

## **SYNOPSIS**

of PhD thesis entitled

### **A Novel and Fast Response Surface Function Thermal Probe for Transient Measurements – Conceptual Design to Field Applications**

Proposed to be submitted in Partial Fulfillment

of the Requirements for the Degree of

### **DOCTOR OF PHILOSOPHY**

by

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The measurement transient surface temperature and quantification of surface heat flux are important indicators for design requirements of thermal applications in scientific and engineering studies. In general, the high temperature ambience is experienced in many practical situations such as combustion chamber in internal combustion (IC) engines, gas turbines and thermal protection systems for high-speed flight vehicles. With respect to aerodynamic flow environments, there is ground-based impulse/blow down facilities (shock tubes, shock tunnel, expansion tubes) in which the test flow durations prevails for about few milliseconds. Hence, the need for potential thermal probes with high response time is realized for the acquisition of temperature data under these impulse/step heat load conditions. Considering wide domain of heat loads from cyclic (in IC engines) to short duration step/impulse (in high-speed aerodynamic facilities), the in-house design of surface junction thermal probes and its test-trials in above experimental facilities are the focus of the present investigation.

In the past, there were several thermal measurements in the applications IC engines, heat exchanger, steam/gas turbines, thermal protection systems for high-speed flight vehicles ([Alkidas and Cole, 1985](#); [Ekkad and Han, 2000](#); [Sahoo et al., 2006](#)). In each of these cases, the technique used for accurate heat flux measurement suits for transient conditions and sensors have a very fast response time to trace variations caused by rapid changes in the flow conditions. For surface heat transfer

mapping, very fast response sensors are used to acquire transient temperature changes in the flow. For high-speed flow environment, the response time of the sensors becomes more crucial because the experimental time-scale of measurement is very small (~ less than milliseconds). Usually, the transient measurement of temperatures is performed by mounting the thermal sensors embedded on the surface of the heated material. The surface heat fluxes are then estimated from the temperature history, by various heat transfer modelling. Moreover, there are certain practical situations in which it may not be feasible to flush-mount the thermal sensors on the surface; rather they are installed at some points inside the medium, where inverse heat transfer modelling helps one to estimate the temperature history at that particular location. The thermal sensors such as coaxial surface junction thermocouples are advantageous because they can be mounted with ease on any surface, for any harsh condition (Sanderson and Sturtevant, 2002; Mohammed *et al.*, 2008; Menezes and Bhat, 2010). A typical coaxial thermocouple design involves two dissimilar metals, which are joined together to form a junction and when exposed to a temperature gradient, a corresponding voltage is generated (Seebeck effect). The voltage difference generated can be measured and the corresponding temperature gradient is estimated with the help of the sensitivity of the sensor. Surface heat flux is predicted using one-dimensional heat conduction modelling on a semi-infinite substrate (Schultz and Jones, 1973; Sahoo and Peetala, 2010). In this thesis, the novel design of a coaxial surface junction probe, its fabrication and calibration along with real-time experiments with a wide range of heat load environment are important themes of discussion. Figure 1 shows the experimental approach followed during the research time frame to achieve the desired objectives.

The core objective of the work involves **design, in-house fabrication, and calibration of Coaxial Surface Junction Thermocouple for real-time applications in transient flow environment**. In order to achieve the key objective, the entire work-package is divided into few sub-categories, which are listed as follows:

- **Fabrication of Coaxial Surface Junction Thermocouple (CSJT):** The design of the various coaxial thermocouple, which involves simulation to validate the dimension of the sensor for short duration time-scale measurements (Chapter 3). The sensors are developed and fabricated in the laboratory with deformation characteristics details of the sensing surface (Chapter 3 and Chapter 4)
- **Calibration of CSJT (temperature and surface heat flux):** The calibration methodology is conducted to check the feasibility of developed sensors (Chapter 4). It is broadly classified into two categories, based on, “known temperature” and “known heat flux input”. Here, the “sensitivity” of the sensor is obtained for the known temperature (static mode of calibration), and linearity in voltage signal is checked. Before the sensor are exposed to the real-time experiment such as impulse facilities, it is desirable to calibrate the thermal sensor with similar nature of heat load such as exposing the sensor to a certain known heat input (dynamic mode of calibration).
- **Determination of Thermal Product for CSJT:** The measurement of transient surface temperature and heat flux are very important requirements in unsteady-heat transfer research. The thermal sensor captures temperature histories and thereafter heat flux histories are

estimated. For a short duration study, the heat flux calculations are carried out using one-dimensional semi-infinite medium solution for a step change in temperature. The equation for heat flux includes the “thermal product” estimation, which is a property of the sensing material. The dynamic calibration for each of CSJT is highly desired for accurate estimation of TP as uncertainties up to 25% can be introduced when the thermophysical values of materials are directly taken from the literature. Analyzing all the aspects, few experiments are attempted by using “water droplet” and “water plunging” techniques to calculate the thermal products experimentally for the surface junction thermocouples ([Chapter 5](#)).

- **Real-time application-based study of CSJT for Heat Flux Measurement:** The sensors are used to capture transient heat flux in real time experiments. The present work is focused on the real-time based study such as stagnation point heat flux estimation in a low supersonic environment such as that of shock-tube ([Chapter 6](#)); heat flux estimation in the short duration hypersonic facilities such as shock tunnel ([Chapter 7](#)); instantaneous heat flux measurement in the combustion chamber of the internal combustion engine ([Chapter 8](#)); qualitative detection of combustion instability in a gas turbine engine ([Chapter 9](#))
- **The packaging of Coaxial Thermal Probe:** In order to have a product-oriented thermal sensor for real-time testing, some important aspects of packaging involving curing process and integrating it with a barrel for housing the sensors are discussed ([Chapter 9](#)).

[Chapter 1](#) describes the background of the work on the usage of the transient heat flux and its associated measurement devices. It provides a history of the temperature and heat flux measuring devices as a whole, giving a brief glimpse of the working principle of each one of them. It discusses the importance of usage of very high response sensor (millisecond duration) in the transient environment. The concept of one-dimensional heat transfer along with semi-infinite gauge has been discussed with emphasis on the various categories of the heat flux measuring devices and their selection with respect to the current study. Finally, the chapter describes the layout of the thesis work.

