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Development of a new fiber-optic multi-target multispectral pyrometer for achievable true temperature measurement of the solid rocket motor plume

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ABSTRACT

This paper describes the development of a novel multi-target multispectral pyrometer to remotely measure the true temperature of the plume of a solid fuel rocket engine in a harsh environment ground test. Using an optical fiber transmission technique, the core part of the instrument can be located 100 m away from the test site, so the influence of the harsh environment can be reduced and the instrument reliability improved. Optics are separated from prisms to accurately locate targets. Based on preamplifier circuits and parallelly adjacent pixels of the photodiode detectors, the measurement lower limit can reach 900 °C. The pyrometer is validated against experimental data from field measurements of a solid fuel rocket motor plume. The results demonstrate that the true temperature of the solid fuel rocket engine plume can be acceptably measured with the proposed pyrometer.

1. Introduction

The plume true temperature is an important parameter to study the propellant combustion process of the rocket engine and to evaluate the engine performance in order to optimize the engine characteristics [1,2]. It is of great significance for the theory and practice to quickly and accurately measure the true temperature of the plume. The temperature measurement methods are divided into contact and non-contact. Due to the dynamic characteristics of a solid fuel rocket motor plume, which presents high temperatures, high speed and two-phase flow, the plume flow field can change physically or chemically during contact measurement, introducing an insertion error. In addition, the contact temperature measurement cannot track the temperature variations of the plume due to its slow response. To avoid interference from the measuring instrument and increase the measurement speed, the radiation thermometry, a non-contact temperature measurement method [3], is a feasible solution.

Radiation thermometry systems frequently use multispectral pyrometry (MSP) [4–6] to overcome the restriction of the unknown emissivity [7] of traditional one-color pyrometer (unknown emissivity) and of the constant emissivity vs. wavelength for the two-color ratio pyrometry [8], and can give true temperature measurements. Fu et al. developed a multi-wavelength pyrometer using two spectrometers with gratings and order sorting filters to measure the true temperature of hot metals [8], and used a near-infrared multicolor pyrometer with a diffraction grating and an order sorting filter for measurements in thermal-structural experiments [9]. Gardner et al. developed a six-wavelength pyrometer with filter array for metal melting application [10]. Hiernaut et al. developed a six-color pyrometer with a fiber-optic bundle [11]. Radousky and Mitchell developed an ultraviolet/visible pyrometer to measure shock temperatures with a half transmitting half reflecting mirror [12]. Levendis et al. developed a three-color ratio pyrometer employing a visible and two near-infrared wavelengths to measure surface temperatures of burning carbonaceous particles [13]. Ng and Fralick explored a multi-wavelength pyrometer with a spectrometer to measure the true temperature of transparent substances and combustion gases [14]. However, Coates [15] already pointed out the high uncertainties which can arise by a non-accurate evaluation of emissivity vs. wavelength distribution. Moreover, these pyrometers inevitably use interference filters, which can cause a radiation attenuation. And filter transmittance can change with temperature, humidity and time, leading to instability of the instrument. To face with these problems, a multispectral pyrometer using prismatic decomposition, which avoids the use of filters, was developed by the Harbin Institute of Technology, based on a standard MSP [16]. It can give the true temperature of a solid propellant rocket engine plume in

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ground test [17,18]. However, the pyrometer working distance results only 6–8 m, and the pyrometer must be placed near the test site. Due to strong mechanical shocks, strong shock waves, electromagnetic interference and dust pollution from the rocket engine, the working environment of measuring instrument is hazardous, and instrument reliability is strongly influenced. In addition, measurement accuracy is limited due to difficulty in the realization of optic and prism separation and location of the target. Furthermore, the lower limit of temperature measurement for the pyrometer is only 1227 °C, which is not satisfactory for the requirements of the measurement range for the new rocket plume true temperature.

In this paper, a new type of multi-target multispectral pyrometer is developed. The core of the presented instrument can be located far from the harsh environment of the test site thanks to optical signal transmission through an optical fiber. The near axis optical separation is designed not only to obtain the target measurement on curve surfaces, but also to precisely aim at the target in the range 0–360°. Meanwhile, the lower limit of temperature measurement for the proposed instrument can reach 900 °C by paralleling adjacent pixels of the photodiode detectors and automatically switching of pre-amplification circuits between two different ranges. The calibrating procedure and the uncertainty analysis of the instrument are also presented. Finally, the proposed pyrometer was tested acquiring data of a solid fuel rocket motor plume and calculating its true temperature.

2. Measurement principles

The proposed pyrometer presents six spectral channels to collect brightness temperature data. It was developed on the basis of the dual measurement algorithm [19] to calculate the true temperature and emissivity [20].

