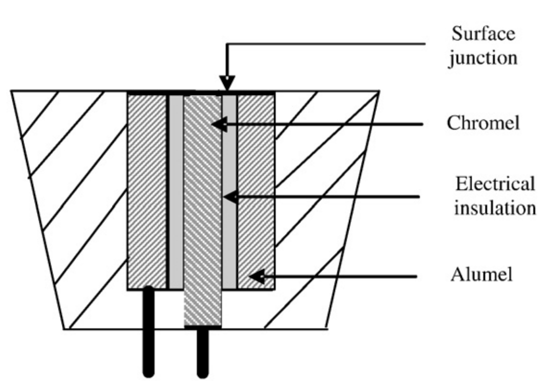

Fig. 1. The schematic diagram of the thermocouple assembly.

Fig. 2. A photograph shows the in-house fabricated CSJT.

Although the thermocouple junction is formed through a direct mechanical contact between the two metals, (small scale plastic deformation of the thermocouple material at the surface), the thermocouples have shown to be quite robust (rise times less than 100 µs) in a harsh environment such as shock tube where the erosion of surface material creates new, low thermal inertia junctions during the process. The greater robustness of the thermocouple may be due to, in part, to the lower temperature attained by the thermocouple junction when exposed to the same flow.

2.2. Lead and electrical connections

Standard teflon wire (34 AWG) was welded at the ends of the thermocouple elements to serve as an extension wire. In fact, any kind of conductive wire can be used as an extension wire, according to the law of intermediate materials [8]. A problem had occurred concerning the welding between the extension wire and the inner element. This problem was solved with the application of a resin right after the welding process, which strengthened its resistance. The outer part of the sensor was a tube manufactured out of a brass with M5 external thread for the installation flash mounted in the test section of the shock tube. Another type of insulation was applied between the brass

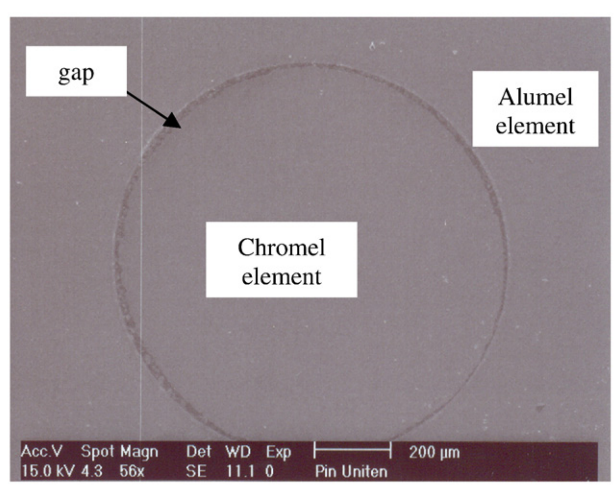

Fig. 3. A photograph shows a thermocouple polished sensing surface using SEM technique.

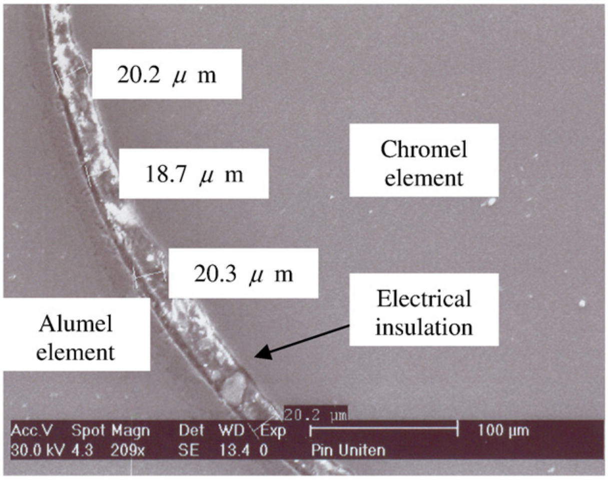

Fig. 4. A photograph shows the thickness of the insulting layer between the thermocouple elements using SEM technique.

tube and the coaxial element to ensure that the measurement was not affected by either materials dissimilarity or lateral heat conduction, as can be seen in Fig. 2.

