DYNAMIC CALIBRATION OF TEMPERATURE SENSORS FROM LIGHT RAYS FOR TRANSIENT MEASUREMENT

by

Rishikesh GOSWAMI and Rakesh KUMAR*

Department of Mechanical Engineering,
Indian Institute of Technology (Indian School of Mines) Dhanbad, Dhanbad, India

Original scientific paper
https://doi.org/10.2298/TSCI170303198G

Measurement of transient heat fluxes in the applications involving very short duration of a heating environment which has been promised for the candidate by measurement of surface heating rates with thin film gauges (TFG). They are basically resistance temperature detectors having to measure in a very short duration of time. In the present study, a platinum based TFG has been fabricated and dynamically calibrated (radiation based) in the laboratory with a view to assessing the performance of platinum thin film gauges (PTFG) in the dynamic environment. These examinations are focusing to explore the probability of using TFG for small duration transient measurements with pure radiation mode of heat transfer. Radiation based heat flux is applied on the gauge by using the halogen bulb in a square box and its response is obtained through measured transient temperature. Subsequently, the surface heat fluxes are estimated by using radiation-based heat transfer. The purpose of this work is to statically calibrate each handmade heat transfer gauges by using quartz as substrate material deposited on platinum paste. This experiment has been carried out by oil bath based experimental technique. The similar experimental environment is also studied to observe the transient temperature response by using numerical simulation. The experiments are carried out by exposing the platinum TFG to various known step heat load of known input wattage, for the duration of 10 seconds. Then, the voltage signals are recorded due to change in temperature of air-flow past the TFG. The numerical simulation (ANSYS-Fluent v. 14.5) is performed in the similar experimental environmental conditions, for the same heating loads. Experimentally recorded temperature signals from the gauges are compared with simulated temperature histories obtained through finite element analysis. Cubic spline methods of the 1-D heat conduction equation are used to predict surface heat flux and compared with input heat loads. The presently developed calibration set-up is seen to very useful for radiation-based measurements of TFG.

Key words: *thin film gauges, radiation based calibration, analytical analysis, numerical analysis*

Introduction

Heat transfer analysis in short duration time scale is very difficult aspects due to the need for fast response temperature sensors. The TFG is a resistance temperature detector which is the combination of a high conducting (sensor) and lower conducting materials (substrate). Measurement of transient measurement transient temperature data for prediction of surface heat flux is the commonly used path in methodologies of these objects. Temperature sensors used in these measurements should have the faster response time and high accuracy in measurement.

*Corresponding author, e-mail: rakesh@iitism.ac.in

Thermocouples and thin film sensors or resistance temperature detectors are among the most commonly used sensors for these measurements. Thin film temperature gauge is an efficient candidate in these applications since they can respond in microsecond durations due to their extremely small thickness (μm or nm). The resistance of the gauge is formed by depositing high conducting materials like platinum, nickel, and silver, (ink/paste/powder/solid form) on the insulating ceramic substrates (such as quartz). Successful implementation of various types of TFG [1, 2] and different types of thermocouples [3-9] has been reported by various research groups.

When the TFG are exposed to transient environments of rapidly changing temperature, the resistance of gauge changes which can be detected by voltage variation provided the temperature coefficient of resistance (TCR) of the gauge. Application and development of the traditional TFG are described by several researchers [10, 11]. The most important characteristics of the TFG include high precision, sensitivity and most importantly rapid response time as low as 10 seconds by Piccini *et al*. [12]. The TFG consists of a high conductive metal mounted on an insulating substrate. Platinum is sensing material commonly used preparing the TFG due to better adhesive properties and higher TCR in comparison with backing materials. Either of these effects is seen to the simple linear relation between resistance and temperature encountered during the measurement of TCR [13-16]. Platinum is adhesive property to make it possible to deposit on commonly used backing materials like quartz. Considering the importance of these platinum based TFG, heat transfer measurements had been performed using these sensors [17]. Their applications have been further extended to in trace the pulsating variation of surface temperature and heat flux in internal combustion engines [18] and real-time measurement of electrolyte temperature detector in a polymer electrolyte fuel cell too [19]. Experimentally obtained transient temperature data from the surface mounted thin film sensors is then used for recovery of local heat flux. Various numerical techniques are developed for this uni-directional inverse heat conduction problem [20-22].

