Design fabrication and static calibration of thermocouple and thin film gauges

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Abstract. Thin film gauges are basically resistance temperature detector (RTD) sensors. It is a combination of high conducting (Sensor) and low conducting (Substrate) material. It operates on the simple principle that penetration of heat pulse from the high conducting material to the low conducting one is very small during the time span of the measurement. The present work is focused at design and fabrication of fast response thermocouples and thin film gauges (TFG) in the laboratory. Three types of thermocouples have been fabricated (E-type, E-type (Welding) and K-type) whereas platinum paste is deposited on the insulating substrate (Quartz) for thin film heat transfer gauge. The purpose of this work is to statically calibrate to each handmade heat transfer gauges by using oil bath technique. Both thermocouples and thin film gauges are calibrated under the same experimental conditions. The sensitivity of thin film gauge is found 268.919 % higher than the other sensing materials.

Key words: Thin film gauge; thermocouple; temperature coefficient of resistance; sensitivity

1. Introduction
The word heat transfer is mainly concerned with temperature and flow of heat. Temperature represents the amount of thermal energy available, while the heat flow represents the movement of thermal energy place to place by virtue of temperature difference. The rate of heat transfer per unit surface area known as heat flux. Thin film gauges are suitable for measuring the transient temperature of any heated body. This nature is susceptible about correct measurement of heat flux. During actual experimentation, this thin film gauge is mounted on the surface or placed at appropriate location where transient temperature history has to measure. Thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. So, they are called as active devices because no other instruments are required to supply the power. The measurement of thin film gauge technique has received a promising means to obtain the transient temperatures and subsequent prediction of surface heat flux [1]. There are many methods of measuring heat flux such as those reported in [2-3]. The advantages of thin film sensors were realized long back and this technique was implemented for measurement of surface temperatures or heat flux in internal combustion engines [4], gas turbine applications [5], and high speed flight experiments[6]. Thermocouples are widely used as the temperature sensor for measurement/control where the heat energy is converted to electric power. Among different types of thermocouple E-type thermocouple (Chromel-Constantan)[7] has a high output (68μV/K) which makes it well suited to “Cryogenic” use. Additionally its Non-Magnetic wide range is -50°C to 740°C. In K-type thermocouple (Chromel-Alumel) sensitivity approximately is found 41μV/K when the junction temperature is higher than reference Temperature. It is inexpensive and a wide variety of probes -200°C to 1350°C. The output change in voltage signals are measured by using source meter. Since, the thin film gauges are passive device, the sensors need to be energized by flow constant current (10mA) across sensors by using a constant current source (CCS) prior to the experiments [8]. CCS is also used to monitor the change in output voltage signals across the gauges for corresponding change in temperatures. However, some other contemporary techniques have been
developed for transient surface temperature measurements such as temperature sensitive paints [9], thin film calorimeter gauges [10], and coaxial surface thermocouple [11]. K-type is the most common general purpose thermocouple with a sensitivity of approximately (41μV/K) Chromel positive relative to alunel when the junction temperature is higher than the reference temperature. K-type was specified at a time when metallurgy was less advanced than it is today, and consequently characteristics may vary considerably between samples[13]. When the material reaches its curie point, this occurs for K- type thermocouples at around 1850°C. Further applications and development of the traditional TFG are described by the several researchers. It is widely used in non-contact temperature measurement applications and temperature monitoring systems. In the present investigation, the attention is focused to thin film gauge and different type of thermocouples. Thin film gauge has very high thermal conductivity with respect to thermocouple. The voltage and sensitivity are then estimated by measuring different temperature using the calibration technique. Several experiments have been carried out to evaluate the thermal coefficient of resistance (TCR) and also to compare the sensitivity of thin film gauge to other sensors. The fabrication of thin film gauges, thermocouple, design of experimental setup, measurement of voltage signal and sensitivity are described below.

2. Design and fabrication of thin film gauge
A thin film gauge is comprised of an insulator as a substrate material (Quartz) painted or sputtered with a higher conducting thin film (platinum) as sensing surface. Quartz is the substrate or backing material for present investigations. These are connected to DAS (Data acquisition system) or multimeter. A quartz rod of diameter of 5mm and length 8mm is used as backing material while making the present thermal sensor. Platinum paste (SPI platinum, west chester, PA 19381, USA) which primarily a liquid having suspension of platinum particles is applied on such appropriately polished substrate surface. Evaporation of the chemical binders of the ink has been ensured by drying the film at a temperature of 650°C in the temperature by blast furnace. It is then followed by natural cooling to room temperature before making the formal electrical contacts. Silver paste is applied either side of 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 350°C in the oven and cooled naturally to room temperature. The photograph of a quartz thin film gauge prepared with the above method is shown in Fig. 1. Thermal conductivity of thin film gauges material are most important role in measured of highly transient heat transfer rate. Platinum is in the form of paste that can be used to fabricate a thin film on the substrate material. The final resistance is measured with a multimeter at the end of the connecting wires. Its resistance is found to be 12Ω.

![Figure 1. Photograph of a Quartz thin film gauge fabricated in-lab](image)
2.1. Fabricated Thermocouple

Thermocouple constitutes two dissimilar metals (wires), joined at one end that produces a voltage corresponding to a temperature difference and open at the other end. The point where the two wires join up is called measuring point or hot junction. Three most common methods for thermocouple junctions are twisted junction, welded junction and soldered junction. These are the RTD sensors that can generate the voltage without any power sources and called as active sensors. It is important that the connection at the chromel-alumel (K-type thermocouple) and cromel-constantan (E-type) junctions are kept clean and free of any oxide or any other particulate matters. E-type (Welding) thermocouple is made by cromel-constantan wire and tip of junction is welded by Tunguston inert gas welding (TIG). Welded junction thermocouples are normally used for measuring the temperature of gas and solid materials. Further, in these environment, it is important to seal the measuring tip of the thermocouple in such a way that no moisture enters into the thermocouple. Diagram of E-type thermocouple is shown in Fig. 2.