2.3. Microstructural analysis

A technique for microstructural analysis of the CSJT materials has been implemented in the present work to identify the surface morphology and to confirm the match of the thermocouple elements. A Philips XL-30 Scanning Electron Microscope (SEM) has been used for this purpose. Fig. 3 identifies the gap and the thickness of the electrical insulation between the two thermocouple elements. While Fig. 4 shows the junction which forms at the surface of the thermocouple. It was observed from SEM graphs the electrical insulation thickness was varied from 15 μm to 25 μm as shown in Fig. 4. The observation of the surface junction through a SEM analysis showed that the sanding of the thermocouple tip smears fine strands of one material across the gap to make contact with the other material as shown in Fig. 5.

2.4. Chemical characterizations

An Energy Dispersive X-ray (EDX) detector for chemical characterization has been used in the current study to qualitatively identify the composition of each constituent of CSJTs' materials. The EDX point analysis has verified the presence of the alumel and the chromel composition over the entire surface of the coaxial thermocouples.

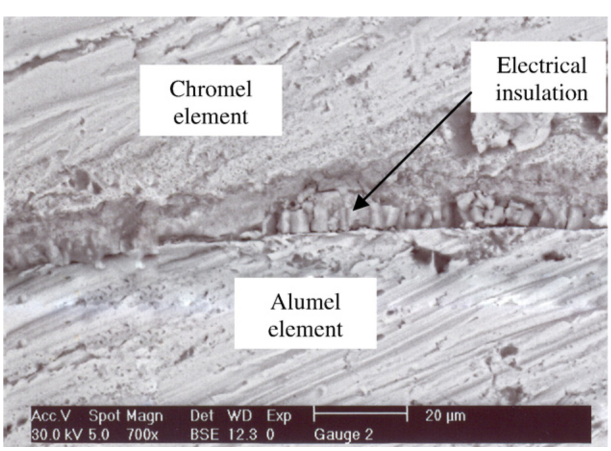

Fig. 5. A photograph shows the thermocouple junction between the two elements using SEM technique.

Table 1
Present EDX spectra and composition data compared with the available literature [8,16–18]

CSJT element	Ni %	Cr %	Al %	Si %	Mn %	Reference
Alumel	95.53	–	2.0	1.47	1.0	Present work
Alumel	95.0	–	2.0	1.0	2.0	Lawton and Klingenberg [8]
Alumel	95.0	–	2.0	1.0	2.0	Caldwell [16]
Alumel	72.0	–	2.0	1.0	25.0	Touloukian [17,18]
Chromel	88.53	9.26	–	2.21	–	Present work
Chromel	88	12	–	–	–	Lawton and Klingenberg [8]
Chromel	90	10	–	–	–	Caldwell [16]
Chromel	90	10	–	–	–	Touloukian [17,18]

EDX spectra and composition data obtained from the alumel and chromel elements are summarized above in Table 1 and compared with the composition given by Lawton and Klingenberg [8], Caldwell [16] and Touloukian [17,18]. The comparison shows that the CSJT materials composition is quite close to the results presented by other investigators.

2.5. CSJT thermal properties selection

Since one of the objectives of the current work is to accurately measure the time-varying surface heat flux using the CSJTs', the needs to precisely know the thermal properties of the substrate or more precisely the value of the thermal product (β) are necessary. So that, the thermal properties selection of thermocouple type-K substrate has been taken from Caldwell [16] and Touloukian [17,18]. However, according to Table 1 although the nickel is the major constituent of K-type materials, there are significant differences in the thermal properties of the chromel and alumel materials as can be seen in Table 1. Data are collated from Caldwell [16] and Touloukian [17,18] and produced in Fig. 6. Because of the values of (β) for both alumel and chromel are differing based on Fig. 6 and it varies with the temperature. Thus, the mean values of the (β) (the line with circles Fig. 6), were taken in the present calculations for the transient heat flux. In addition, the mean value of (β) for chromel and alumel was ranged from 9300–15400 J/m^2 K s$^{1/2}$ respectively with different temperature range. Conclusively, the thermal products for the alumel and chromel materials differ from the mean value by around 15% at ambient temperature; so that a dynamic calibration procedure for