[Chapter 2](#) gives the exhaustive literature survey on various aspects in the area of heat transfer gauges. It is divided into broad categories namely, mathematical modelling of transient heat transfer measurement; design, fabrication and calibration of coaxial surface junction thermocouple, estimation of thermal product value (i.e. ' $\beta = \sqrt{\rho ck}$ '). The utilization of shock tube as a tool for shock wave device for testing thermal sensors, application of coaxial surface junction thermocouple (internal combustion engine, hypersonic facilities, gas turbine), a simulation-based study on thermal sensors are also the focal point of literature discussions. Lastly, the assessment is inclined to research undertaken in IIT Guwahati with respect to “coaxial surface junction thermocouple”. The chapter focuses on some of the key work in connection with this area of research such the designing and fabrication of K-type coaxial surface junction thermocouple ([Mohammed et al., 2008](#)). Further, the reported literature ([Buttsworth, 2001](#)) has a remarkable impact on the area of thermal product estimation for coaxial thermal sensor both in a millisecond as well as in microsecond duration. In continuation, the work attempted by [Sanderson and Sturtevant \(2002\)](#) for the development and testing of a new form of a thermocouple, the design of which involves the use of tapered fit between two coaxial thermocouple elements is also

appreciated. The development of E-type coaxial thermocouple and its application to measuring stagnation heat flux has added a valuable insight work (Irimpan *et al.*, 2015). The pioneering work in IIT Guwahati by Kumar *et al.* (2013) on the fabrication and calibration of K-type CSJT has given a motivation for the scope of work that needs to be attempted. Lastly, describing the objective of the present set of investigation along with its motivation.

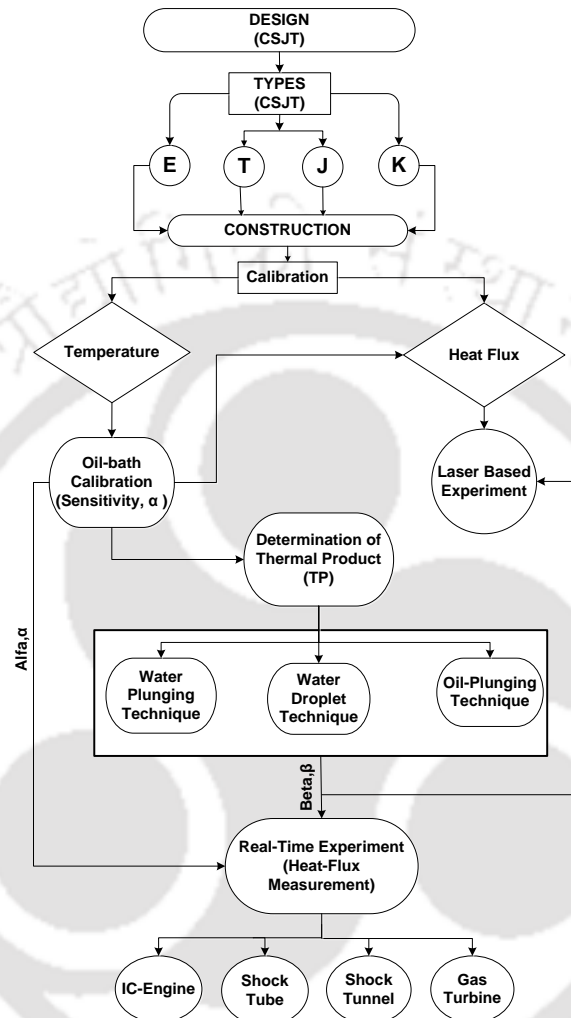
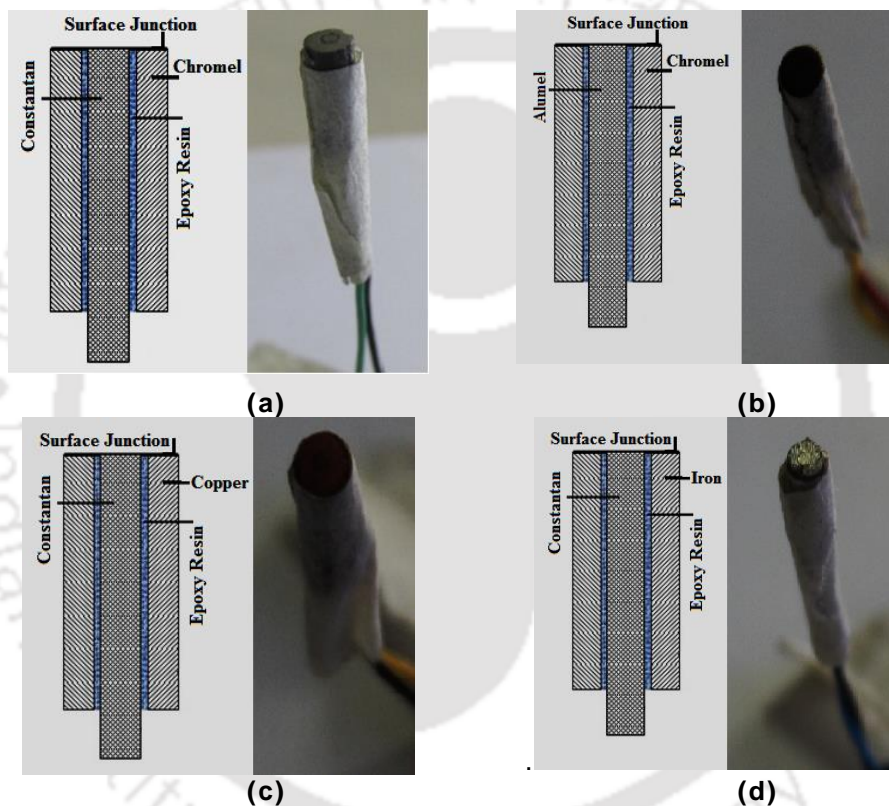


