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Study on Sapphire Fiber Optic Sensor for High Temperature

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Abstract

The accurate measurement of temperature and heat flux has been one of the key problems in the development of hypersonic vehicle. In many high temperature processes, it is important to have accurate knowledge of temperature, especially in the materials processing in the metal and glass industries, measurement of turbine inlet temperatures in jet engines and in stationary gas turbine power plants. The maximum temperatures of these processes can reach as high as above 2000K, and the environments are always chemical corrosive or strong electromagnetic. Ordinary thermocouples cannot meet the requirements for stable and accurate operation in such high temperature applications. Optical-based temperature measurement systems have several advantages, including the ability to withstand high temperature and immunity from electrical noise due to their all-dielectric construction. The sapphire fiber-optic temperature sensor based on Black-Body radiation law, is a new technique of high temperature measurement in extreme environment, which combines techniques of radiometric thermometry and optical-based temperature measurement. In this paper, a system is established and conducted in FD-02 combustion gas flow tunnel in China Academy of Aerospace Aerodynamics (CAAA). This tunnel used the fuel-oxidant mixtures of air/kerosene to produce combustion gas flow, whose nozzle outlet diameter is 200mm. The mach number is 3 with the gas flow of 5kg/s. Results approved that the sapphire fiber-optic temperature sensor based on Black-Body radiation law has high sensitivity and is suitable for 800-1600 ℃ temperature measurement. The results are in good agreement with the Platinum-rhodium thermocouple. It was confirmed that sapphire fiber-optic temperature sensor could be used for accurate measurement of temperature in extreme environment with a millisecond response time.

Keywords: *high temperature；sapphire fiber-optic；transient；black-body radiation*

Nomenclature

C1 – the 1st radiation constant
C2 – the 2nd radiation constant

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1. General Introduction

In many high temperature processes, it is important to have accurate knowledge of temperature. This is true for processes such as materials processing in the metal and glass industries, and is equally true in the measurement of turbine inlet temperatures in jet engines and in stationary gas turbine power plants. However, the maximum temperatures in these processes can reach as high as above 2000℃, and the environments are always chemical corrosive or strong electromagnetic. Ordinary thermocouples cannot meet the requirements for stable and accurate operation in such high temperature applications. Optical-based temperature measurement systems have several advantages, including the ability to withstand high temperatures and immunity from electrical noise due to their all-dielectric construction.

The sapphire fiber-optic temperature sensor based on Black-Body radiation law, is a new technique of high-temperature measurement in extreme environment, which combines techniques of radiometric thermometry and optical-based temperature measurement[1-3]. In the paper, a system is established and tested.

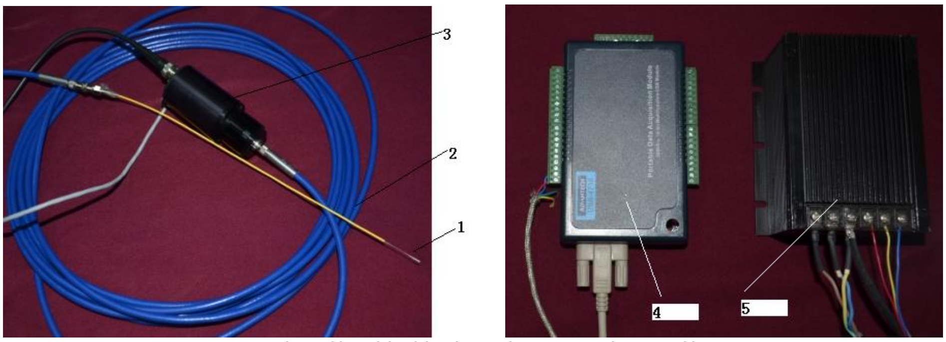
2. A sapphire fiber optic temperature sensor

Sapphire (α-Al_2O_3) is an excellent near-infrared heat-resistant optical material, its single crystal melting point is as high as 2045 ℃, corrosion resistant, very stable physical and chemical properties, well mechanical strength, and has good light transmission at 0.3 ~ 4.0um band. Sapphire fiber is an optical waveguide appropriate to high temperature environment.