After critical review of literature it is found that very few researchers have attempted to calibrate the TFG with platinum as sensing and quartz is substrate material. In order to justify the effectiveness of TFGs in applications where the basic mode of heat transfer is *radiation* it is essential to calibrate such sensors in similar environments. The objective of the study is to devise a calibration method for TFG with respect to radiation mode of heating for short duration transient heating environment. Thus, the implementation calibration method of TFG for radiation based heat transfer and development of an experimental set-up are two important expected outcomes of this study. In this backdrop, the hand-made PTFG of adequate resistance is prepared with *quartz* as substrate material. Prediction of recovered heat flux from the measured temperature data is also one of the present research activities. The results of experiments and numerical simulation are compared for evaluating the performance of PTFG. Details of the experimental set-up, TCR estimation, sensitivity, experimental procedure and data reduction are discussed in the following sections.

Fabrication and study of thin film gauge

The TFG is the combination of higher conducting thin film (platinum/nickel) with a poor conducting substrate material (pyrex/macor/quartz). In present investigations, the gauges are prepared using platinum ink mounted on the quartz substrate. Quartz is the substrate or backing material for present investigations. Very low thermal conductivity and good electrical lining properties are the major reasons for obvious selection of quartz as the substrate material without current flow through the wire and measured output data. They are generally used data acquisition system DAS or multimeter. A quartz rod of the diameter of 5 mm and length 8 mm is used as backing material while making the present thermal sensor. Platinum paste (SPI platinum, West Chester, Penn., 19381, USA) which primarily a liquid having suspension of platinum particles is appliedon such appropriately polished substrate surface.

Evaporation of the chemical binders of the ink has been ensured by drying the film at around 650 °C in the temperature by the blast furnace. These quartz materials are then naturally cooled the atmospheric temperature before making the formal electrical contacts. Silver paste has applied either side of the sensor is used to achieve necessary electrical connections with the wires. These quartz material painted with silver paste are first dried by gradual heating till small blast furnace (Oven) up to heating 350 °C in the oven and cooled naturally to room temperature. The photograph of a quartz TFG prepared with the above method is shown in fig. 1 and schematic diagram of TFG shown in fig. 2. The thermal conductivity of thin film gauges material is the most important role in measuring of highly transient heat transfer rate. Platinum is in the form of the paste that can be used to fabricate a thin film on the substrate material surface. Electrical connections are made on the additional silver stripes by soldering lead wires on them and these lead wire connections are wrapped with *teflon* to secure them. The final resistance is measured with a multimeter at the end of the connecting wires. The typical TFG fabricated in laboratory with above procedure in shown fig. 1. Its resistance is found to be 12 Ω.

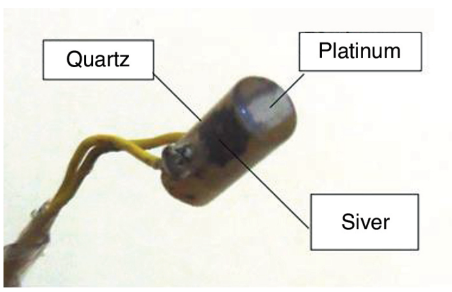

Figure 1. Photograph of a quartz TFG fabricated in-lab

Working principle of thin film gauges

The resistance of a thin film sensor is more sensitive to temperature and increases when exposed to a heating environment. Mathematically, it may be expressed as

$$R = R_0 [1 + \alpha (T - T_0)] \tag{1}$$

where R is the resistance of the gauge at any arbitrary temperature T, R_0 is the resistance at room temperature T_0 and α is the TCR. The TFG are passive sensors and have to be powered by a constant current source (CCS). In the present case, a constant current is 0.55 amp is used to energize the sensor for which the initial resistance is maintained around 12 Ω. The constant current is applied using a source meter (Keithley) which also has the provision to record the change in voltage and resistance. Using Ohm's law, the relation between change in voltage and change in temperature signal is given by equation:

$$\alpha = \frac{1}{v_0}\left(\frac{V - V_0}{T - T_0}\right) = \frac{1}{v_0}\left(\frac{\Delta V}{\Delta T}\right) \tag{2}$$