Fig. 1: Flowchart highlighting the overview of thesis work

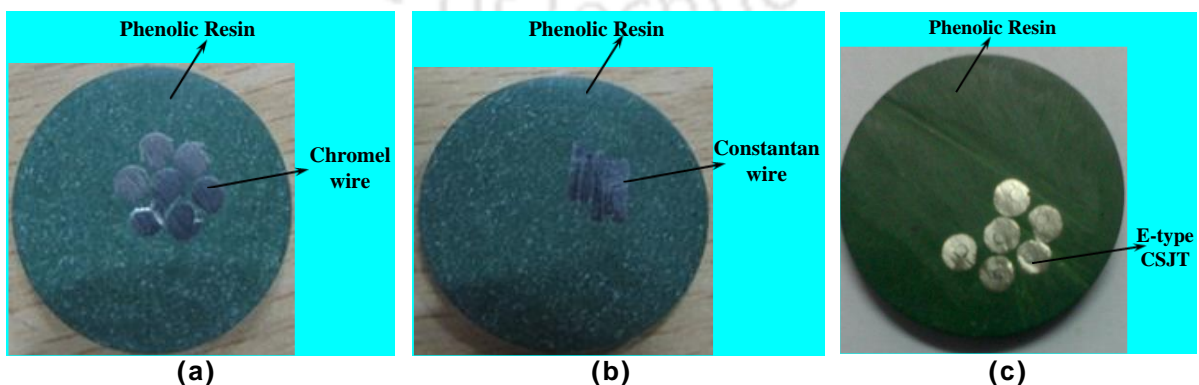
**Chapter 3** describes the numerical modelling of coaxial surface junction thermocouple using commercial package (ANSYS-Thermal Transient) to validate the use of the assumption theory of one-dimensional heat conduction into semi-infinite solid and in turn strikeout an appropriate dimension for the thermal sensor. The study has confirmed the choice of the dimension of the thermal sensor for the validation of the semi-infinite theory up to one-second timescale of temperature data. Additionally, mathematical details with respect to one-dimensional heat conduction equation for recovery of heat flux in relation to fitting related to linear, polynomial and cubic-spline based have been discussed (Schultz and Jones, 1973; Sahoo and Peetala, 2010). The chapter also highlights the design parameter that needs to be considered before fabrication of a coaxial thermal sensor.

**Chapter 4** throws a valuable contribution on the details of the fabrication of the coaxial surface junction thermocouple along with the characterization of the sensor using X-ray diffractometry technique (to

validate the discussion of plastic deformation of the thermocouple material at the junction). Four different types of coaxial surface junction thermocouple namely, E (Chromel-Constantan), K (Chromel-Alumel), T (Copper-Constantan) and J (Iron-Constantan)-types respectively has been fabricated (Fig. 2). The XRD analysis confirmed the formation of plastic deformation when one thermocouple material is swaged over the other material (Figs. 3). The motivation for the attempted fabrication has been to strike out a best possible coaxial thermal sensor, which can be applied to any environment. Additionally, it gives a valuable insight as to why spot-welded or connecting welds are more reliable than the joint attempted by soldering the lead wire. In conjunction, a calibration methodology using both temperatures with oil-bath technique (sensitivity determination) and constant heat flux technique with a laser of constant wattage have been worked out. The sensitivity value of 58.96, 28.47, 43.82 and 36.02  $\mu\text{V}/^\circ\text{C}$  respectively has been obtained for E, T, J and K-type respectively (Fig. 4).