The sapphire fiber-optic temperature sensor based on Black-Body radiation law, by measuring the radiation intensity of the probe, get the brightness temperature of the radiator. The sapphire fiber-optic temperature sensor may consists of four main components[4], 1) sensing probe 2) optic light guide 3) photoelectric conversion and amplification section 4) data processing section.

The system illustrated below includes a blackbody probe, a fiber optic light guide, a photodiode and a signal amplifier, the data collection device and data processing software, shown in Fig 1 .

Place the blackbody probe directly into the measured temperature environment, the black body cavity perceives heat quickly and radiates infrared light signal. Optic signal from the black body radiating cavity was conducted along the sapphire fiber to a low temperature fiber. The light output from the low temperature fiber passed through a notch filter and was detected by a detection system based on an InGaAs photodiode. The photodiode converts the light at a particular wavelength(λ=830nm) easily isolated with the notch filter using the Planck relationship into an electrical current, amplifier in an optoelectronic unit condition the analog signal, and a program in a computer converts the analog signal into usable engineering units of temperature.



1- Sapphire fiber blackbody probe, 2- conduction fiber,
3- The photodiode and signal amplifier, 4- data collection device, 5- Power

Fig 1. The sapphire fiber-optic temperature sensor

Sapphire fiber-optic temperature sensor uses contact temperature measurement methods, namely the sensor head is placed directly in the test temperature environments. Due to the small volume, it can respond quickly to temperature changes and achieve thermal equilibrium with measured object. So the technology has high sensitivity and good reliability. Clearly, stability of the blackbody probe is a prerequisite for the system working in good order. Therefore, the production of blackbody probe is a crucial step to achieve high-temperature measurements.

The blackbody probe is formed of a single crystal sapphire rod divided into a wave guide region and a cavity region. The cavity region is generally coated with an infrared radiation emitter having a high melting temperature. The nature of the materials used to form the probe may vary considerably. Some materials require the use of a separate emitter in order to provide infrared radiation in response to the sensed temperatures, while others do not. Many of the probes utilize materials such as refractory materials (including oxides of aluminum, silicon, zirconium and yttrium), black bodies formed of finely dispersed carbon and a silicon adhesive, quartz or glass, noble metals, steel, luminescent materials, and the like. Yttria-stabilized zirconia which can be used at temperature in excess of 2300℃ is selected here as the cavity ceramic material.

Currently there are two main blackbody cavity production methods, one is to cover end of the sapphire fiber with thin ceramic coating and sintered at high temperature. Another is sputtering the noble metal or ceramic on the sapphire single crystal substrate. In this paper, A thin film is coated on a 450-μm single crystal sapphire fiber by plasma spray. Plasma jet has high enthalpy, high-temperature and high-speed features, the most refractory material can be melted in a plasma jet and sprayed forming. Its particle ejection has high speed and high temperature, which makes sure the sprayed coating has good quality and well bonded. To strengthen the bond strength, before plasma spraying, we do the roughness treatment to the sapphire end and clean it repetitiously.

The probe has a wall thickness of about 100μm, a length of about 600μm, and an outer diameter of about 650μm. Thus the length/ diameter ratio is about 10 to 1. Thinner walls, especially at the forward end of the probe, improve the response time, but also compromise the life and durability of the probe. Accordingly, depending upon the relative importance placed on response time as opposed to longevity, thinner or thicker walls may be used relative to the 100μm wall illustrated.

3. Temperature measurement principle

sapphire fiber-optic temperature measurement is based on the radiation optic signal detection. According to the Planck Blackbody Radiation Law[5,6],

$$\Phi(\lambda,T)=C_1\lambda^{-5}/\left[\exp\left(C_2/\lambda T\right)-1\right] \tag{1}$$

when $\frac{C_2}{\lambda T}>1$,Wien obtained an expression

$$\Phi(\lambda,T)=C_1\lambda^{-5}\exp\left(-C_2/\lambda T\right) \tag{2}$$

Assuming the notch filter's spectral response function is $f(\lambda)$, the center wavelength of the filter is λ_0, the bandwidth is $\Delta\lambda$, the spectral response function of photodiode is $D(\lambda)$, taking into account the more general case, the monochromatic emissivity of the probe is $\varepsilon_A(\lambda)$, the optic signal transmission loss in fiber is $\eta(\lambda)$, the ultimate output voltage of the photodiode is

$$V(\lambda_0,T)=\int_{\lambda_0-\frac{\Delta\lambda}{2}}^{\lambda_0+\frac{\Delta\lambda}{2}}\eta(\lambda)\times f(\lambda)\times D(\lambda)\times\Phi(\lambda,T)\,d\lambda=KR(T) \tag{3}$$

