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Research Progress and Development of Sapphire Fiber Sensor

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Abstract: Sapphire fiber thermometers have become a new potential option in the field of high-temperature measurements. Recent research progress of sapphire fiber sensors is summarized; operational principles, advantages, disadvantages, and applications of sapphire fiber sensors are introduced. Research has shown that sapphire fiber sensors can be used to accurately measure very high temperatures in harsh environments and has been widely applied in fields such as aviation, metallurgy, the chemical industry, energy, and other high temperature measurement areas. Sapphire optical fiber temperature measurement technology will move toward miniaturization, intelligence following the advances in materials, micro-fabrication and communication technologies. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Sapphire single crystal fiber, Optical fiber sensor, Black-body cavity, Calibration system

1. Introduction

Fast, highly accurate measurements are very important in the fields of aviation, metallurgy, chemistry, energy, construction etc. Presently, high-temperature thermocouples made with platinum, rhodium, or other precious metals are mainly used for high temperature measurements. These thermocouples are expensive, have poor high temperature corrosion resistance ability, short life spans, low spatial and temporal resolution, and several other inadequacies which affect normal production and scientific research work. For example, a large steel mill of China spends about ￥30 million annually in thermocouple costs. Around the country of China, there is several billion dollars' worth of thermocouple consumption and the country's lack of platinum, rhodium, and other precious metal resources causes a dependence on foreign markets. In addition, thermocouples cannot be used in many special high-temperature furnaces, such as high-frequency furnace, microwave oven etc. due to electromagnetic interference caused by these furnaces. Especially, temperature measurements are immense in the aircraft engine development process, measuring the combustor and turbine import and exporting flow temperatures, and oftentimes thermocouples cannot meet these needs. Similarly, spacecraft and rocket development temperature sensors are needed to measure engine airflow temperatures that oftentimes exceed the temperature range capable of being measured by thermocouples. In addition, thermocouples have a large time constant which makes it unable to meet transient temperature measurement requirements. Compared with thermocouples, sapphire fiber sensors have a fast thermal response, long operational life, low cost, are capable of adapting to a variety of harsh environment and possess good thermal stability.

R. R. Dils [1, 2] of the U.S. National Bureau of Standards used a sapphire fiber to make the first high-temperature fiber optic sensor. Due to having a working temperature of up to 2000 °C, having high thermal stability, and being capable of gathering reliable data, sapphire fibers and fiber optic high-temperature sensors have become a research hotspot. Sapphire fiber sensor with good thermal stability, and the time constant is much smaller than the traditional thermometer, which is adopted to measure the T56 type engine [3-4] high-speed high enthalpy gas flow temperature in foreign. Y. H. Shen et al [5-7] developed a sapphire fiber sensor that uses high emissivity ceramic, sintered under high temperature conditions, to produce a miniature fiber thermal cavity. This sensor has good thermal stability and high measurement accuracy capable of measuring temperatures ranging from room temperature to 1800 °C with an accuracy of 0.2 %. W. Li et al [4, 8] adopted new photo detectors and coating materials, greatly improving the temperature range and signal to noise ratio of the sapphire fiber optic sensor, making it capable of measuring to an upper limit temperature 2000 °C, reducing the response time to less than 100ms, allowing it to meet temperature measurement requirements of special circumstances encountered in research and industrial production. J. Zhao et al [5, 9] completed a sapphire fiber temperature sensor design whose prototype pushed the measurement temperature range to above 2200 °C allowing it to accurately measure the high gas temperatures of aircraft engines. With the rapid development of science and technology, sapphire optical fiber temperature measurement technology will be applied to the field of temperature measurement, having particularly broad application prospects in the area of high-temperature measurement.

2. Sapphire Fiber Optic Sensor Measurement System Architecture

Sapphire fiber optic sensor measurement system consists of sapphire fiber blackbody cavity probe, fiber optic coupler, quartz conductive fiber, optical detector, temperature data logger, PC software and other components, as shown in Fig. 1. The sapphire optical fiber is created through laser heated pedestal growth and blackbody material is deposited on the sensing tip of the sapphire fiber forming the blackbody radiation cavity. The sapphire fiber has a diameter of no more than 1mm and has a very low heat capacity, allowing the blackbody cavity to quickly reach thermal equilibrium with the outside test temperature. The sapphire optical fiber emits an electromagnetic signal based on the equilibrium temperature that is transmitted via high temperature optical fiber to the photoelectric detector. The electromagnetic signal is converted to a corresponding voltage signal that is read by the data acquisition system and the measured temperature value is displayed after signal processing.