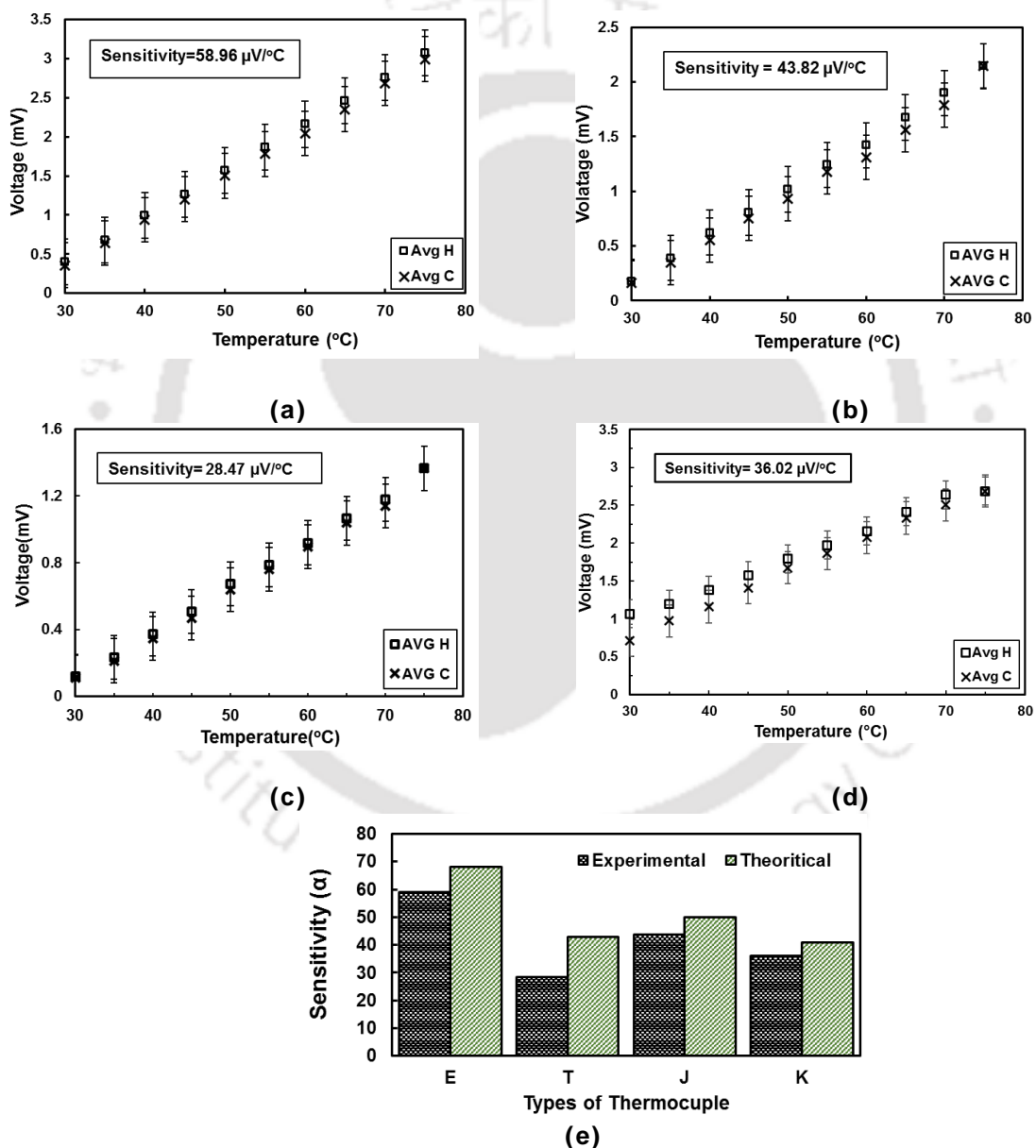


**Fig. 2:** Schematic and pictorial representation of the in-house fabricated CSJT namely, (a) E-type, (b) K-type, (c) T-type, (d) J-type

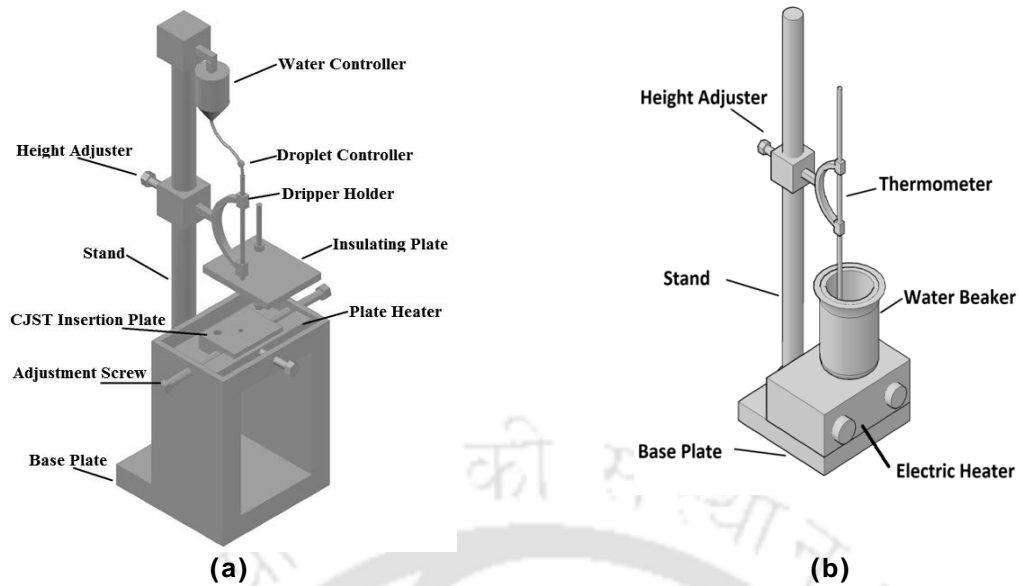


**Fig. 3:** Mould created for the experiment using phenolic resin (a) chromel wire, (b) constantan wire, and (c) E-type CSJT

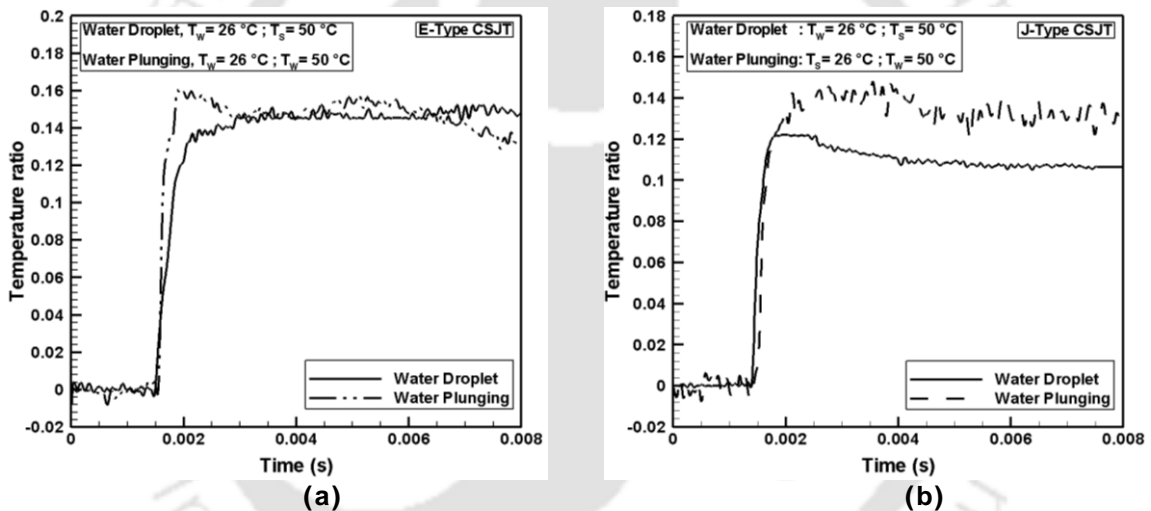
Chapter 5 describes the experimental techniques for the thermal product estimation by using the water-droplet and water-plunging methods for the fabricated thermocouple of E and J-type respectively (Fig. 5). The experimental evaluations of TP values are compared with the corresponding theoretical estimates for both types of CSJTs (Fig. 6). Subsequently, the effects of TP values on surface heat fluxes are analyzed by comparing them with peak and average heat loads. The surface temperature histories and average heat flux for all the experiments are in very good agreement. The experimental determination of TP values for E-type CSJTs are in close resemblance (within  $\pm 3\%$  accuracy). Based on the results of experiments, the E-type CSJTs are found to be better in comparison to J-type CSJTs in terms of its sensitivity and consistency in predicting surface heat flux accurately.



**Fig. 4:** Calibration graph showing a variation of voltage with a temperature of (a) E-type, (b) J-type, (c) T-type, and (d) K-Type CSJTs; (e) the bar chart showing the comparison of sensitivity value between theory and experiment.