Where, *K* is the conversion factor, *R*(T) is the radiation flux。

When the bandwidth of notch filter is narrow, it can be assumed: $\eta(\lambda)=\eta(\lambda_0)$, $f(\lambda)=f(\lambda_0)$, $D(\lambda)=D(\lambda_0)$, then

$$\begin{aligned}K&=\eta(\lambda_0)\times f(\lambda_0)\times D(\lambda_0)\times\varepsilon_A(\lambda_0)\\R(T)&=\int_{\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda}\Phi(\lambda,T)\,d\lambda=-\frac{C_1T^4}{C_2^4}\left(x^3+3x^2+6x+6\right)e^{-x}\Big|_{x_1}^{x_2}\end{aligned} \tag{4}$$

For a calibration temperature, *K* can be derived from the measured voltage value, and then the temperature index table is elicit.

$$R(T)=\int_{\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda}\Phi(\lambda,T)\,d\lambda\approx\Phi(\lambda_0,T)\Delta\lambda \tag{5}$$

Further simplified, for narrowband radiation,

$$T=\frac{C_2}{\lambda_0\times\ln\left(\frac{KC_1\Delta\lambda}{\lambda_0^5V}+1\right)} \tag{6}$$

4. Test and Result Analysis

Place the optical fiber probe and thermometer in the same point as comparison. The contrast thermometer using B-type WRR-130 platinum and rhodium thermocouple, whose temperature measurement range is 0 ~ 1800 ℃, is connected to data acquisition card and the temperature values display through computer software. Sapphire fiber-optic temperature sensor is connected to a computer via a data acquisition card collecting the output voltage of the fiber optic sensing system at the same time, shown in Fig 2.

As there is a certain degree of light transmission with the probe, which will cause interference to the signal acquisition, the test is carried out in a dark room, ignoring the ambient light interference.

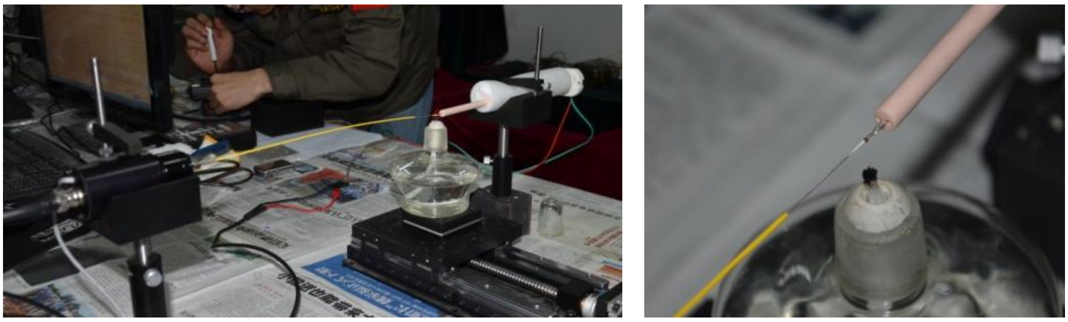


Fig 2. Sapphire fiber test system set up

It was found that when an alcohol lamp was elected as the heat source, due to the low temperature of alcohol lamp flame, about 600 ~ 800 ℃, the black body radiation intensity is weak, the voltage signal is still smaller than 200mV after amplification, Fig 3 as following. The data is processed and compared with the thermocouple result, shown in Fig 4.

