Measurement 61 (2015) 291–298

Contents lists available at ScienceDirect

Measurement

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

Technical note

Performance evaluation of coaxial thermocouple against platinum thin film gauge for heat flux measurement in shock tunnel

Kiran Joy Irimpan, Nithin Mannil, Hemendra Arya, Viren Menezes *

Department of Aerospace Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form 2 September 2014
Accepted 30 October 2014
Available online 10 November 2014

Keywords:
Thermocouple
Thin films
Heat flux
Hypersonic
Shock tunnel
Coaxial

ABSTRACT

Data on surface heat flux is critical in all hypersonic missions due to the extent of risk and the penalty associated, when it is not properly accounted for. In the present study an E-type coaxial thermocouple has been designed, fabricated, validated and benchmarked against a more established platinum thin film sensor. The study proves that coaxial thermocouples used in impulse facilities do not require cold junction compensation. The comprehensive study conducted in IIT Bombay Shock Tunnel (IITB-ST) has confirmed the performance, ruggedness and reliability of the coaxial thermocouple, ascertaining it to be an effective, impulse, heat flux sensor.

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1. Introduction

Man's quest for outer space has brought about a tremendous increase in vehicular speed, yielding an increased complexity and design uncertainty. An accurate estimation of wall heat flux before a mission on a hypersonic vehicle is necessary in order to optimise its weight and ensure safety as the heat loads are enormous, making thermal survival impossible without a rated thermal protection system. Hence, exhaustive ground-based tests are mandatory prior to such a mission in order to ensure its success. Unlike continuous tunnels, impulse hypersonic test facilities never achieve equilibrium temperatures making the heat flux measurements feasible, though the test gas temperature is enormous. Also, the test model in such facilities need not be cooled, as the surface temperature rise may be a few degree celsius owing to an ultra-short test duration [1].

Heat flux measurements in impulse, hypersonic test facilities are carried out by capturing the transient temperature rise over the sensors flush mounted in the wall of the test model. The working principle behind this can either be the change in resistance or change in emf of the sensor due to change in temperature. Platinum thin film sensors and thermocouples are the classic examples of heat flux measurement techniques used in impulse facilities such as shock tunnels. Thin films are either painted or sputtered metal residues on an insulator substrate and are inherently fragile owing to their weak metal–insulator bonding. The high-speed freestream in a shock tunnel erodes away the metallic residue, changing the resistance of the sensor in the course of the test, inducing measurement errors. Moreover, thin films are passive, resistive sensors that require an external excitation through a complex, constant-current power supply, which often induces self or Ohmic heating that can result in measurement uncertainties [2]. The

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* Corresponding author. Tel.: +91 22 2576 7130; fax: +91 22 2572 2602.
E-mail address: viren@aero.iitb.ac.in (V. Menezes).

http://dx.doi.org/10.1016/j.measurement.2014.10.056
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coaxial thermocouple designed and developed in the present study has a better ruggedness, is free of interference and does not require frequent maintenance/replacement compared to platinum thin film sensors [3].

This article presents the details of the development and validation of a coaxial, fast response thermocouple, developed in-house, for shock tunnel applications. The objective of the work was to calibrate the thermocouple for its effective thermal product, as the error in the effective thermal product reflected in the measured heat flux. Most of the calibration techniques follow the formulation presented by Buttsworth [4], wherein a step temperature change is imparted to the thermocouple sensing junction through a working fluid at a high temperature, and the effective thermal product is determined from the response of the thermocouple. In order to obtain accurate results of heat flux measurements, the selection of effective thermal product is a crucial step. Also, the set of experiments carried out in the present study dismiss the ambiguity of the requirement of cold junction compensation for coaxial thermocouples used in impulse facilities. A re-emphasis on the accuracy of the technique was laid by exposing the thermocouple and a platinum thin film gauge to a hypersonic freestream on geometrically similar models, simultaneously. The stagnation point of a hemisphere is an ideal location for such tests as the errors associated with wear and tear of the thin film gauge are minimal at the stagnation point.