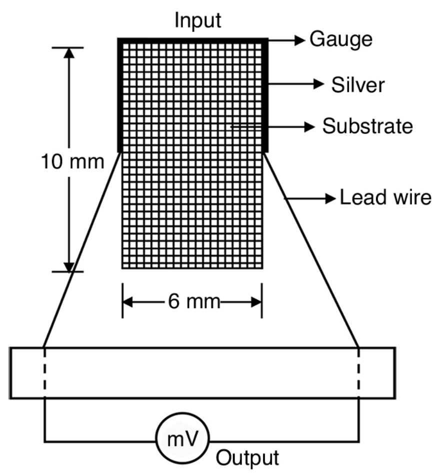

Figure 2. Schematic diagram of thin film heat transfer gauge

Change in output signal voltage is directly proportional to the change in temperature applied to the heat transfer gauges. Sensitivity is defined as the change in physical properties per unit temperature. It is denoted by S. Sensitivity of a material is conventionally defined as:

$$S = \frac{\Delta V}{\Delta T} \tag{3}$$

So, the information of TCR of the sensing material is mandatory for inferring the temperature change and is generally obtained using oil bath technique.

Static calibration of thin film gauge

In typical experimental set up for evaluation of TCR determination using oil bath technique is shown in fig. 3. Static calibration generally used to check resistance of TFG increases or decreases uniformly with temperature or not. The oil bath arrangement provides a gradual increase in temperature fed to the sensors by creating a natural draught of hot air over the sensor. The same sensor can be cooled naturally to span the voltage variation with temperature. In the present study, a voltage change in sensor due to temperature variation is recorded from the source meter during heating and cooling process. Simultaneously, the temperature is monitored using a scientific thermometer placed at the same height of the sensor. The K-type thermocouple is used to measure the temperature of inner chamber. The TFG were fabricated and after that static calibration then check the resistance of TFG and accuracy and then after radiation based dynamic calibration is performed 3 to 5 times after that certain time interval (23 minute) reached the steady-state and then recorded the transient temperature. Natural convection is maintained with help of constant temperature and pressure. Experiments have been repeated five times and drawn plot is average value of experimental data. When the temperature of the air is increased the readings are taken from 45 °C to 85 °C the interval of 10 °C followed by heating and cooling at same interval fig. 4. After that, a linear relationship between voltage with change in temperature during heating and cooling process is obtained. Resistance of sensor is measured carefully just before the experiment at room temperature to obtain initial voltage, V_0. It is seen that the heating curve and cooling curve vary linearly with voltage and do not follow the same path getting initial value of temperature. There is a lag between the internal and the external field *i.e.* behaviour of resistance change is different during heating and cooling. This behaviour results in a loss of energy, commonly called as the *hysteresis loss* in the form of heat. Hence, the average value of TCR for both heating and cooling experiments is evaluated. Repeatability and reproducibility are ways of measuring precision. In generally, perform the same experiment several times in order to confirm their findings. Finding may show variation. In the

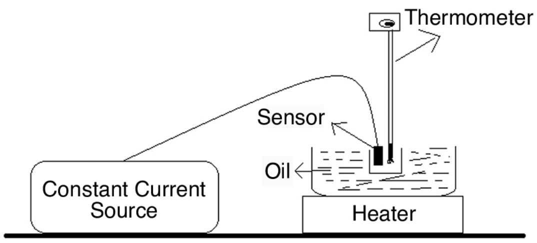

Figure 3 Schematic diagram of oil bath method to determination of TCR

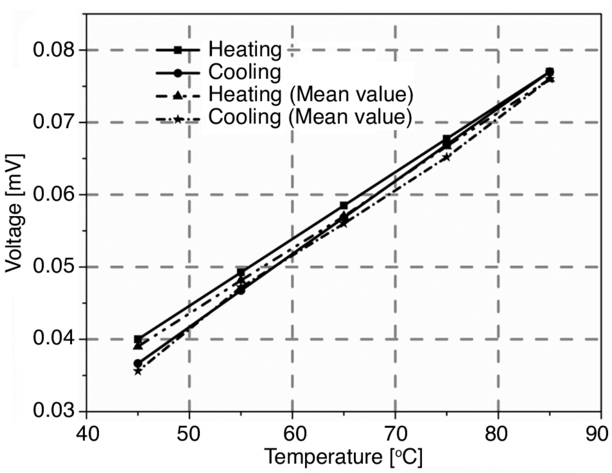

Figure 4. Variation of voltage with temperature during heating and cooling process in oil-bath experiments

experiment, repeatability measures the variation in measurements taken by a single instrument or person under the same conditions, while reproducibility measures whether an entire study or experiment can be reproduced in its entirety. For present experiments, the average value of TCR is measured to be 0.036415 K^{-1} and sensitivity is 475μV/K, fig. 5.