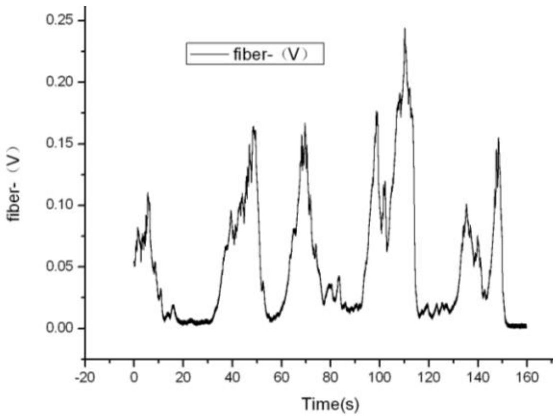


Fig 3. the output voltage of Sapphire fiber-optic temperature sensor under alcohol lamp heat

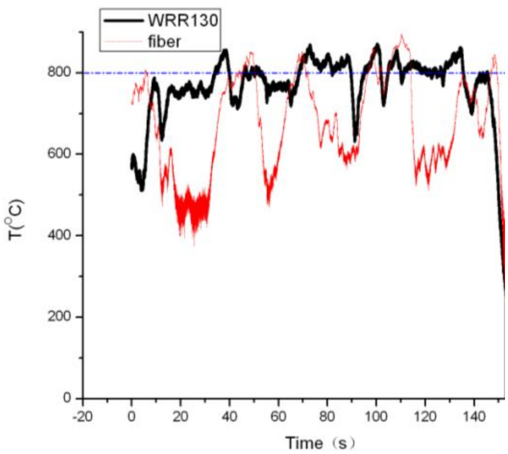


Fig 4. optic fiber and thermocouple data comparison under alcohol lamp heat source

Bold line is the thermocouple detecting temperature changes; thin line is the processed optical data. Two curves agree well above 800 ℃, the two curves deviate greatly below 800 ℃. In conjunction with Fig 3, at the time when the temperature is below 800 ℃, there is almost no signal voltage of fiber optic sensor to be detected. Due to the blackbody radiation is almost zero at low temperature, temperature sensing based on black-body radiation law is no longer applicable.

When using a spray gun as the heat source, blackbody radiation is strong at high temperature, the test result is shown in Fig 5 , we can see the radiation intensity reacted very sensitive to the temperature change. The data is processed and compared with the thermocouple result, shown in Fig 6 .

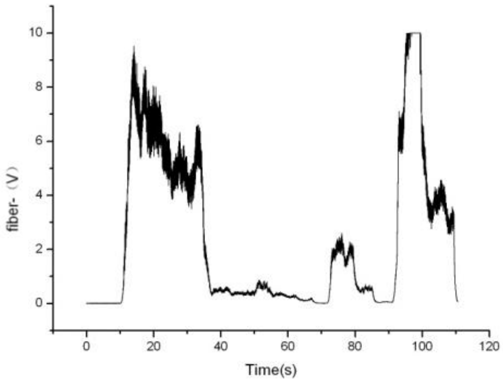


Fig 5. The output voltage of Sapphire fiber-optic temperature sensor under a spray gun heat

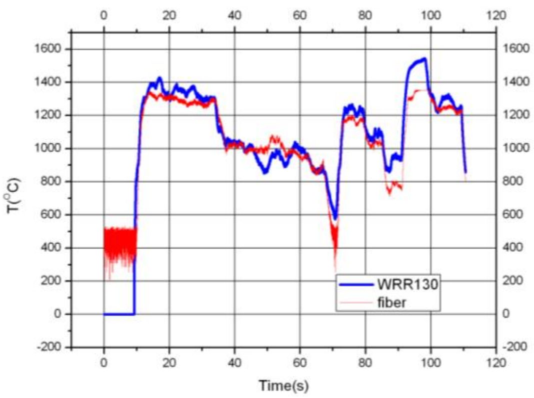


Fig 6. Optic fiber and thermocouple data comparison under a spray gun heat source

Two curves are quite consistent, showing that the sapphire fiber optic sensor work well at the temperature region of 800-1600 ℃. Experiments show that the sensor is not suit for the temperature measurement below 800℃. But at high temperature region of 800-1600℃, the test data achieved high consistency with the thermocouple results measured at the same heat point over the butane gas gun.

The test was carried out in the air heater of FD-02 gas flow wind tunnel. In the process of modification, a heater using air/kerosene as oxidant/fuel was added to conduct thermal test on the test piece. On the basis of the thrust chamber design of the liquid rocket engine, the air kerosene heaters of the aircraft engine and hypersonic wind tunnel are used for reference. Basic parameters are as follows: the material gas flow is 5 kg/s, temperature is about 1800 ℃, diameter of the outlet nozzle is 200 mm, The Mach number of nozzle outlet is about 3.0.