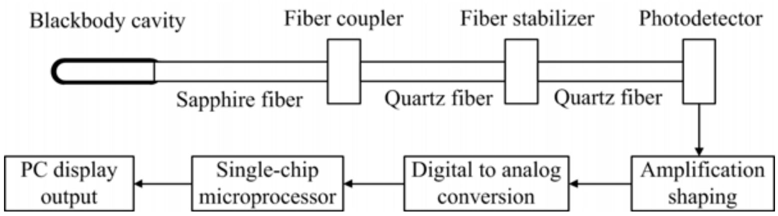

Fig. 1. Sapphire Fiber Sensor Measuring System.

2.1. Blackbody Cavity Production

Synthetic sapphire is artificially grown from single crystal alumina (α-Al_3O_2) and has good thermal stability, high strength, high corrosion resistance, high melting point (upwards of 2045 °C). It transmits wavelengths in the range of 0.14 μm ~ 6.5 μm and can be matched with the spectral response of the photoelectric detector, making it an excellent near-infrared, high-temperature resistant material for optical fibers. Recently, single crystal sapphire fiber is the most suitable optical waveguide material in high temperature environments due to both its thermal characteristics and waveguide characteristics. The blackbody probe is the radiation sensitive element in thermal radiation temperature measurement and is the key component for the sapphire optical fiber high-temperature sensor. The features of the blackbody cavity will directly determine the performance of the sensor. The probe material and coating process determines the upper temperature limit capable of being measured, the dynamic response time, service life, and most importantly the thermal radiation characteristics of the probe itself, thus affecting the accuracy, repeatability, and stability of the temperature sensor. There are many ways to produce the blackbody cavity, the two main ways are: (1) Use the high emissivity and high temperature characteristics of iridium (Ir), platinum (Pt) and other precious metals to produce the blackbody cavity. During production, the precious metal is added on to one end of the sapphire fiber through a thin film deposition process and then a film of aluminum oxide ($A1_2O_3$) is deposited to act as a protective film in order to prevent volatilization of the precious metal at a high temperature. (2) Use the high emissivity characteristic of ceramic by sintering a ceramic blackbody cavity at one end of the sapphire fiber. Blackbody cavities made through the above two methods can both satisfy the high emissivity; high temperature resistance, stability, and temperature sensing requirements needed and can firmly bind to the sapphire fiber. Producing the blackbody cavity with high temperature ceramic is more widely used due to lower production costs. Currently, research is being done to further reduce the cost of blackbody cavity production. X. J. Hao [8, 10] has found cheaper metal coating materials, coating the sapphire fiber first with a metalized tantalum or molybdenum film and then plating with an outside layer of zirconium ceramic protective film to produce blackbody cavity. Z. Liu [11] adopted new ceramic materials, first depositing a layer of titanium nitride film, and then depositing a layer of zirconium oxide protective film to produce blackbody cavity. This process has the advantages of low costs and improved temperature measurement maximum and will further promote the use of sapphire fiber sensors in practical processes.

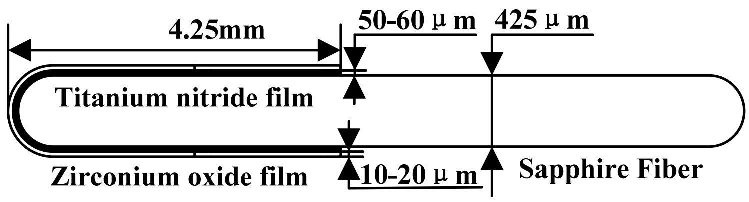

Fig. 2. The Sapphire Fiber Sensor Blackbody Cavity.