Radiation based dynamic calibration of thin film gauge

Experimental analysis with the help of light rays

The main aim of the dynamic experimental set-up is to supply constant heat flux of known wattage to the platinum TFG for radiation mode of heat transfer. Dynamic calibration process involves calibration of measured that changes with time. An oral thermometer is used to measure temperature. As temperature changes with time, the type of calibration recommended is dynamic calibration. For this purpose, the present set-up is comprised of a constant power supply source, CCS and computer-based DAS. Box wall is well insulated with the help of teflon material therefore reflection of light inside the box initially occurs. The temperature inside the box has been measured with the help of K-type thermocouple shown in fig. 6. The role of the constant power supply source is to provide constant heat flux at one end of the sensor. First we have switch on lamp, then after certain interval of time (after 23 minute) temperature inside the box becomes constant then. Transient temperature have been measured with the help of TFG. The main objective of this chapter is to explore the implementation of heat transfer gauges for short duration transient measurements with pure radiation mode of heat transfer. A simple dynamic calibration set-up has been developed for supplying known input heat flux of different magnitudes to a handmade thermal sensors fabricated in lab. Experiments are carried out by applying heat load on the sensors by halogen bulb (500 W) through radiation which provides constant input heat flux at the sensing junction. Halogen bulb (500 W) have been fitted in the box rays are incident of box and also some error due to reflection, absorption. Finally the heat flux due to radiation evaluated is 33.67 KW/m^2 with the help of TFG. Thermal radiation emitted by a box at any temperature consists of a wide range of frequencies. The incandescent light bulb has a spectrum overlapping the black body spectra of the Sun and the

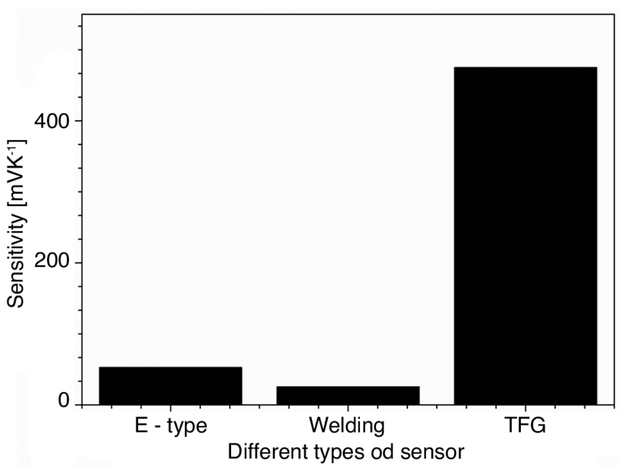

Figure 5. Comparison of sensitivity between different types of sensors

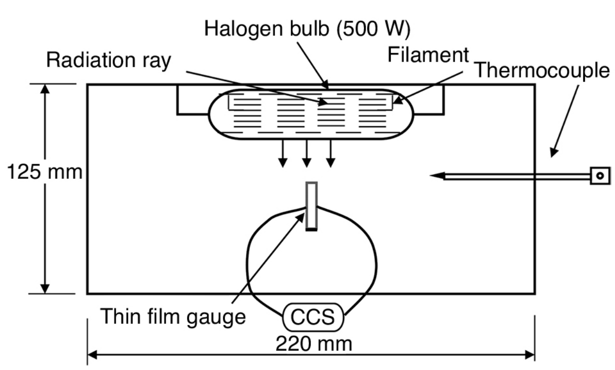

Figure 6. Schematic diagram of an experimental set-up for conduction based calibration of TFG