The test state is shown in Fig 7 The optical fiber temperature sensor is installed in the center of the nozzle outlet, and the thermocouple is installed on the wall surface of the combustion chamber. The thermocouple is specially encapsulated and protected. Therefore, the optical fiber temperature sensor head has greater air flow scour and higher temperature than the thermocouple initially.

Fig 7. Test state of combustion

The variation curve of the temperature measured by kerosene, air pressure and fiber during the experiment is shown in Fig 8. The blue curve is the actual temperature measured by optical fiber, the P_{if} is the pressure value of kerosene, and the P_{io} is the pressure value of air. The main valve of air opens at t=5s. The optical fiber immediately detect changes in temperature. As the improvement of air flow and kerosene , nozzle outlet reached the highest temperature of 2000 ℃. The bottle volume (4 m^3) limit the air flow rate further. The temperature rise again to 1775 ℃ around 9.6 s, and the optical fiber sensing head was completely damaged until 14.3 s.

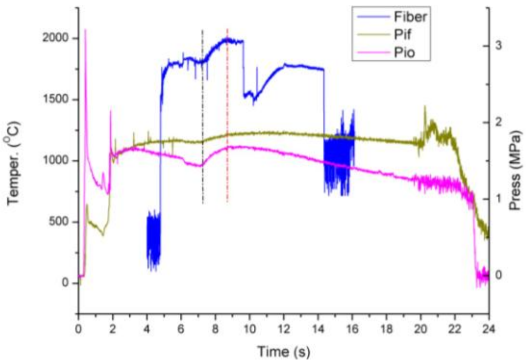


Fig 8. Time-varying curves of fiber temperature and Kerosense/air pressure

The simultaneous temperature result of the optical fiber and the thermocouple is shown in Fig 9. Since the two sensors are not installed in the same position, the test temperature data are different. However, both are in the same temperature field. Especially at 10 ~ 14s, the temperature of the flow field tends to be stable, and the measurement results of fiber and thermocouple are basically consistent. The signals covered by both sensors are noise after t=14s, and the optical fiber sensor and thermocouple are completely damaged, which is a certain reference value for the lifetime.

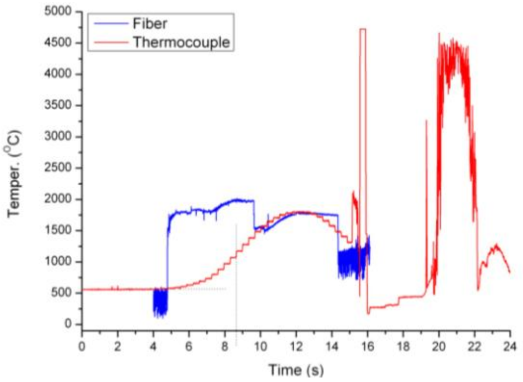


Fig 9. Fiber result compare to thermocouple measurement

The response time of the fiber sensor is extremely fast. The acquisition frequency is set at 1000Hz in the measurement, and the response time is lower than 1ms shown in Fig 10.

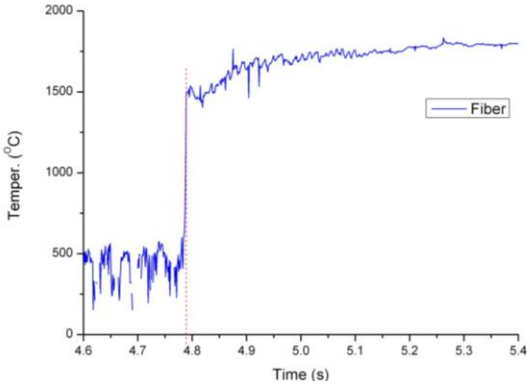


Fig 10. Response time of fiber sensor

5. Conclusions

In conclusion, the plasma sprayed ceramic blackbody cavity endures through the high temperature environment, which is also satisfying the rigour requirements such as chemically stable and well-bonded with the fiber body. The black body results of this study demonstrate that the plasma sprayed ceramic thin film is suitable for sapphire fiber cladding for high temperature applications. The tests approved that the sapphire fiber-optic temperature sensor based on Black-Body radiation law has high sensitivity and is suitable for 800～1600℃ temperature measurement.

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