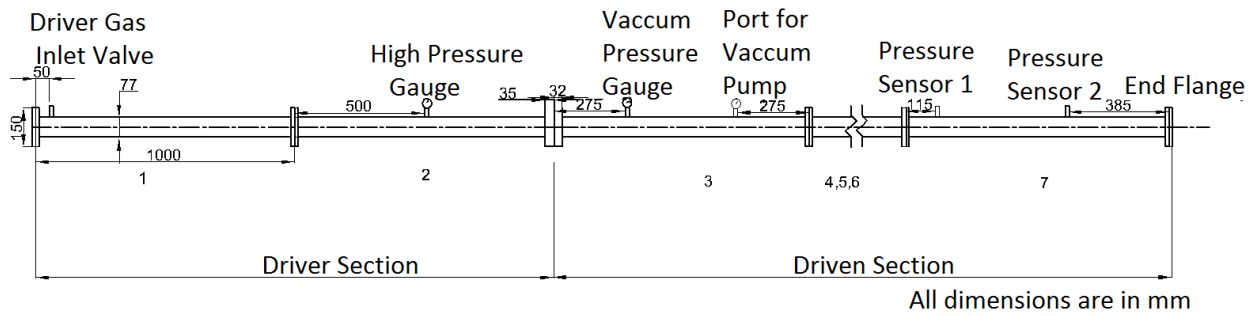
**Fig. 5:** Experimental arrangement CSJTs for determination of thermal product: (a) water droplet technique; (b) water plunging technique



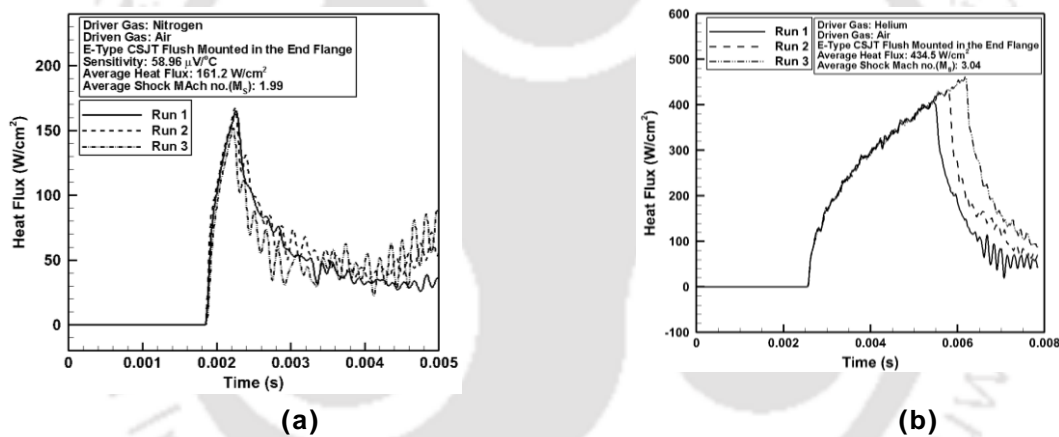
**Fig. 6:** Transient variations of non-dimensional temperature ratio for CSJTs during water droplet (WD) and water plunging (WP) technique at fixed water temperature and the surface temperature of the plate: (a) E-type; (b) J-type

Chapter 6 dwell on the comprehensive investigation of the development of a moderate size shock tube (Fig. 7) suited for a variety of interdisciplinary applications and in turn determine the stagnation heat flux by using in-house fabricated coaxial surface junction thermocouple (driver gas: helium/nitrogen and driven gas: air). The measurement of heat flux has been aimed by flush mounting a thermocouple at the driven section end of the shock tube mainly by two means namely flush mounting directly on the end flange and secondly flush mounting on a hemispherical model fitted at the end flange. The first technique is utilized to calibrate the shock tube and demonstrate it as an additional measurement diagnostics for calibrating the thermal sensors. From the experimental results, it was observed that the maximum rate of temperature rise recorded by the presently designed thermocouple is noted to be 7800 K/s. This limiting value is marked to be a characteristic constant of the sensor since it is found to be independent of the magnitude of the step change in temperature. Further, the second

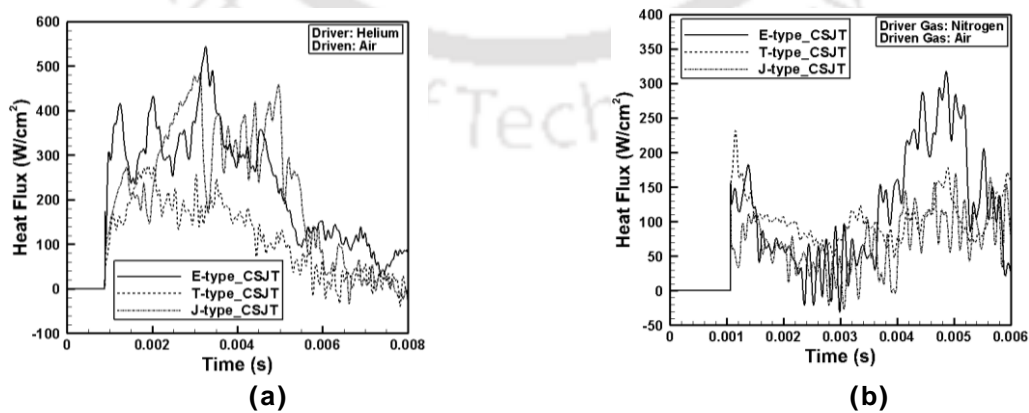
methodology is aimed at measuring the stagnation point heat using different in-house fabricated thermal sensors. The experimental evidence shows a reasonable agreement between theoretical results. In addition, the shock tube is used to measure the stagnation point heat flux using the in-house fabricated thermal sensors housed on a 10 mm radius hemispherical model. The experiment intends for a comparative assessment of different thermal sensor in a low supersonic environment. The obtained results have shown reasonable accuracy among the different thermal sensor justifying the usability of the thermal sensor in the low supersonic region (Figs. 8 and 9).



**Fig. 7:** Schematic of the shock tube facility at IIT Guwahati



**Fig. 8:** Surface heat flux histories from E-type CSJT mounted on the end flange of the shock tube.



**Fig. 9:** Heat flux signal obtained from the temperature history of CSJTs flush mounted on the hemispherical model fitted at the end-flange of the shock tube.