2.2. Sapphire Fiber Optic Probe Thermal Radiation Characteristics

The absorption coefficient of single crystal sapphire is in the range of 10^{-6} m ~ 10^{-5}m depending on the temperature, and sapphire fiber core diameter is only a few hundred microns. Thus, the heat radiation absorbed by the thermal cavity surface is very small. The sapphire fiber blackbody can be reasonably viewed as a cylindrical, isothermal diffusion cavity. Since the sapphire fiber blackbody cavity can be seen as an isothermal cylindrical cavity, the effective emissivity formula of the cylindrical, isothermal diffusion cavity can be derived from Gouffe's thermal radiance theory shown by Eq. 1.

$$E_0 = \frac{\varepsilon\left[1+(1-\varepsilon)\left(0.25g-01875g^2\right)\right]}{\varepsilon+(1-\varepsilon)\left(0.25g-0.125g^2\right)}, \quad (1)$$

where g = D/L, L is the length of the cylindrical cavity blackbody; D is the diameter of the sapphire fiber; ε is the emissivity of the coating material. Eq. 1 represents the effective optical emissivity of the blackbody cavity. The effective optical emissivity is not only dependent on the emissivity of the coating materials, but also the structure and size of the blackbody cavity. Sapphire crystal has a refractive index of n=1.75. The radiation emitted from the blackbody cavity at the end is limited to within a small solid angle along the fiber axis. Therefore, it can approximate that the radiation propagates along the fiber axis as a one-dimensional light propagation. Matlab was used to simulate the change in effective emission rate of the cylindrical blackbody cavity for different blackbody dimensions. Fig. 3 shows the theoretical calculation results for effective emissivity of the blackbody cavity. From the figure, when the emissivity of the thermal medium coating material is greater than 0.5 and the ratio of the blackbody cavity dimensions L/D is greater than 10, the effective emissivity E_0 is not only is very close to 1 but also remains very stable. At this point, the fiber optic sensor probe is very close to an ideal blackbody cavity. Meaning the blackbody cavity has stable heat radiation characteristics across a wide temperature range. In order for the sapphire optical fiber sensor thermal cavity to be seen as an ideal blackbody cavity, the blackbody cavity design should optimally have an L/D ratio of approximately 10.

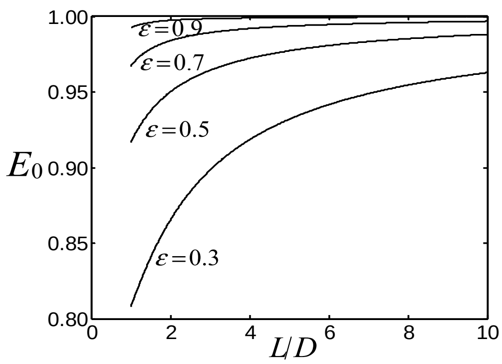

Fig. 3. Optical Fiber Temperature Sensor Cavity Effective Emissivity.

3. Sensor Temperature Measurement Principle

The principle of operation for sapphire fiber temperature sensors is based on the blackbody cavity radiation theory of colorimetric method [12-14]. According to Planck's law of blackbody radiation, if the sensor probe is placed in an area with temperature T, the monochromic radiation flux is:

$$M(\lambda,T)=\frac{\varepsilon(\lambda,T)C_1}{\lambda^5\left[\exp(C_2/\lambda T)-1\right]}, \quad (2)$$

According to Wien's formula, when $\lambda T << 1$, the approximate expression for Planck's law is:

$$M(\lambda,T)=\varepsilon(\lambda,T)C_1\lambda^{-5}\exp\left(-\frac{C_2}{\lambda T}\right), \quad (3)$$

Assuming the object being measured is at the same temperature T, the radiated power ratio $R(T)$ radiated from the measured object of two wavelengths λ_1 and λ_2 and monochromatic radiation of $M(\lambda_1, T)$, $M(\lambda_2, T)$ is:

$$R(T)=\frac{M(\lambda_1,T)}{M(\lambda_2,T)}=\frac{\varepsilon(\lambda_1,T)}{\varepsilon(\lambda_2,T)}\left(\frac{\lambda_1}{\lambda_2}\right)^5\exp\left[\frac{C_2}{T}\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\right], \quad (4)$$