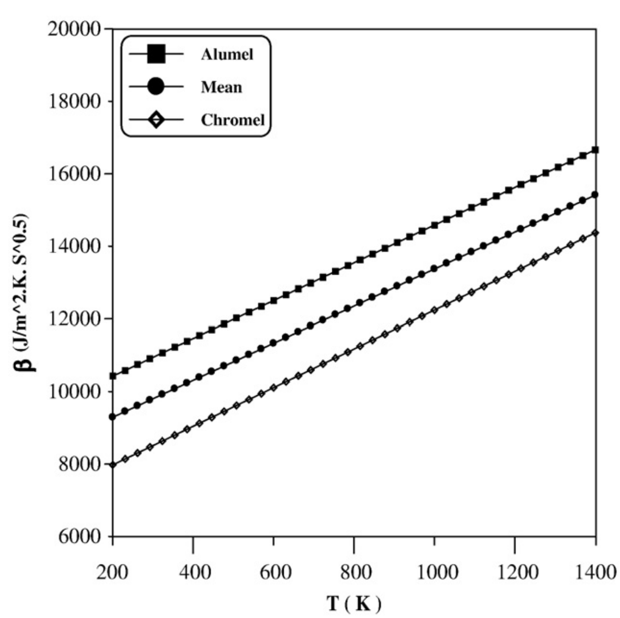

Fig. 6. The thermal product (β) variation with the temperature for type-K thermocouple elements.

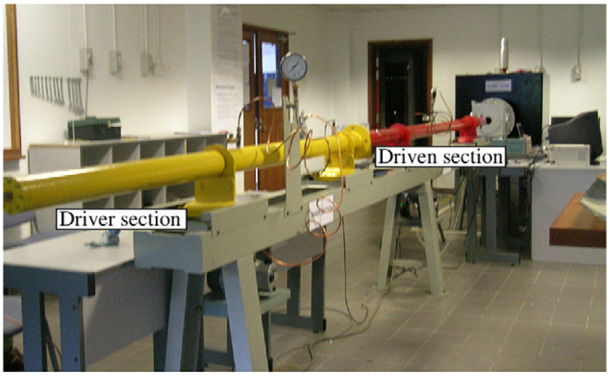

Fig. 7. A photograph shows UNITEN's shock tube facility.

each particular CSJT is required for accurate results (as will be investigated in the future work).

3. Amplification and filtering electrical circuits

The signal from a thermocouple is relatively small (0.798 mV) at 20 °C for a type K thermocouple. Because of this signal is so small, the thermocouples are sensitive to errors caused by noise. Thus, the noise on a thermocouple signal can be excluded by use either low pass filter to exclude the high frequencies, or a high-pass filter to exclude the low-frequency noise. A combination of these can be used to exclude together the low-and high frequency noises. Thus, in the present work, amplification and filtering circuits have been fabricated and developed in-house, to provide low noise and a strong signal according to the method outlined in Sedra and Smith [19]. This amplification and filtering circuits have also been numerically simulated using P-Spice software to compare the results with the experimental one and it shows consistent and same trend.

