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Radiation based calibration of thin film gauge for transient measurement

Tanweer Alam[a,*], Rakesh Kumar[b]

[a] Department of Mining Machinery Engineering, Indian Institute of Technology (Indian School of Mines) Dhanbad, IIT (ISM), Dhanbad, Jharkhand 826004, India
[b] Department of Mechanical Engineering, Indian Institute of Technology (Indian School of Mines) Dhanbad, IIT (ISM), Dhanbad, Jharkhand 826004, India

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ABSTRACT

Surface temperature history and determination of heating rate are the two important designing aspects in many research activities involving the surface heating due to thermal radiation encountered to the rocket base surface from the exhaust plumes, internal combustion engine surfaces due to burned gases etc. The measurement of heat flux attributed to thermal radiation for such application involves the use of thermal gauges to estimate the values from measured surface temperature history. Thin film gauges in general are preferred for the measurement of heat flux for its ability to give faster response along with high sensitivity value. The heat flux measurement using thin film gauge is mainly based on the sudden application of heat load to the sensor. In the present study, in order to produce the sudden heat load, a shutter is imposed in between incident radiation and the fabricated thin film gauge. The thin film gauge is in-house built with platinum as sensing element and quartz as an insulating substrate. This study aims to establish a new calibration technique for radiation based heat transfer mode. A fabricated calibration set-up is used to expose the thin film gauge to an environment where heat transfer will take place only due to radiation. The recorded transient temperature data during the experiment is further used to estimate heat flux. Moreover, the finite volume based numerical analysis is also carried out to recover the heat flux values. The excellent agreement of the experimental and numerical analysis results, authenticate the experimental set up as well as the effectiveness of the thin film gauge.

1. Introduction

The analysis of heat transfer is one of important aspect of the design of many engineering systems involving base surface heating. Such conditions are mostly encountered during high- speed flights, the operation of gas turbines, internal combustion engines etc. In all these cases both convective and radiative heat transfer mechanism greatly affects the expected life of the system. The amount of heat flux contributing to the system body surface, is one of the important parameter required for the design methodologies of various engineering objects. Heat flux is basically the moving thermal energy through the surface. It is one of the vital factors in terms of decision making for material selection of an engineering system for a particular engineering application [1–4].

The accurate prediction of heat flux value is one of the challenging tasks. There are basically three methods, which are employed for the prediction of heat flux values with varying degree of success. One of the approaches involve the direct measurement of heat flux using heat flux gauges [4–6]. Such heat flux gauges consist of a thermopile and basically measures the temperature differences, which is further converted to heat fluxes. The sluggish response time, flow disturbances and calibration requirements are the few disadvantages associated with such techniques. The second method involves the use of calorimeter for the determination of heat flux values. One of the major drawbacks with this technique is the complication in the actual measurement of heat flux values due to the distribution of non-uniform heat load across the surface [5]. The heat load across the surface is non-uniform due to the consideration of lateral heat conduction. Other drawbacks with this technique is similar to the first technique of slow response time and flow disturbances [6]. The recently developed third technique of heat flux measurement involves the use of thermo-chromatic liquid crystals for heat flux measurement. In this technique, with the gradient in temperature the layers of crystals aligns themselves. Further, the spectral measurement of the reflected light is used to infer the orientation. Presently, this technique has found a limited application and also suffers from lagging response time [7].

Nowadays, one of the popular and most extensively used technique is the prediction of heat flux value from the direct measurement of temperature histories and then implementation of a suitable data reduction method for the recovery of this heat flux [8–10]. Heat flux measurement technique for a system component requires the temperature measurement of the surface or near to the close proximity of

* Corresponding author.
E-mail addresses: tanweer@iitism.ac.in (T. Alam), rakesh@iitism.ac.in (R. Kumar).

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Nomenclature		*Greek Symbol*	
C	specific heat, [$Jkg^{-1}K^{-1}$]	Δ	difference
K	thermal conductivity, [$Wm^{-1}K^{-1}$]	τ	dummy time variable
Q	heat flux, [W/m^2]		
R	resistance of thin film, [Ω]	*Subscripts*	
T	temperature, [K]		
Z	direction along which heat conduction occurs	o	initial
A	coefficient of thermal expansion, [K^{-1}]	s	surface
δ	thickness, [m]	t	time
T	time, [s]	τ	dummy time variable

the surface component with the help of a temperature sensor. The placement of sensor for the measurement of surface temperature, either on to or near the surface causes the disruption in the surface body and thermal energy associated with it. The effectiveness of the sensors for temperature measurement pertaining to heated environment depends upon the extent to which the disturbance due to the sensor presence may be minimized [11]. It has been observed that two important factors; the surface roughness and continuity at edges related to sensor needs more attention for measuring temperature histories. The sensors involved in the transient temperature measurement should be capable to give highly accurate temperature data of proper temporal nature and have a faster response time [12,13].

