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Research Paper

Gardon gauge measurements of fast heat flux transients

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HIGHLIGHTS

- A fast heat flux transient measurement method using Gardon gauges is introduced.
- Simulations and experiments of heat flux transient measurements verify the method.
- Convert Gardon gauge with a limited response to fast-response heat-flux sensor.
- Gardon gauge measurement accuracy is improved for heat flux transients.

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ABSTRACT

Heat flux measurements are widely used in thermal analyses. Gardon heat flux gauge are a widely used diffusion type heat flux gauge that can be used in harsh thermal environments such as in fires, combustors, and aerospace applications. However, Gardon gauges are usually regarded as quasi-steady-state sensors with a limited frequency response and are not often used for transient measurements. This paper introduces a fast radiative heat flux transient measurement method using Gardon gauges. The analysis assumes that the heat flux transient is a continuous function of time in every small/micro time interval. The transient heat flux density functions are determined from the transient output voltages of the gauge. Two cases with fast and slow heat flux transients were numerically investigated to verify the method. The analyses show that the gauge transient response must be corrected not only for fast heat flux transients, but also for slow heat flux transients. The gauges were then tested in experiments to measure radiative heat flux transients on a hot graphite plate in a vacuum chamber to evaluate the effects of the corrections. This method can use a limited frequency response Gardon gauge for fast heat flux measurements without other instrumentation adjustments. The Gardon gauges measurement accuracy is then greatly improved with transient measurements. The analysis shows how to accurately measure transient heat fluxes and improve the performance of Gardon gauges.

1. Introduction

Heat flux measurements are often needed in thermal studies and have been widely used for engineering and research applications [1–8], for example, building and environmental studies, fire safety, electronic systems, material structures, combustion chambers and engines, and aerospace applications. Heat flux measurements are important for controlling heating processes, to assess device performance at high temperatures, to optimize systems for energy production and for designing the thermal protection systems for combustors in industrial and power engineering projects. The interests in the measurements of unsteady heat transfer phenomena was increasing due to the need to understand the heat transfer process occurring in inherently unsteady environments. Transient heat flux measurements were widely needed in applications including high enthalpy plasmas, high power pulsed lasers, structural thermal tests and other fields. The well-established single-point heat flux gauges are widely available for various applications in thermodynamics and fluid. Measurement techniques of single-point heat flux, for example, null-point calorimeters, thin-film gauges, coaxial thermocouples, Schmidt–Boelter gauges, and Gardon gauges, have been developed to measure heat fluxes in various types of thermal environments.

The transient null point calorimeter was first developed by Powars et al. [9] in 1972 and has been widely used to measure transient heat fluxes due to its simplicity, very wide flux range and favorable response time characteristics. Löhle et al. [10–12] made some

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significant improvements in the null-point calorimeter for high heat flux applications in a plasma wind tunnel facility.

Thin-film gauges are classic fast-response sensors for very fast transient heat flux measurements with frequency responses up to 1 MHz [13–20]. They are usually fabricated by painting or sputtering a thin resistance layer onto an insulator substrate so they are usually fragile due to the weak layer-substrate bonding. Coaxial thermocouples [21–24] are more rugged than thin-film sensors and do not require frequent maintenance for transient heat flux measurements in harsh thermal environments. Irimpan et al. [23] designed a fast response coaxial thermocouple for shock tunnel applications, evaluated the coaxial thermocouple response against a platinum thin film gauge for heat flux measurements in a shock tunnel. However, the short working time characteristics of the thin-film gauges and coaxial thermocouples greatly restrict their applications.

Schmidt-Boelter gauges [21,25–28] and Gardon gauges [29–34] are available devices with excellent measurement characteristics with metal bodies, blackbody sensor foils and water cooled designs. Schmidt-Boelter and Gardon gauges are classified as diffusion-type or one-dimensional sensors that deduce the heat flux by measuring the temperature gradient in a material. The gauges are more suitable for high radiative or convective heat flux measurements with long working times in harsh environments such as in combustion flames, rocket motors, hyper sonic wind tunnels, etc. For example, Kidd et al. [21] developed a fast-response heat flux sensor, based on a modified Schmidt–Boelter gauge principle for heat transfer measurements in hypersonic wind tunnels. Gifford et al. [26] performed experiments to characterize the performance of Schmidt–Boelter heat flux gauges in stagnation and shear convective air flows. Nakos et al. [27] analyzed the heat transfer from an idealized Schmidt–Boelter heat flux gauge and showed that the theoretical sensitivity coefficients in radiative and convective environments differed. Sudheer et al. [28] measured the incident heat flux on a target for open gasoline pool fires with Schmidt–Boelter heat flux gauge measurements. The Gardon gauge (also called a circular foil heat flux gauge) was first introduced by Gardon in 1953 [29]. There have been many applications and calibrations of Gardon gauges [30–34]. The Gardon gauge is more useful for heat flux measurements over wide ranges than Schmidt–Boelter gauge so there is a great need for accurate Gardon gauges for measurements involving wide ranges of heat fluxes.