4. Determination of the transient heat flux

In short duration flow (hypersonic facilities) usually the surface temperatures of the models do not reach the high levels that occur with the real vehicle during flight, so that the temperature itself is of a minor interest. The heat flux is a more meaningful quantity which can easily be simulated and remains constant during the test time in the shock tube facility (as an example). The technique used to derive the heat flux involves the measurement of the surface temperature history and the subsequent calculation of the surface heat flux history by means of unsteady one-dimensional heat conduction theory as reported by Beck [20] by using the following assumptions: (1) the sensing surface of the thermocouple has negligible effect on the surface thermal behaviour; (2) the thermal penetration depth is less than the thickness of the substrate; and (3) the surface junction thermocouple may be considered as a uniform semi-infinite solid. For constant thermal properties the mathematical formulation of the one-dimensional conduction equation can be solved to give the following expression for the surface heat flux in terms of the surface temperature:

$$q(t) = -\kappa \frac{\partial T(0,t)}{\partial x} = \frac{\beta}{\sqrt{\pi}} \int_0^t \frac{\mathrm{d}T_s}{\mathrm{d}t} \frac{1}{\sqrt{t-\tau}} \mathrm{d}\tau \tag{1}$$

The parameter β is the thermal product of the thermocouple which describes the influence of the thermal properties of the material on the unsteady heat transfer. Because of the temperature derivative, the integral in Eq. (1) is not suitable for numerical evaluation. It is more customary to use the following equivalent expression for the evaluation of the surface heat flux:

$$q_s(t) = \frac{\beta}{\sqrt{\pi}} \left(\frac{T_s(t)-T_i}{\sqrt{t}} + \frac{1}{2} \int_0^t \frac{T_s(t)-T_s(\tau)}{(t-\tau)^{1/2}} \mathrm{d}\tau \right) \tag{2}$$

The numerical algorithm using Matlab routine was used to solve Eq. (2) and to obtain the surface heat flux from the measured surface temperatures history according to Cook and Flederman [21].

5. Experimental work

5.1. Shock tube facility

The experiments were preformed in UNITEN's shock tube facility at the Universiti Tenaga Nasional at shock tunnel laboratory. The preliminary tests were carried out in order to determine the response time of the CSJTs' and to confirm that these devices are capable of measuring the transient surface temperature and consequently making the transient heat flux calculations in short duration facilities. A brief description of the shock tube and setup is given below.

The UNITEN's shock tube facility is made of stainless steel tubes, with a 90 mm OD and 50 mm ID for both driver and driven sections. The driver section length was 2.5 m but the driven section length was 4.25 m as shown in Fig. 7. The driver section is separated from the driven section by a diaphragm (aluminium sheets) with 0.2 mm in thickness. These diaphragms will burst if subjected to a pressure ratio of 5±0.07 MPa. The driver and the driven sections were subjected to

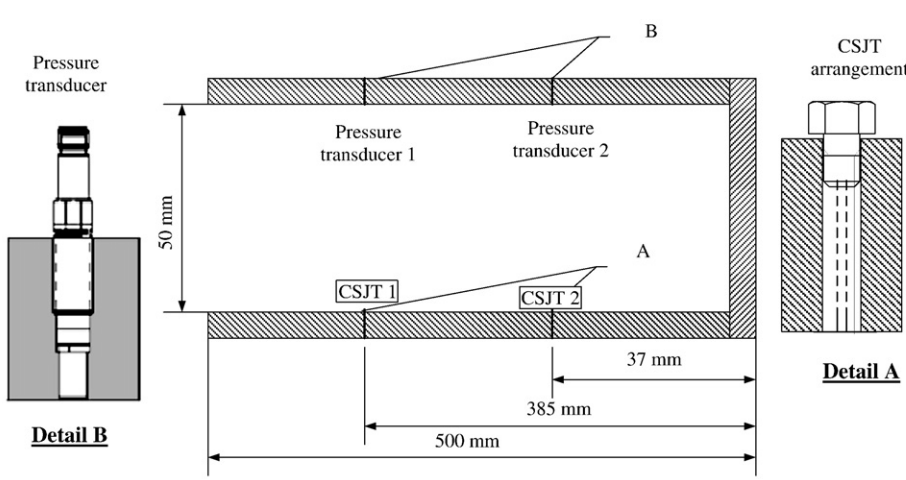

Fig. 8. Test section instrumentations (pressure transducers and CSJT's mounting).