Earth. Whenever electro-magnetic radiation is emitted and then absorbed, heat is transferred. Box wall is well insulated with the help of teflon material therefore reflection of light inside the box initially occurs. But after certain period it becomes constant. Recorded transient temperature data are refined for estimation of input wattage using numerical and analytical models. For the known input heating load, temperature signal is also predicted using 1-D transient heat conduction solver of ANSYS and MATLAB. Hence, heat is conducted from one end to other with minimum loss through the surrounding surface during measurement of steady-state temperature through inside the box. Both sensor and thermocouple are fitted in the box and heated continuously till steady-state and temperature is recorded. Times constant are calculated as the TFG are 15.377 ms. This steady-state heat flux is used as the source of known radiated heat flux applied to TFG. The first source is the emission from the target object. However, not all radiation emitted by the target object is accepted by the box as a function of the transmittance of the atmosphere, τ_{atm}, some is absorbed by the atmosphere. In this numerical value using radiation equation $Q_{\mathrm{rad}} = \varepsilon \times A \times \sigma \times T^4$ where ε is the emissivity of plywood (0.83-0.98), A is the surface area of box, T is the measured temperature and σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}$ W/m^{2}K^4).
By using $T_{\mathrm{measured}} = 1012.011$ K, and following radiation heat transfer equation equations:

$$E_{obj} = \varepsilon_{\mathrm{obj}} \tau_{\mathrm{atm}} \sigma T^4{}_{\mathrm{obj}} \tag{4}$$

$$E_{refl} = \rho_{\mathrm{obj}} \tau_{\mathrm{atm}} \sigma T^4{}_{\mathrm{refl}} \tag{5}$$

$$E_{\mathrm{atm}} = \varepsilon_{\mathrm{atm}} \sigma T^4{}_{\mathrm{atm}} \tag{6}$$

$$W_{\mathrm{total}} = E_{\mathrm{obj}} + E_{\mathrm{refl}} + E_{\mathrm{atm}} \tag{7}$$

Heat flux was calculated as 24.68157 KW/m^2 [19].

Since the TFG are passive sensor and they are powered by 0.55A current using a CCS during the experiment. The output port of the CCS is connected to the data acquisition system for the monitoring the variation of voltage across the TFG. The thin film sensor which is initially at room temperature is brought suddenly in contact with the smooth surface of the sensor to apply the step heat flux. The voltage signal is recorded for the duration of 10 sec in the data acquisitiundson system. The calculated value of transient temperature data is obtained from the voltage signal. The same process is repeated for other step heating loads to obtain the temperature histories.

Finite element simulation for thin film gauge

The aim of numerical analysis is to configure the temperature signal for known heat flux values applied to a sensitive material. The commercial software (ANSYS) is used for 2-D finite element modelling of the TFG. In this transient analysis of the TFG, composite conduction studies are carried out by modelling platinum and quartz to simulate the sensing surface and substrate properly. The thickness of the platinum film is considered to be 1 μm while that of the quartz substrate is 10 mm and the width of the computational domain is to be 6 mm as shown in fig. 7. Extreme care has been arrested while meshing the computational domain due to a constraint of a very small thickness of a platinum layer. Mesh autonomy studies are also carried out for the authorization of computational results. Finally chosen mesh configuration includes 260 numbers of grid points in the platinum layer and 6500 number of grid points in the quartz side. Although surface heat flux is treated to be uniform along the width of the sensor, 70 number of node points are studied along the diameter of the gauge. Thermal properties of the materials used for simulation are given in tab. 1. The typical computational domain and the analogous boundary conditions are shown fig. 8. The boundary conditions applied at assorted surfaces build top wall exposed to sudden heating load (for platinum), a bottom wall as the isothermal wall (for quartz), adiabatic wall for side surfaces for platinum as well as quartz and the heat flux continuity interface between platinum and quartz. Uniform temperature of 300 K is considered as the initial condition in the computational domain.

Initial conditions for entire computational domain:

$$T\,(x,0) = 300\text{ K},\ 0 \le x \le L \tag{8}$$

Boundary conditions:

– At the top wall

$$X = 0 \text{ and } t > 0\ q\,(0,t) = \text{constant} \tag{9}$$

– At the bottom wall

$$X = L \text{ and } t > 0\ T(L,t) = 300\text{ K} \tag{10}$$

– At the interface of platinum and quartz

$$X = L \text{ and } t > 0\ \left[k\frac{\mathrm{d}T}{\mathrm{d}y}\right]_{\text{Platinum}} = \left[k\frac{\mathrm{d}T}{\mathrm{d}y}\right]_{\text{quartz}} \tag{11}$$