Although Gardon gauges are widely used diffusion type heat flux gauges and have been extensively studied, the use of Gardon gauges in harsh environments is still restricted for transient applications. Gardon gauges as well as Schmidt–Boelter heat flux gauges are usually regarded as quasi-steady-state sensors with a limited frequency response and are rarely used in transient applications. It’s unable to obtain accurate heat fluxes using Gardon gauges in transient applications although the merit of high heat flux and long working times measurements is remarkable. Therefore, this paper describes an optimized measurement method of fast transient radiative heat fluxes based on a traditional Gardon gauge. The measurement accuracy of the Gardon gauges is also greatly improved for transient measurements. The merit of this work is to convert a traditional Gardon gauge with a limited frequency response to a fast-response heat-flux sensor which also has a wide range of heat fluxes and can be operated with long working times in thermal environments. The measurement principles of Gardon gauges are analyzed to improve the measurement method for transient heat fluxes. Numerical simulations and experimental measurements of typical heat fluxes verify the applicability and effectiveness of the measurement method. The analysis provides a useful reference for accurate measurement of transient heat fluxes and improves the measurement ability of Gardon gauges.

2. Principles

2.1. Traditional measurement method

The Gardon heat flux gauge is a diffusion type heat flux. A sketch of a copper-constantan circular foil heat flux sensor is shown in Fig. 1. A circular constantan foil coated with a diffuse, highly absorbing coating is attached to a copper heat sink. The heat sink can be cooled to a low temperature so the gauge can be exposed to high heat flux environments. There is a large temperature gradient along the foil radial direction due to the effects of the heat flux on the foil surface. The metal leads are attached to the center and the edge (or the copper heat sink) of the foil to form a thermocouple joint. The voltage output of this thermocouple joint is proportional to the temperature difference across the foil. Therefore, the measured voltage gives a quantitative representation of the heat flux through the foil.

The temperature gradient along the foil thickness is negligible and the heat losses from the back of the foil and from the center metal wire are also neglected. The foil surface of the gauge is assumed to be a highly absorbing gray diffuse surface. Then, the heat transfer equation and boundary conditions describing the radial temperature distribution in the foil are:

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r\frac{\partial T(r,\tau)}{\partial r}\right)+\frac{q(\tau)}{\delta}=\rho c\frac{\partial T(r,\tau)}{\partial \tau} \\ T|_{\tau=0}=T_0, \quad T|_{r=R}=T_0, \quad \partial T/\partial r|_{r=0}=0 \end{cases} \tag{1}$$

where T_0 is the heat sink temperature, τ is the time, r is the foil radius axis, $T(r,\tau)$ is the temperature at time τ and position r on the foil surface, $q(\tau)$ is the heat flux reaching the foil surface due to convective or radiative heat transfer at time τ, δ is the thickness and R is the constantan foil radius. ρ is the foil density and c is the specific heat capacity of the foil which are both assumed to be constant. λ is the thermal conductivity of the constantan foil expressed as a linear function of temperature,

$$\lambda=\lambda_0(1+b(T-T_0)) \tag{2}$$

where $\lambda_0=20.9\ \mathrm{W/(mK)}$ at $T_0=0°\mathrm{C}$ and $b=0.00231\,\mathrm{K}^{-1}$ for a temperature range of 0~200 °C.

The thermo-electromotive voltage output, E, of the copper-constantan thermocouple formed by the Gardon gauge is expressed as the function of the temperature difference, ΔT, between the center and the edge of the constantan foil as,

$$E=k\Delta T(1+g\Delta T) \tag{3}$$

where $k=0.0387\,\mathrm{mV/K}$ and $g=0.0012\,\mathrm{K}^{-1}$.

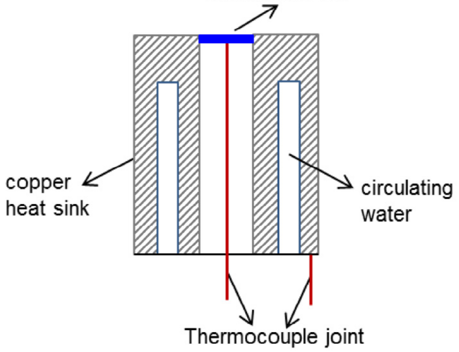

Fig. 1. Sketch of the Gardon heat flux gauge.