ambient conditions before test runs. Then, the driver section of the shock tube was filled with compressed air gas till a maximum pressure of 1.2 MPa. The driven section of the tube was subjected to ambient conditions (air in this work) for some test runs and other test runs the air was regulated to 0.025±0.07 MPa using a vacuum pump (Winters Co., model no. P6033 ALT) with accuracy of 0.2±0.07 MPa. The driver section pressure, P_4, was measured by a pressure gauge (Winters Co., model no. P6039 ALT) with a maximum pressure range up to 16 MPa with accuracy of ±70 kPa. Accurate measurements of P_4 are actually unnecessary because the input pressure pulse can be obtained from accurate measurements of shock wave speed (u) or from Mach number (M_s), driven section pressure (P_1) and temperature (T_1). A run was initiated when the aluminium diaphragm separating the driver-and-driven-tubes was burst.

5.2. Data acquisition system

A GRAPHTEC DAQ (model midi LOGGER dual GL500), 24 channels, digital recording with a maximum sampling rate up to 500 M sampling/s per channel was used to gather the pressure and the surface temperature data. Channels 1 and 2 were used to gather data from the PCB pressure transducers which have been used as shock tube instrumentations to analyze the transient time of the incident and reflected shock waves, while channel 3 monitored the diaphragm burst pressure, and other channels were used to gather the CSJTs' responses. The CSJTs' were again used in conjunction with an electric amplifier designed in-house as mentioned earlier and supplied with an excitation of several volts from a DC dual power supply (model Tektronix PS 280).

5.3. Test section instrumentations

The test section, was located at the downstream end of the driven tube with a length of 500 mm, was instrumented with two piezo-electric pressure transducers (PCB Piezotronics Inc., model 111A24) in a recessed cavities at a distance of 37 mm from the shock tube end wall and the second one was placed at a distance of 385 mm from the end wall, with two signal conditioners, one for each sensor (PCB Piezotronics Inc., model 482A21) as shown in Fig. 8. Ten CSJTs' were successfully fabricated with different forms of scratched junctions but two of them were instrumented and glued into bushes in this work, at the test section surface with different axial locations, which were themselves located on a recessed shoulder and locked in place with a nut as illustrated in Fig. 8. The test section CSJTs' were aligned with the inner surface of the driven section to within approximately 0.1 mm. The CSJTs' were inserted into a copper thread, so that the sensing point approximately flash mounted with the inner surface of the test section. Care should be taken during the mounting of the CSJT to ensure that the sensing point was flush with the contour of the inner driven surface.

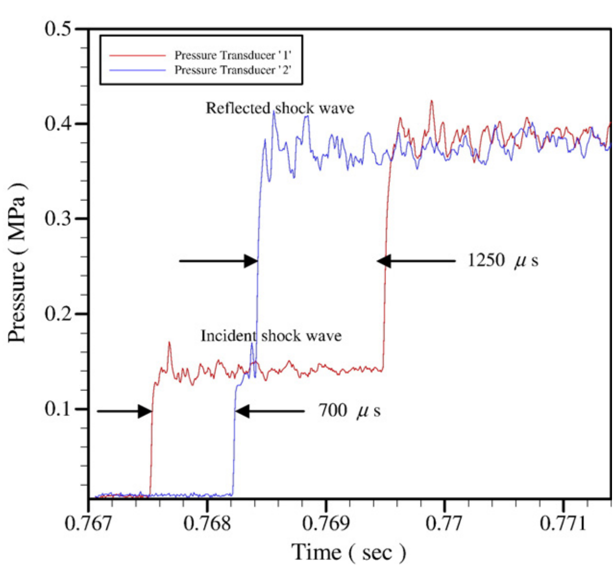

Fig. 9. The pressure history from the two pressure transducers versus time.