The development of sensor for the prediction of heat flux has always been focussed towards certain specific applications employed for a given thermal environment. Now these days' sensors adopted for predicting absorbed energy (heat flux) are designed in such a way that during the experiment, temperature-time history of the sensor needs to be measured at only a single arbitrary location [14]. Sensors like Schmidt-Boelter gauges, null-point calorimeters, Gardon gauges, thin film gauges (TFGs) and coaxial thermocouples comes under this category [8]. For radiative and convective heat transfer mode, Schmidt-Boelter gauges and Gardon gauges are generally preferred for high heat flux values with large time duration and subjected to harsh environment like fires and flames within the combustor, rockets, wind tunnels designed for hypersonic conditions etc. [14,15]. They are made up of metal body with water cooled design and have black body sensor foils. In such sensors, heat flux values are deduced by measuring temperature gradient in the material. The null point calorimeter with features of measuring wide flux range is generally used for transient conditions. Further modifications has also been made to the null point calorimeter for its application in plasma wind tunnel facility [16]. Coaxial thermocouples and TFGs are generally preferred for short duration situations [17,18]. Coaxial thermocouples have the features of more rugged design, less maintenance requirement and suitability for a harsh environment in comparison to TFGs. Moreover, TFGs are preferred over coaxial thermocouples in short duration conditions for their simplicity and ease of fabrication, fast response time and high sensitivity value [19,20]. Recently TFGs are also successfully employed for temperature measurement in harsh conditions like testing of flight, rockets etc. [21].

TFGs are used for heat flux deduction by measuring transient temperature data because they have fast response features with frequency responses may tending to the value of 1 MHz [21,22]. It consists of a thin film of few micrometre thickness of highly conductive metal placed on an insulating substrate also termed as the backing material. TFGs are usually fragile in nature due to the weak layer substrate bonding. TFGs come under the category of resistance temperature detectors (RTD) as mentioned by several researchers [23]. In RTD, the detection of temperature change is evaluated from the variation in thin conductive film resistance. In order to energize the TFG, a constant current source capable of supplying milli-ampere current is used. Further, the exposure of TFG to the heated environment causes the change in resistance of the conductive film with the change in surface temperature. In absence of any contaminant to the surface of TFG and any induced strain, a linear relationship between change in resistance and temperature difference is obtained [24,25]. A number of research studies have mentioned about the importance of Platinum based TFGs for the measurement of heat transfer. It is customary to predict the heat flux from the measured transient temperature data by using Platinum based TFGs [25,26]. Among all highly available existing conductive metal, platinum is generally preferred for their better adhesive properties and higher value of temperature coefficient of resistance (TCR). TCR value of the TFG is evaluated from the linear relationship obtained between the resistance and temperature [4,11–13]. For platinum, the relationship between the resistance and temperature is most stable than any other conductive metal for a temperature range varying from room temperature to 1234.91 K [2]. Fig. 1, represents the temperature range 'a' for which the linear relationship between change in resistance and temperature change for platinum is more stable in comparison to the nickel. The platinum film TCR value is very much dependent on entrapment of minute contaminating particle as well as any strains encountered to the film during the measurement. This necessitates to keep the film surface free from any impurities and avoiding any minimal effect of strain on the film or its backing material [12]. Generally, insulating material like QUARTZ, MACOR and PYREX is used as a backing material. The thermal properties of these insulating material show negligible variation in thermal properties with temperature [27,28]. In addition, to having constant thermo-physical properties, the selected substrate is also an electrical insulator in nature [29]. The thin film acts as an active element and hence serves as a resistance thermometer with the

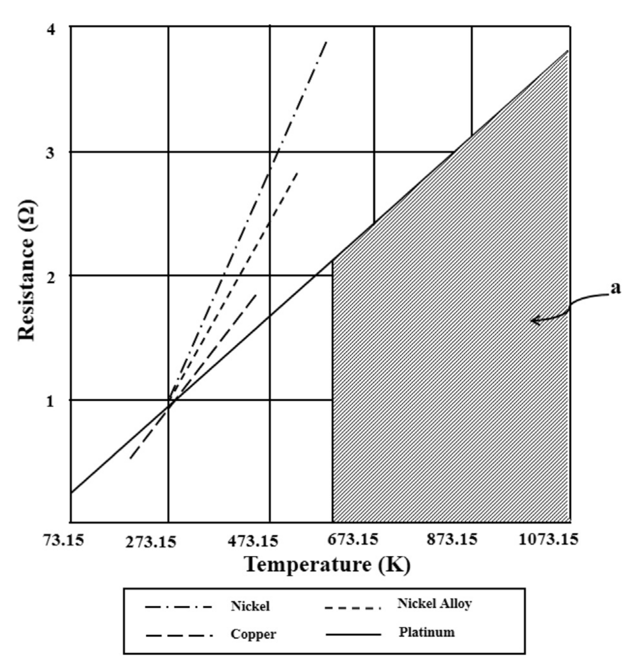

Fig. 1. Resistance versus Temperature relationship for various metals [2].