– and $[T(L,t)]_{\text{Platinum}} = [T(L,t)]_{\text{quartz}}$

Table 1. Thermal properties of sensing and substrate material

Sensor	Thermal conductivity [Wm^{-1}K^{-1}]	Specific heat c [JKg^{-1}K^{-1}]	Density, ρ [Kgm^{-3}]
Platinum	72	130	21450
Quartz	1.4	670	2200

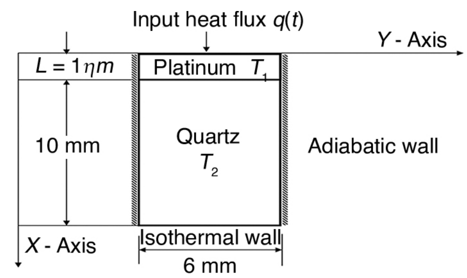

Figure 7. Schematic diagram of gauge-substrate system used for computational study

where k is the thermal conductivity, q – is the heating rates, T – is the temperature at any location, and t – is the time.

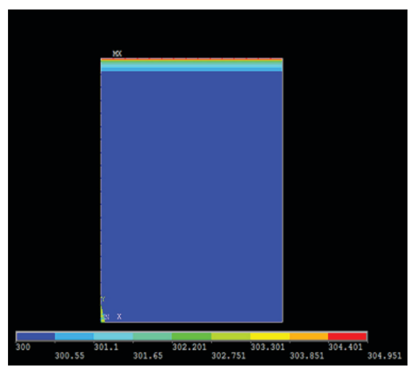

Figure 8. Temperature contours obtained from finite element simulation.

Determination of temperature history from analytical formulation

Transient temperature data can also be obtained from analytical formulation for the present heat transfer gauge configuration from constant heat flux by using 1-D heat conduction equation with a semi-infinite assumption for the backing material. This formulation can be obtained by solving 1-D unsteady heat conduction equation using Laplace transform technique:

$$T_1 - T_i = \frac{2\left(\frac{q_s}{A_s}\right)\sqrt{(\alpha_1\tau)/\pi}}{k_1}\exp\left(\frac{-x^2}{4\alpha_1\tau}\right) - \frac{(q_s/A_s)x}{k_1}\left(1 - \operatorname{erf}\frac{x}{2\sqrt{\alpha_1\tau}}\right) \tag{12}$$

where T_i is the ambient temperature and A_s is the cross-sectional area of the sensing material, α_1 $(= k_1/\rho_1 c_1)$ is the thermal diffusivity of gauge or sensing gauge material and τ is the time variable. Therefore, temperature history for the step heat load on the top surface of the sensing junction material ($x = 0$) heat transfer gauge or semi-infinite body can be calculated from eq. (12) and the expression is given by:

$$T_1 = \frac{2\left(\frac{q_s}{A_s}\right)\sqrt{\frac{(\alpha_1\tau)}{\pi}}}{k_1} + T_i \tag{13}$$

The temperature signals obtained from experiments for the heat loads and its comparison with Simulated and analytical temperature history is shown in the fig. 9. It is found that temperature rises instantaneously in the initial period and the trend of temperature variation is parabolic in all the cases. The parabolic rise of temperature plots ensures the analogous behaviour. With respect to the use of heat transfer gauges in transient applications.

Prediction of surface heat flux

The surface heating rates from transient temperatures in short duration time scale can be capture by using approximate 1-D heat conduction modelling. Since the thermal penetration distance during experimental run times is small compared to the linear dimension of the gauge, the system can be modelled by considering unsteady, linear conduction of heat in a 1-D semi-infinite solid. The following assumptions are made: temperature measured by the sensing element is identical to the temperature of surface of the substrate, no lateral heat conduction through the substrate and that heat is conducted only in the direction normal to the surface, and thermal properties of the substrate material is constant. The convolution integral equation is used to recover the surface heat flux from the temperature history [3] and it is given as:

$$q_s(t) = \sqrt{\frac{\rho c k}{\pi}} \int_0^t \frac{1}{(t-\tau)} \frac{\mathrm{d}\{T(\tau)\}}{\mathrm{d}\tau} \mathrm{d}\tau \quad (14)$$

The thermal properties for the substrate material (ρ, c, k) are given in tab. 1. Experimental temperature is represented by third order cubic spline method for reduction of surface heat flux. More details of this technique are available in literatures. These heat flux signals recovered from the temperature and heat flux data fig. 9, using the convolution integral eq. (14), are as shown in fig.10. Temporal natures of the heat flux and temperature traces obtained from present investigations are compared with the same reported in the literature for long duration testing. These results show excellent agreement between the applied and recovered heat signals in term of trend and magnitude. This observation reconfirms the unidirectional heat transfer and semi-infinite thickness of the substrate material.

