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Conduction based calibration of handmade platinum thin film heat transfer gauges for transient measurements

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ABSTRACT

Heat transfer measurement using thin film gauges (TFG) is the most prevalently used technique for determination of surface heat flux. They are best suited for short duration transient surface temperature measurements and typically used in the applications where convection is a dominant mode of heat transfer such as gas turbine engines, high speed flights etc. However, in few interdisciplinary research areas, there are practical issues and difficulties in exposing the gauges for convection based measurements. These present investigations are aimed at exploring the possibility of using thin film gauges for short duration conduction based transient measurements with pure conduction mode of heat transfer. A simple calibration set-up has been used to supply known heat flux of different magnitudes to the thin film gauges that are fabricated in-house with platinum as sensing element and pyrex as an insulating substrate. Experimentally recorded temperature signals from the gauges are compared with simulated temperature histories obtained through finite element analysis. Convoluted integral of one-dimensional heat conduction equation is used to predict the surface heat flux and compared with input heat loads. The presently developed calibration setup is seen to be very useful for conduction based measurements of thin film gauges.

1. Introduction

Heat transfer analysis is the vital prerequisite for designing many engineering systems or sub-systems like heat exchanger, electric motor, steam and gas turbines, high speed flights etc. Measurement of transient temperature data for prediction of surface heat flux is the commonly used path in design methodologies of these engineering objects. Temperature sensors used in these measurements should have the capability of faster response time and high accuracy in measurement. Prediction of proper temporal nature of the heat load and precise quantification of the heat flux are the roots of these capability requirements from a typical thermal sensor. Thermocouples and thin film sensors or resistance temperature detectors (RTD) are among the most commonly used sensors for these measurements. Successful implementation of various types of thin film gauges [1,2] and different types of thermocouples [3–13] has been reported by various research groups.

Amongst the traditionally used sensors, thin film gauges (TFG) are more sensitive and suitable, compared to the thermocouple, for surface heat flux measurement, by the virtue of the traits of these sensors [14]. Application and development of the traditional TFG are described by several researchers [15,16]. The most important characteristics of the TFG include high precision, sensitivity and most importantly rapid response time as low as 0.1 μs by Piccini et al. [17]. The TFG consists of a high conductive metal mounted on an insulating substrate. Platinum is the commonly used sensing material while preparing TFGs due to better adhesive properties and higher temperature coefficient of resistance (TCR) in comparison with contemporary materials. However, platinum is extremely sensitive to the strains and minute contaminating impurities. Either of these effects is seen to alter the simple linear relation between resistance and temperature encountered during the measurement of TCR [18–20]. Excellent adhesive property of platinum makes it possible to deposit on commonly used backing materials like PYREX and MACOR. Considering the importance of these platinum based TFGs, heat transfer measurements had been performed using these sensors [21]. Usefulness of TFG based measurements for harsh test conditions like flight testing has also been proven [22]. Experimentally obtained transient temperature data from the surface mounted thin film sensors is then used for recovery of local heat flux. The theory of one dimensional transient heat conduction with assumption of semi-infinite sensor depth governs the physics of this measurement. Various numerical techniques are developed for this uni-directional inverse heat conduction problem [22–25].

It is clear from the exhaustive literature survey that thin film based transient temperature measurements and onwards data

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Nomenclature

q_s	Surface heat flux (W/m^2)	β	Temperature coefficient of resistance (K^{-1})
K	Thermal conductivity (W/(m K))	R	Initial thin film gauge resistance (Ω)
c	Specific heat (J/(kg K))	I	Current through the thin film gauges (A)
ρ	Density (Kg/m^3)	τ	Time variable (s)
α	Thermal diffusivity (m^2/s)		
ΔT	Change in temperature (K)		