Chapter 7 focuses on a comparative study using thermal sensors to estimate stagnation point heat flux in the hypersonic facilities such as shock tunnel at a flow Mach number of 8.2 (Fig. 10). Two sets of experiments are repeated, one with the rake assembly (hemispherical body) and the other with the use of flat plate inclined at an angle  $30^\circ$  (Fig. 11). For the first set, all of them are mounted simultaneously in a rake along with a pitot-probe, in the test section of the tunnel where they experience a step heat load through a slug of test gas prevailing for 1 ms flow duration (Fig. 12). Similarly, for the second set, a total of nine CSJTs are mounted on a wedge assembly at a different location of 4 mm, 24 mm and 44 mm away from the leading edge respectively; each x-location is equipped with all the three sensors. Subsequently, the transient temperature histories are recorded at stagnation point as well as over the wedge body using the junction probe and surface heat fluxes are predicted through one-dimensional heat conduction modelling. Side by side, both the stagnation and the leading edge heat flux are estimated independently through numerical simulations. For the stagnation heat flux, the estimation is also done with analytical methods under same experimental flow conditions. The surface heat flux is recovered within a reasonable accuracy for E and T-type probes when experimental results are compared with numerical simulation for both sets and analytical solutions for stagnation heat flux.

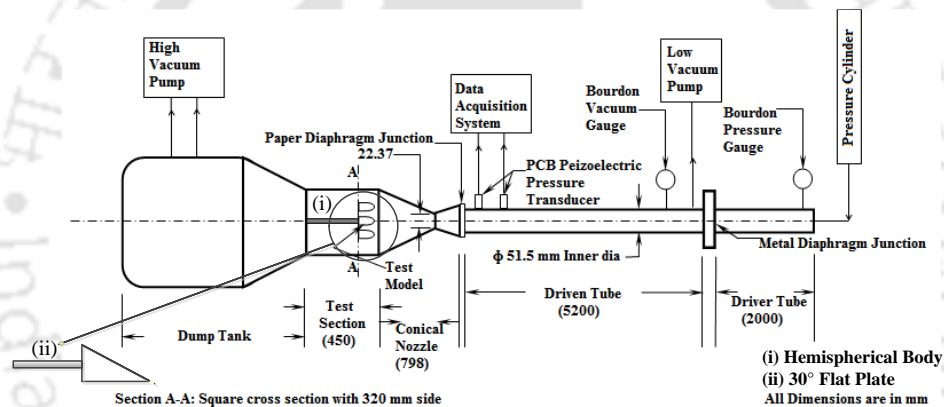


Fig. 10: Hypersonic shock tunnel experimental facility

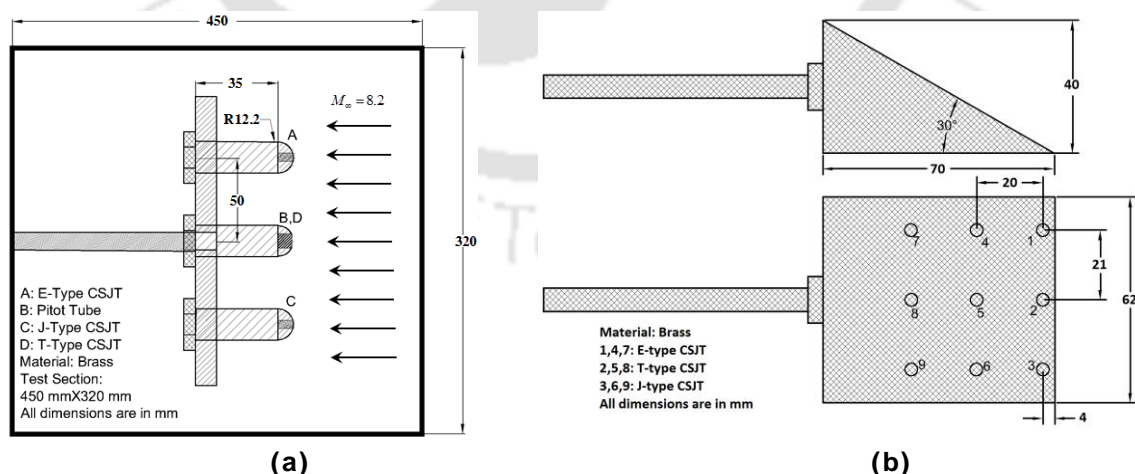
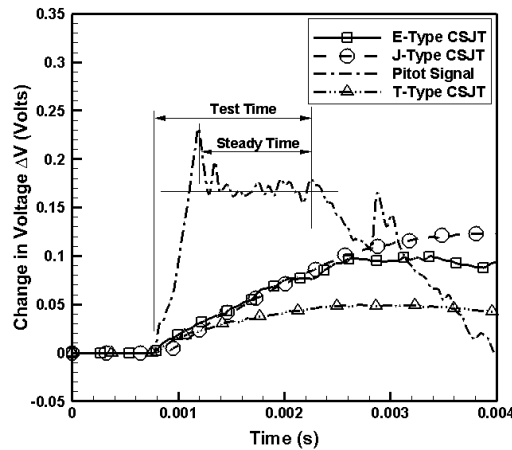
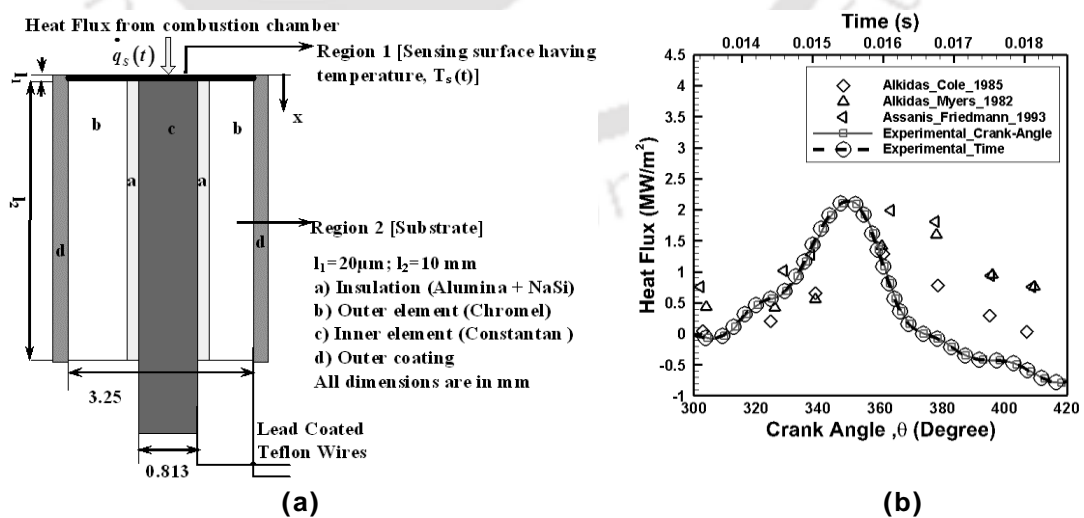