If a multispectral pyrometer has n channels, the relationship between brightness temperatures T_{λ_i} in channel i and true temperature T is given by

$$\frac{1}{T}-\frac{1}{T_{\lambda_i}}=\frac{\lambda_i}{c_2}\ln\varepsilon_{\lambda_i} \tag{1}$$

where the effective wavelength is represented by λ_i; ε_{λ_i} is the spectral emissivity and c_2 denotes the second Plank constant (14388 μm·K).

From Eq. (1), the estimated emissivity value $\varepsilon^0_{\lambda_i}$ of channel i at the first temperature point can be written as

$$\varepsilon^0_{\lambda_i}=exp\left[\frac{c_2}{\lambda_i}\left(\frac{1}{T_0}-\frac{1}{T_{\lambda_i,1}}\right)\right] \tag{2}$$

where $T_{\lambda_i,1}$ is the brightness temperature (output) of channel i of the first temperature point and T_0 indicates the estimated value of the first true temperature.

Assuming the following equation as emissivity model at temperature T,

$$\varepsilon_{\lambda_i}=\varepsilon^1_{\lambda_i}[1+k(T-T_0)] \tag{3}$$

where $\varepsilon^1_{\lambda_i}\epsilon(\varepsilon^0_{\lambda_i}-\varepsilon,\varepsilon^0_{\lambda_i}+\varepsilon),\varepsilon>0; T\epsilon(T_0-M,T_0+M),M>0$ and $k\epsilon(-\eta,\eta),\eta>0$.

From Eqs. (1) and (3), we can obtain

$$T_i^2=\frac{1}{\frac{1}{T_{\lambda_i,2}}+\frac{\lambda_i}{c_2}\ln\varepsilon^1_{\lambda_i}[1+k(T_i^2-T_0)]} \tag{4}$$

where T_i^2 and $T_{\lambda_i,2}$ are the calculated true temperature and brightness temperature of channel i at another second temperature point respectively. The algorithm to calculate the true temperature consists of evaluating the minimum variance of T_i^l, that is

$$F_{min}=\sum_{l=1}^{2}\sum_{i=1}^{n}\left[T_i^l-\frac{1}{n}\sum_{i=1}^{n}T_i^l\right]^2. \tag{5}$$

3. Design of the pyrometer

The block diagram and the photo of the proposed pyrometer are shown in Figs. 1 and 2 respectively. The device mainly consists of an optical system, an electronic system and a control system for data processing. The optical system is used to focalize, transmit and collect radiation from the plume targets. The signals from six channels are synchronously acquired and processed (amplified) by the electronic system. A USB2850 data acquisition card acquires data and transmits them to a PC to store, process and display. The main technical specifications of the proposed pyrometer include: optical fiber transmission till to 100 m, temperature measurement range of 900–2400 °C, working distance of 3–20 m, temperature measurement uncertainty of 3%, 6 spectral channels of a single target and 3 different targets.

3.1. Design of the optical system

The optical system (Fig. 1) includes three optics to aim at the plume targets and focalize radiation, three optical fibers to transmit the radiation signals from optics, and three prisms which disperse the radiation in continuous spectrums, and finally produce an image of the source on the detectors.

3.1.1. Optical fiber transmission technique

In order to avoid the problems of harsh environment (strong mechanical vibrations, shock waves, electromagnetic interference and dust pollution of the test site), the core parts of the pyrometer (prisms, electronics and PC) are placed far away from the test site and radiation is collected by the optics and transmitted to the

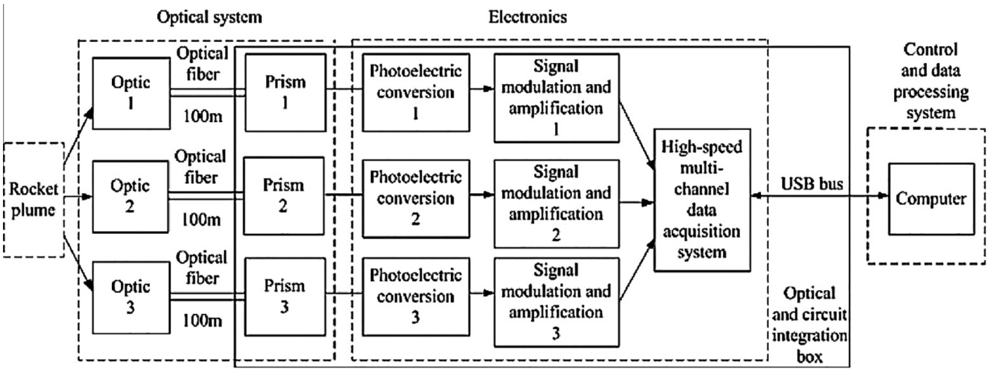

Fig. 1. Block diagram of the instrument.