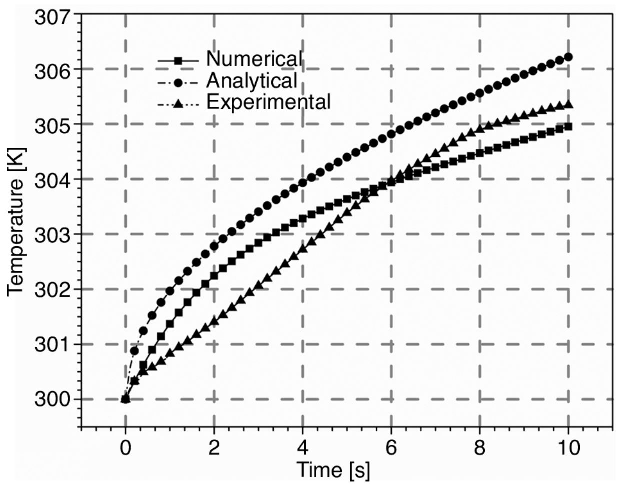

Figure 9. Comparison between transient temperature histories for platinum TFG obtained from experimental, numerical and analytical

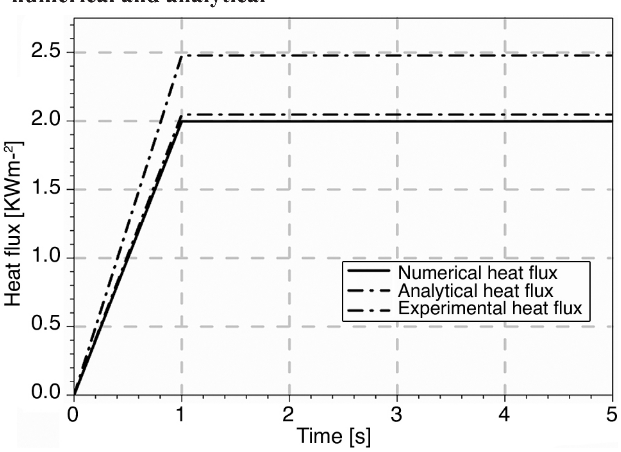

Figure 10. Calculated temperature values at dry machining

Conclusion

Radiation-based heat flux input technique has been developed to examine the transient temperature response of TFG. A TFG made by platinum paste mounted on a quartz substrate has been prepared in the lab. The temperature coefficient of resistance and sensitivity are measured using oil bath technique. A simple experimental set-up is run to supply the heating load of different magnitudes for the gauges. For same heat load, finite element analysis is performed using ANSYS and MATLAB to recover the temperature histories. Cubic spline and convolution integral method are performed to predict the surface heat flux by using all transient temperature data's. All these recovered signals for temperatures and surface heating rates are seen to be matched well within a reasonable uncertainty. Based on earlier observation it is found that rise in temperature in this technique is increased by 97.93% which proves the better time response within 10 seconds.