Fig. 11: (a) Hemispherical model housing surface junction probes and pitot pressure transducer for shock tunnel experiments; (b) schematic of the  $30^\circ$  inclined flat plate (wedge-body).

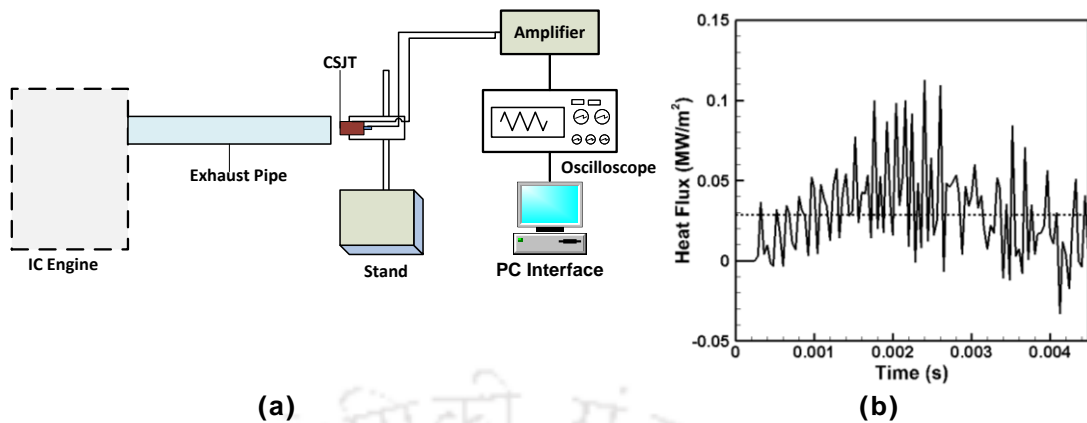


**Fig. 12:** The voltage signal from Pitot transducer and thermal probe during shock tunnel experiments

The core theme of [Chapter 8](#) remains to investigate the feasibility of the use of coaxial surface junction thermocouple to measure heat flux inside the combustion chamber of an internal combustion engine ([Fig. 13-a](#)) and further, at the exhaust port of the engine ([Fig. 14-a](#)). The chosen CSJT is slightly different from the one explained in [chapter 4](#), a different epoxy-resin (a mixture of alumina and sodium silicate instead of Araldite) is used to withstand the high temperature environment ([Fig. 13-a](#)). In short, the study intends to evaluate the measurement capability and endurance of the sensor for a periodic change in heat load ([Fig. 13-b](#) and [Fig. 14-b](#)). Both the experiments have been conducted and have shown a satisfactory trend and magnitude ([Fig. 13-b](#) and [Fig. 14-b](#)). The obtained results from the combustion chamber have been compared with the similar work attempted by the previous researchers ([Alkidas and Cole, 1985; Alkidas and Myers, 1982; Assanis and Friedmann, 1993](#)). Both, the study has shown the feasibility of the development of a cost-effective, rugged, robust and reusable E-type coaxial thermal sensor for its application in the combustion chamber of the internal combustion engine. Further, it is observed from the study that the same thermal sensor as explained in [chapter 3](#) can be used in different applications with just slight alteration in its insulation material.



**Fig. 13:** (a) Schematic of the CSJT fabricated for its application in the combustion chamber of the internal combustion engine; (b) Comparison of heat flux results.

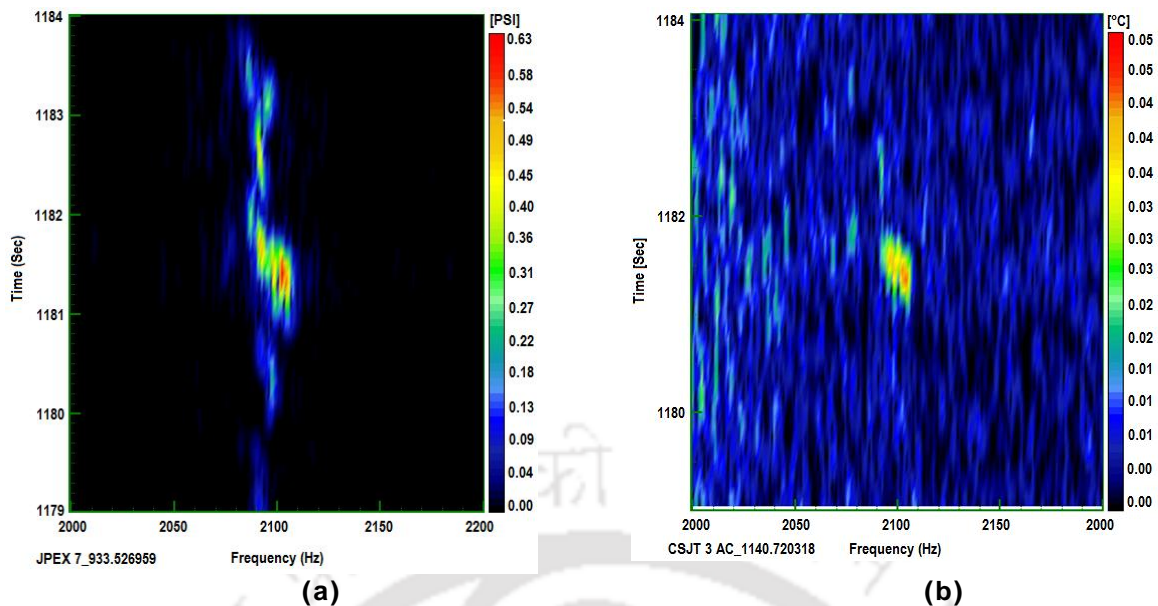


**Fig. 14:** Schematic representation of experimental setup for measuring exhaust gas temperature using a coaxial surface junction thermocouple.