![Figure 2. Handmade E-type thermocouple](image)

2.2. Static Calibration Method

Typical experimental set up for evaluation of TCR determination using oil bath technique is shown in Fig. 3. The oil bath arrangement provides gradual increase in temperature fed to the gauges by creating a natural draught of hot air over the sensor. Same sensor can be cooled naturally to span the voltage variation with temperature. In the present study, voltage change in sensor due to temperature change 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. When temperature of air is increased the readings are taken from 45°C to 85°C at the interval of 10°C followed by heating and cooling at same interval (Fig. 4,5,6,7). A linear relationship has been observed between voltage and temperature variation during heating and cooling process. Resistance of sensor is measured carefully just before the experiment at room temperature to obtain initial voltage (V₀). For present experiments, the average value of TCR is measured to be 0.034617 K⁻¹, 0.0133906K⁻¹, 0.01327221K⁻¹ and 3.521527×10⁻3 K⁻¹.
2.3. Working Principal of the Heat Transfer Gauges
An Estonian physicist, Thomas Johann Seebeck, discovered that when any Conducting material is subjected to a thermal gradient then it will generate a Voltage. The heat transfer gauges also operate on the same principle that the resistance of metal increases with a rise in surface temperature. When using heat transfer gauges the surface temperature is determined from the change in resistance of the sensing film materials. Resistance of sensing materials varies linearly with Temperature as

\[ R(T) = R_0[1 + \alpha (T - T_0)] \]  

(1)

Here, \( R_0 \) is the initial resistance of the gauge at temperature \( T_0 \) and \( \alpha \) is the TCR of the gauge. Since, TFGs need to be activated using a constant current source, the resistance can be converted to voltage form by using ohm’s and \( \alpha \) can be represented by following expression:

\[ \alpha = \frac{1}{V_0 \sqrt{T - T_0}} = \frac{1}{V_0} \left( \frac{\Delta V}{\Delta T} \right) \]  

(2)

The voltage parameters (\( V_0 \) and \( V \)) represent the corresponding voltage values at their respective temperatures (\( T_0 \) and \( T \)). Change in output signal voltage is directly proportional to the change in temperature applied to 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

\[ S = \frac{\Delta V}{\Delta T} \]  

(3)

3. Results and Discussions
All the sensors are connected to their respective constant current source devices and with reference thermal voltage corresponding to reference temperature from the digital thermometer. The static calibration results of sensors recorded in two cases, one with gradual increase of temperature of air from 45°C to 85°C. The temperature and voltage of the heat transfer gauges element were recorded in step of 10°C during heating and cooling process. Calibration results of thin film gauges with platinum and shown in Fig. 4. It indicates linear variation of voltage with temperature during heating and cooling process. The resistance of the gauge carefully measured just before the experiment at room temperature using multimeter. The voltage in Fig.4 reached 0.034V at 85°C due high resistance of platinum thin film. The thermal coefficient of resistance (\( \alpha \)) is calculated and found to be 0.034617 K\(^{-1}\) for Fig.4. Calibration results of E-type, E-type (Welding) and K-type thermocouples are shown in Fig. 5-7. The voltage of the thermocouples was determined at 85°C with the reference junctions at 0°C. The voltage of E-type, E-type (Welding), and K-type thermocouple reached 0.08 mV, 0.09 mV and
0.07mV respectively at 85°C. The thermal coefficient of resistance ($\alpha$) is calculated and found to be 0.0133906 K$^{-1}$, 0.01327221 K$^{-1}$ and 3.521527×10$^{-3}$ K$^{-1}$. Sensitivity of different sensor are calculate and shown in Fig. 8. Here, calibration data indicates that a linear variation of voltage with temperature in both cases when temperature of air increases as well as when temperature of air decreases. The temperature sensitivity of the sensors is checked regularly and it is found that for research purposes thin film gauges and thermocouples can be used to measure the temperature variations.

![Graph showing typical temperature–voltage signal obtained from platinum thin film gauge with Quartz as substrate materials.](image1)

**Fig 4.** Typical temperature–voltage signal obtained from platinum thin film gauge with Quartz as substrate materials.

![Graph showing typical temperature–voltage signal obtained from E-type thermocouple.](image2)

**Fig 5.** Typical temperature–voltage signal obtained from E-type thermocouple
Fig 6. Typical temperature–voltage signal obtained from E-type (Welding) thermocouple

Fig 7. Variation temperature-voltage signal obtained from K-type thermocouple

Fig 8. Comparison of Sensitivity between different types of Sensors
4. Conclusion
Oil bath type method for the fabrication and calibration of thin film heat transfer gauges and different types of thermocouples has been focused. The sensitivity and TCR are evaluated from the readings of thermometer used in experiments both for heating and cooling. Thermocouple junctions are generally formed by welding and soldering and therefore, during measurement analysis there are chances of errors. While, thin film gauges are generally formed by pure platinum materials and therefore error is minimized. E-type thermocouple with soldering has more sensitivity as compare to the welding due to higher purity. From results it is evident that, for all the sensors, thin film gauge has very high sensitivity with respect to other sensors. In welding the sensitivity is low due to impurity caused by melting. The main advantages are ease of manufacturing, reusability, and cost effectiveness.

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