2. Materials and methods

2.1. Test facility

The coaxial thermocouple was tested for its response in a hypersonic shock tunnel, IITB-ST (IIT Bombay Shock Tunnel) [5,6], which worked on the reflected-shock mode of operation. The test facility consisted of a shock tube and a wind-tunnel, which were separated by a soft, paper diaphragm to maintain an initial pressure differential between the two. The wind tunnel portion had a hypersonic nozzle with an area ratio for Mach 8, a rectangular test section of dimensions 300 × 300 × 450 mm and a dump tank of 1 m diameter. The tunnel section was equipped with a multistage vacuum pump to generate a high vacuum of the level of 10^{-6} mbar. The shock tube was divided into driver and driven sections separated by an aluminium diaphragm of 1.2 mm thickness. The driven section contained the test gas (air) at a relatively low pressure. The shock tube was operated by exploding the aluminium diaphragm by pressurizing the driver section with the driver gas. The explosion produced an incident shock wave in the driven tube that propagated and reflected totally from the end of the driven section, enhancing the shocking effect, producing a heated and pressurized reservoir of test gas at the entry to the nozzle/wind tunnel of the facility. Formation of the high-pressure reservoir at the end of the driven section (entry to the nozzle) ruptured the paper diaphragm between the nozzle and the shock tube thereby starting the flow through the hypersonic nozzle. Schematic of the IITB-ST with salient dimensions is presented in Fig. 1. A dynamic pressure transducer placed in the tube at the entry to the hypersonic nozzle measured the reservoir pressure, which was found steady for a period of 1000–1200 μs during the present experiments. A similar pressure transducer placed at the exit of the nozzle in the test section measured the surface stagnation (pitot) pressure. The ratio of these pressures was the measure of the freestream Mach number generated through the nozzle, which could be given by Eq. (1) [7].

$$\frac{P_{02}}{P_0} = \left[\frac{(\gamma+1)M_\infty^2}{2\left(1+\frac{(\gamma-1)}{2}M_\infty^2\right)}\right]^{\frac{\gamma}{(\gamma-1)}} \left[\left(\frac{2\gamma}{\gamma+1}M_\infty^2\right) - \left(\frac{\gamma-1}{\gamma+1}\right)\right]^{\frac{-1}{(\gamma-1)}} \tag{1}$$

where P_{02} and P_0 are the pressures measured at the exit and entry of the nozzle, γ is the ratio of specific heats of the test gas and M_∞ is the freestream Mach number.

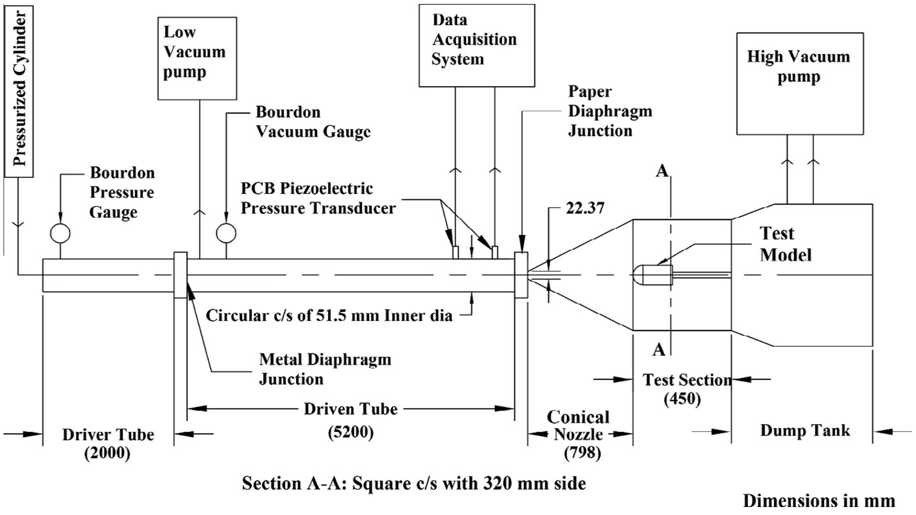

Fig. 1. Schematic of the shock tunnel, IITB-ST.

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