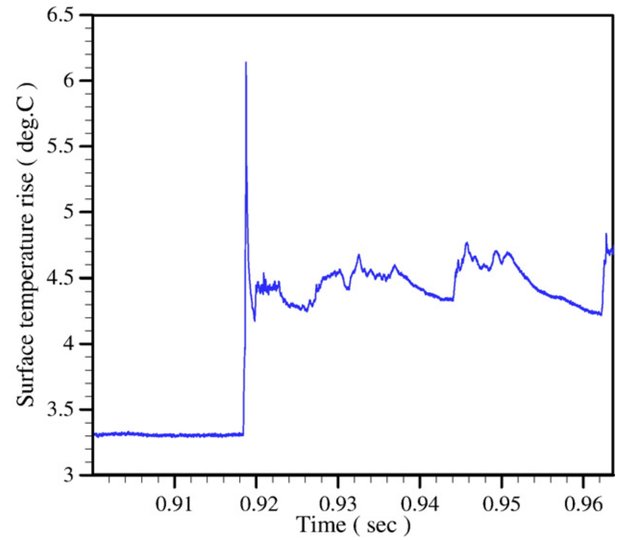

Fig. 10. A sample plot of the surface temperature rise history measured by the CSJT.

6. Results and discussion

A total of ten test runs were carried out using the new CSJT sensors in UNITEN's shock tube facility to demonstrate the performance of these sensors. The transient surface temperature was measured to deduce the heat transfer rate within the shock tube wall. The test conditions were based on measurements of the initial shock tube fill pressure and temperature. The remaining test section parameters, included the incident shock speed prior to reflection, reflected shock wave speed, the temperature and pressure of the reflected shock wave, are determined directly from the measured quantities using the ideal gas dynamics equations given by Zurcow [22] and Anderson [23].

The pressure transducers were used to measure the shock wave speed and to determine the precise time of the shock wave passed over the CSJT. Experiments indicate that the theoretical computed shock

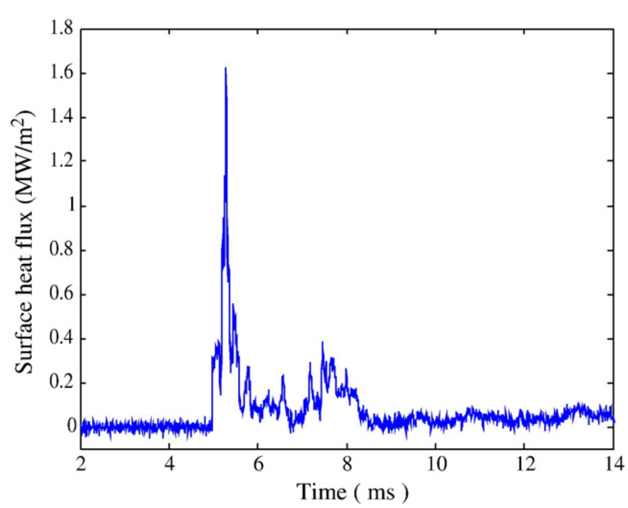

Fig. 11. A sample of the transient heat flux history produced from the measured surface temperature history.

strengths are higher than those actually attained. Initially, the diaphragm burst delays the formation of a one-dimensional shock wave. Then, as the shock wave moves down the tube, it decreases due to boundary layer growth. Therefore, the shock speed must be measured to evaluate the actual shock strength. Shock speeds can be determined by finding the lapsed time of the wave as it passes two points.

Fig. 9 shows the pressure transducer outputs during a test run. The first time lapse shown on the graph indicates the passage of the incident shock wave, while the second indicates the passage of the reflected shock wave from the downstream end of the driven tube. The time elapsed for the oncoming shock to travel between the two transducers was 700 ± 2 μs. Therefore, the experimental shock Mach number was determined to be 1.45 ± 1%. The corresponding shock speed was 497.2 m/s ± 1%. In addition, the time elapsed for the reflected shock wave to travel between the two transducers was 1250 ± 2 μs. This gave a reflected shock Mach number of 0.82 ± 1% which corresponds to a speed of 278.4 m/s ± 1%. The shock Mach number, in the overall test runs used in this work, was ranged from 1.45 to 2.03 which correspond to shock wave speed from 497.2 to 696 m/s ± 1% respectively.