reduction for heat flux is well-established for convective heat transfer measurements. There are potential research areas in which the transient measurements with TFGs can be extended for pure conduction mode of heat transfer. One of the applications for such measurements includes prediction of thermal properties of biomaterials where the sensor is not in contact directly with the heating medium rather inserted in the soft tissues of living plant/animal bodies [26]. The few other applications include characterization of thermo-physical property of various materials [27], thermal conductivity measurement of humidity sensors [28] and thermal perturbation sensor for ground temperature measurement [29]. In many applications there are difficulties in exposing the gauges directly to heating medium rather indirect measurements are performed with gauges in contact with certain materials where 'conduction' is dominant mode of heat transfer. In this back drop a research work has been initiated to explore the possibility of TFG for conduction based measurement in the laboratory. So the studies are planned for calibration of this useful sensor for conduction mode of heat transfer with known heat flux by using a simple experimental set-up. The implementation of TFG for pure conduction based heat transfer and development of a calibration experimental set-up are two important expected outcomes of this calibration methodology. Prediction of error in the recovered heat flux from the measured temperature data is also one of the objectives of present research activities. The thin film gauges are prepared with platinum as sensing element mounted on a pyrex substrate. Heat conduction experiments are carried out by exposing the platinum thin film gauges to various known step input wattage for the duration of 100 ms. Finite element simulation using ANSYS is performed for same heating loads to recover the surface temperature history of same time duration. Experimentally obtained temperature signal is compared with simulated temperature history. Also one-dimensional heat conduction modeling is used to recover the heating loads for both the transient temperature data and then compared with the known input heating loads. Details of the experimental set-up, temperature coefficient of resistance (TCR) estimation, experimental procedure and data reduction are discussed in the following sections.

2. Thin film gauge preparation and determination of TCR

A typical thin film gauge is comprised of an insulator as a substrate material (Pyrex/Macor/Quartz) painted or sputtered with a higher conducting thin film (platinum/nickel) as the sensing surface. Pyrex is selected as the substrate or backing material for the present investigations. Very low thermal conductivity and good electrical insulations properties are the major reasons for obvious selection of pyrex as the substrate material. In addition, it has higher permissible heating temperature of the order 1000 °C without significant geometric deformations. During the gauge making process, it has been ensured that the surface of pyrex is smooth and highly polished. Efforts are made to keep the backing material surface highly smooth and polished through the use of dry silicon carbide sand paper and crocus cloth along with the rotating flat disk. This polished and smooth surface ensures negligible contact resistance which is the prime requirement for conduction heat transfer measurement using a TFG. A pyrex rod of diameter 6 mm and length 10 mm is used as backing material while making the present thermal sensor. Platinum ink (SPI Platinum, West Chester, PA19381, USA) which is primarily a liquid having suspension of platinum particles is applied on such adequately 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 controlled oven. These platinum films are then naturally cooled to the atmospheric temperature before making the formal electrical contacts. Thickness of the platinum film of the present sensor is of the order of few micro-meters. Silver paste applied on either sides of the sensor is used to achieve necessary electrical connections with the wires. Due to use of silver paste, thickness of the silver film remains much greater than the platinum film. These silver films are first dried by gradual heating till 350 °C in the oven and then cooled naturally to room temperature. The photograph of a platinum thin film gauge prepared with the above method is shown in Fig. 1.

The change in resistance of sensing material by the virtue of change in temperature in the presence of heat source or sink is the principle of operation the gauge [18–20]. Measured transient voltage along with the known temperature coefficient of resistance (TCR) of the sensing material should be used to obtain the temperature history. In addition, it is also desired to have thermo-physical properties of backing materials for the recovery of surface heat flux using the numerical technique. Hence, prior knowledge of TCR of the sensing material is mandatory for determination of surface heat transfer rate.

In general, the oil bath technique is used to determine the TCR of the thin film sensor [18–20]. This oil bath arrangement provides gradual increase in the temperature (from room temperature till 85 °C) in the presence of natural draught of hot air over the gauge (Fig. 2). Afterwards, the same gauge is allowed to cool naturally to

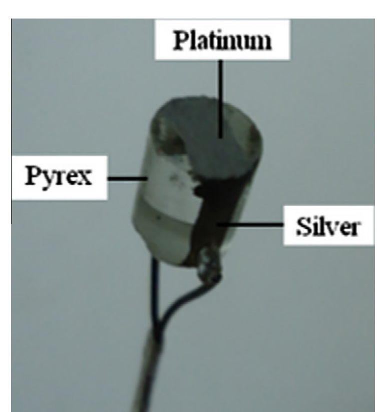

Fig. 1. Photograph of a platinum thin film gauge fabricated in-house.