Chapter 9 explores the design and fabrication of a special type of K-type coaxial surface junction thermocouple along with its implementation in the indigenous afterburner turbofan engine (Fig. 15-a) to detect the combustion instability (screech phenomenon) [Saravanamutto *et al.*, 2001]. In this chapter, the author intends to utilize this sensor as “product-oriented thermal probe” for industrial application (Fig. 15-b). The focus is inclined towards mounting the thermal sensor in the “jet pipe section” of the large-scale gas turbine engine where the expected temperature is more than 1000°C. In nutshell, the investigation is intended for possible application of coaxial surface junction of thermocouple beyond heat flux measurement in the rig of the gas turbine engine. Few preliminary experiments have been performed for checking the feasibility of the developed sensor for its application in the high-temperature environment of the gas turbine engine. The recovered signals from the experiments have shown some interesting results depicting the usability of the thermal sensor for capturing the transient phenomenon in the jet pipe (Fig. 16). Lastly, Chapter 10 gives the summary and scope of future research work.



**Fig. 15:** (a) Miniature CSJT probe housed in a barrel, (b) packaged sensors for gas turbine engine testing



**Fig. 16:** Spectrogram showing screech phenomena in a gas turbine engine: (a) pressure transducer; (b) In-house developed K-type surface junction probe.

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## List of Publications

### **Book Chapter:**

1. Agarwal S and Sahoo N (2016) Exhaust gas flow field simulation of an internal combustion engine for a thermal sensor, *Fluid Mechanics and Fluid Power – Contemporary Research*, Springer India, pp.195-203 ([https://doi.org/10.1007/978-81-322-2743-4\\_20](https://doi.org/10.1007/978-81-322-2743-4_20)).

### **Journal Paper:**

1. Agarwal S and Sahoo N (2018) An experimental investigation towards calibration of a shock tube and stagnation heat flux determination, *International Journal of Aerodynamics (IJAD)*, 6, 18-40 (<https://doi.org/10.1504/IJAD.2018.089780>).
2. Agarwal S, Irimpan KJ, Sahoo N, Menezes V and Desai S (2017) Comparative performance assessments of surface junction probes for stagnation heat flux estimation in a hypersonic shock tunnel, *International Journal of Heat and Mass Transfer*, 114, 748-757 (<https://doi.org/10.1016/j.ijheatmasstransfer.2017.06.109>).
3. Agarwal S, Sahoo N and Singh RK (2016) Experimental techniques for thermal product determination of coaxial surface junction thermocouples during short duration transient measurements, *International Journal of Heat and Mass Transfer*, 103, 327-335 (<http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.062>).
4. Nanda SR, Agarwal S, Sahoo N and Kulkarni V (2017) Shock tube as an impulsive application device, *International Journal of Aerospace Engineering*, 2010476 (<https://doi.org/10.1155/2017/2010476>).
5. Agarwal S and Sahoo N (2017) Stagnation point heat flux measurement in the shock tube using coaxial surface junction thermocouple, *Journal of Energy Heat and Mass Transfer* (under review).
6. Agarwal S and Sahoo N (2017) Determination of instantaneous surface heat flux inside the combustion chamber of an internal combustion engine using coaxial thermal probe, *Journal of The Institution of Engineers (India): Series C*, (under review).

### **Conferences:**

1. Agarwal S and Sahoo N (2017) Surface junction temperature probe in shock tube flows, *24<sup>th</sup> National and 2<sup>nd</sup> International Conference on Heat and Mass Transfer (IHMTTC)*, 27-30 December, BITS Pilani Hyderabad, India.
2. Agarwal S and Sahoo N (2016) Comparative analysis of stagnation point heat flux over a hemispherical model using different types of thermal sensors in the shock tube, *4<sup>th</sup> National Symposium on Shock Waves (NSSW)*, 25-26 February, Karunya University, Coimbatore, India.
3. Agarwal S and Sahoo N (2015) Coaxial surface junction thermocouple for transient measurements in the combustion chamber of an internal combustion engine, *International Conference on Advances in Energy Research (ICAER)*, 15-17 December, IIT Bombay, India.
4. Agarwal S and Sahoo N (2015) Stagnation point heat flux measurement in the shock tube using coaxial surface junction thermocouple, *23<sup>rd</sup> National and 1<sup>st</sup> International Conference on Heat and Mass Transfer (IHMTTC)*, 17-20 December, Thiruvananthapuram (ISRO), India.
5. Agarwal S and Sahoo N (2015) A coaxial surface junction thermocouple – fabrication and testing in internal combustion engine, *Frontier Energy Research with Industry Academia Partnership (FERIAP)*, March 20-21, IIT Guwahati, India.
6. Shrutidhara S, Agarwal S and Sahoo N (2014) Numerical and experimental study for measurement of exhaust gas temperature and heat flux using thermal sensors in an internal combustion engine, *Sixth International Conference on Theoretical, Applied, Computational and Experimental Mechanics*, December 29 – 31, 2014, IIT Kharagpur, India.
7. Agarwal S, Siddhant P and Sahoo N (2014) Numerical analysis of a coaxial surface junction thermocouple for temperature measurement in the exhaust of an internal combustion engine, *5<sup>th</sup> International and 41<sup>st</sup> National Conference on Fluid Mechanics and Fluid Power (FMFP)*, December 12-14, IIT Kanpur, India.
8. Agarwal S, Siddhant P and Sahoo N (2014) Fabrication and static calibration of a coaxial thermocouple for short-duration transient measurement, *3<sup>rd</sup> National Symposium on Shock Waves (NSSW)*, February 21-22, IIT Bombay, India.