Fig. 10 presents an example of the output produced by the current CSJTs'. This figure reveals that there was a very small surface temperature change, because of the thermal product (β) of the working fluid (air in this case) is small relative to that of the coaxial thermocouple, even though there was a large change in the air temperature due to shock wave compression. The air in contact with the surface junction thermocouple remains stationary for only a short period of time following shock reflection due to the boundary layer jetting effect which will affect the air at the end of the shock tube. It can be seen from this figure that there are two peaks in the surface temperature. The first peak indicates that the shock wave has compressed and heated the air to a higher temperature (around 3.85 °C). The second peak indicates that the reflected shock wave has again compressed and heated the air to a higher temperature (around 6.15 °C). Then, the surface temperature starts to be steady after the strengths of the shock wave and the reflected shock wave became weak.

Fig. 11 presents an example of the transient heat flux history produced from the surface temperature history using the method outlined in the preceding section (see Section 4). Based on the accuracy of the recording data, the variability in the CJST output from the test runs were within ±4%. The overall accuracy of the heat transfer data was expected to be of the order of ± 10%.

In the present work, the uncertainty bounds were estimated for all the values of driver pressure, driven pressure, shock wave speed, and surface temperature for all test runs using the method outlined by Moffat [24] and [25]. Experiments under the same conditions were periodically conducted to ensure the repeatability of the results. The difference between the duplicated experimental runs was within ± 2%.

7. Concluding remarks

The design and construction technique of hand-made, inexpensive, reliable, and rugged CSJTs' was described in this paper. It has been proved that these types of CSJTs' are suitable for using in transient facilities. The conclusions from this investigation, as discussed, are summarized as follows:

1. The construction technique produced CSJT's with the desired characteristics. By closely following the construction technique, an experienced investigator can produce a reliable, rugged, low cost, hand-made CSJT as required.
2. Microstructural and chemical characterizations of the CSJT's included SEM and EDX detector have identified the surface morphology and qualitatively evaluated the CSJT materials composition.
3. The EDX point analysis has verified the presence of the alumel and the chromel compositions over the entire surface of the CSJTs' compared with the available literature.
4. The preliminary shock tube tests have proved that the hand-made CSJTs' can be used to accurately measure the surface temperature and heat transfer rates in transient facilities.
5. The presented results have shown a relative success of the use of CSJTs' as transient surface temperature sensors with microsecond time response.
6. The present work still in progress, but the preliminary results indicate many possibilities for applications of these thermocouples under development. Additional studies by using different types of thermocouples as well as different Mach numbers with different locations are necessary for demonstrating and improving the construction technique.
7. The effect of the thermal product (β) for each particular thermocouple will be evaluated and investigated in the future work since there is uncertainty about 25% of the thermal properties if it has been taken from the available literature such as Kuzman [26]. Furthermore, the accurate thermal product (β) value of a particular thermocouple depends upon whether the junction was actually located on the alumel/chromel substrate materials or on both and on its proximity to the thin insulating layer between the two thermocouple materials.

Acknowledgements

The authors would sincerely acknowledge the financial support by the Ministry of Science Technology and Innovation (MOSTI) under IRPA code 03-99-03-10002-EAR. Additional thanks are due to Mr. Asmawi Mohd Khailani (TPM), Mrs. FarahHani Nordin (EE Dept.), Mr. Tan Chou Yon (Ceramics Technology lab.), Ms. Roslah Johari (UNITEN-library) and Mr. Abubaka Ahmad (ILSAS). Mr. Mohd Fahmi Abdullah and Mrs. Norlia Berahim (TNBR) are also thanked for their extremely useful help and advise in several occasions. Many thanks are tendered to Mr. Benedict Foo for his fundamental assistance in this work.

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