References

[1] Doorly, J. E.,Oldfield, M. L. G., The Theory of Advanced Multi-Layer Thin Film Heat Transfer Gauges, *Int. J. Heat Mass Transfer*, *30* (1987), 6, pp. 1159-1168
[2] Guo, S. M., *et al*., The Application of Thin Film Technology to Measure Turbine Vane Heat Transfer and Effectiveness in a Film Cooled Engine Simulated Environment, *Int. J. Heat Fluid Flow*, *19* (1998), 6, pp. 594-600
[3] Schultz, D. L., Jones, T. V., (1973) Heat Transfer Measurements in Short Duration Hypersonic Facilities, Report, AGARD-AG-1965, Advisory Group for Aerospace, Research and Development (AGARD), NATO,Washinton DC, 1974
[4] Lee, L. Y. W., *et al*., Liquid Solid Contract Measurements Using a Surface Thermocouple Temperature Probe in Atmospheric Pool Boiling of Water, *Int. J. Heat Mass Transfer*, *28* (1985), 8, pp. 1415-1423
[5] Marr, M. A., *et al*., A Fast Response Thermocouple for Internal Combustion Engine Surface Temperature Measurements, *Exp Thermal Fluid Sci*, *34* (2010), 2, pp. 183-189
[6] Alkidas, A. C., Cole, R. M., Transient Heat Flux Measurements in a Divided Chamber Diesel Engine, *ASME J Heat Transfer*, *107* (1985), 2, pp. 439-444
[7] Chen, J. C., Hsu K. K., Heat Transfer During Liquid Contact on Superheated Surfaces, *ASME J Heat Transfer*, *117* (1995), 3, pp. 693-697
[8] Mohammed, H., *et al*., Design and Fabrication of Coaxial Surface Junction Thermocoupes for Transient Heat Transfer Measurements, *Int. Commun. Heat Mass Transfer*, *35* (2008), 7, pp. 853-859
[9] Mohammed, H. A., *et al*., Determination of the Effusivity of Different Scratched Coaxial Temperature Sensors Under Hypersonic Flow, *Int. J. Thermophys*. *31* (2010), 11-12, pp. 2305-2322
[10] Mohammed, H., *et al*., The Transient Response for Different Types of Erodible Surface Thermocouples Using Finite Element Analysis, *Thermal Science*, *11* (2007), 4, pp. 49-64
[11] Mohammed, H. A., *et al*., Dynamic Calibration and Performance of Reliable and Fast Response Temperature Probes in a Shock Tube Facility, *Exp. Heat Transfer*, *24* (2011), 2, pp. 109-132
[12] Piccini, E., *et al*., The Development of a New Direct-Heat-Flux Gauge for Heat-Transfer Facilities, *Measurement Science Technol*., *11* (2000), 4, pp. 342-349
[13] Mohammed, H. A., *et al*., Thermal Product Estimation Method for Aerodynamics Experiments, *Eng. Phys. Thermophys*., *84* (2011), 4, pp. 785-794
[14] Mohammed, H. A., *et al*., Fast Response Surface Temperature Sensor Sensor for Hypersonicvehicles, *Instrum. Exp. Techn., 53* (2010), 1, pp. 153-159
[15] Mohammed, H. A., *et al*., The Effect of Scratch Technique on Thermal Product of Temperature Sensors, *Thermophys. Aeromech., 18* (2011), pp. 51-64
[16] Vidal, R. J., Model Instrumentation Techniques for Heat Transfer and Force Measurements in a Hypersonic Shock Tunnel, Report No, Cornell Aeronautical Laboratory, WADC, Dickson, Tenn., USA, 1956, pp. 56-315
[17] Benedict, R. P., *Fundamental of Temperature, Pressure and Flow Measurements*, *Resistance Thermometry*, John Willey and Sons, New York, USA, 1984. pp. 53-64
[18] Dunn, M. G., *et al*., Heat Flux Measurements for the Rotor of a Full Stage Turbine, in: ASME 31st int. Gas Turbine Conference, Dusseldorf, West Germany, 1986, pp. 8-12
[19] Maldague, X., *Theory and Practice of Infrared Technology for Non-destructive Testing*, Wiley, New York, USA, 2001
[20] Kumar, R., *et al*., Design Fabrication and Calibration of Heat Transfer Gauges for Transient Measurement, Proceedings, *ASME International Conference*, 2010, Vancouver, British Columbia, Canada

[21] Kumar, R., Sahoo, N., One Dimensional Heat Flux Analysis of Heat Transfer Thin Film Gauges forTransient Measurements, Proceedings, 5th International Conference on Theoretical, *Applied Computational and Experimental Mechanics*, IIT Kharagpur, India, 2010
[22] Kumar ,R., Sahoo, N., Analysis of Gauge and Substrate Material of Heat Transfer Platinum Thin Film Sensors, Proceedings,International Conference on Mechanical, Industrial and Manufacturing Engineering, *World Academy of Science, Engineering and Technology*, Holiday Inn Pairs, 2011 Paris, France, 2011

Paper submitted: March 03 2017
Paper revised: May 15 2018
Paper accepted: July 14 2018