The radiation signal is first filtered through the filter before the optical detector converts the radiation into electrical signal. The signal intensity is:

$$I(\lambda_0,T)=\int_{\lambda_0-\Delta\lambda/2}^{\lambda_0+\Delta\lambda/2} f(\lambda)\times D(\lambda)\times F(\lambda)\times M(\lambda,T)\,\mathrm{d}\lambda, \quad (5)$$

where $F(\lambda)$ is to account for radiation loss from transmission through the optical signal transmission fiber (the sapphire fiber and quartz transmission fiber) and from the insertion of components such as fiber optic connectors and other optical elements which cause insertion loss. Fiber connector insertion loss is:

$$I_L=-10\log\frac{p_1}{p_0}(\mathrm{d}B), \quad (6)$$

where p_0 is the input optical power, p_1 is the output optical power. Optical fiber transmission attenuation is:

$$I(z)=I_0 e^{-\infty}, \quad (7)$$

where I_0 is the initial light intensity entering into the fiber core (z=0 point), z is the longitudinal distance along the fiber, when the interference bandwidth filter is narrow, $f(\lambda)$, $D(\lambda)$, $F(\lambda)$, $\varepsilon(\lambda, T)$ are usually considered to be independent of wavelength and become constants. In this paper, with two fiber Bragg gratings as the narrow-band filter of the test system, formula (5) can be simplified to

$$I(\lambda_0,T)= f(\lambda_0)\times D(\lambda_0)\times F(\lambda_0)\times\varepsilon(\lambda_0,T)\cdot, \int_{\lambda_0-\Delta\lambda/2}^{\lambda_0+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda \quad (8)$$

Two photodetectors convert the received radiation signal into current signal, the ratio $R(T)$ is:

$$\frac{I(\lambda_1,T)}{I(\lambda_2,T)}= \frac{f(\lambda_1)\times D(\lambda_1)\times F(\lambda_1)\times\varepsilon(\lambda_1,T)}{f(\lambda_2)\times D(\lambda_2)\times F(\lambda_2)\times\varepsilon(\lambda_2,T)}\times, \frac{\int_{\lambda_1-\Delta\lambda/2}^{\lambda_1+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda}{\int_{\lambda_2-\Delta\lambda/2}^{\lambda_2+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda} \quad (9)$$

if we define

$$K=\frac{f(\lambda_1)\times D(\lambda_1)\times F(\lambda_1)\times\varepsilon(\lambda_1,T)}{f(\lambda_2)\times D(\lambda_2)\times F(\lambda_2)\times\varepsilon(\lambda_2,T)}, \quad (10)$$

and

$$R_1(T)=\frac{\int_{\lambda_1-\Delta\lambda/2}^{\lambda_1+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda}{\int_{\lambda_2-\Delta\lambda/2}^{\lambda_2+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda}, \quad (11)$$

then we have

$$R(T)=K\times\frac{\int_{\lambda_1-\Delta\lambda/2}^{\lambda_1+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda}{\int_{\lambda_2-\Delta\lambda/2}^{\lambda_2+\Delta\lambda/2} M_0(\lambda,T)\,\mathrm{d}\lambda}=K\cdot R_1(T), \quad (12)$$

where K is the device constant unrelated to the temperature of the test system. Eq. 12 ignores the change caused by changes in temperature, the optical signal loss during transmission, coupling, and other optical elements insertion and changes in emissivity. Considering the actual test environment this omission is permissible, as only the sensor blackbody cavity probe in the high temperature environment and the transmission part is not affected by the high temperature environment. K can be obtained through a static calibration system. One possible type of calibration to determine K is the colorimetric method. The colorimetric method can effectively improve temperature measurement accuracy, and also eliminates the influence of the environment and emission rate. The colorimetric measuring system is shown in Fig. 4.

4. Static Calibrations

Fig. 5 shows a fiber optic sensor static calibration device. The hot end of a standard platinum-rhodium thermocouple is placed in the calibration furnace along with the sapphire fiber blackbody cavity probe so that they are at the same temperature. The cold end of the thermocouple is kept at a constant temperature of 0 °C. Multiple temperature measurement points are uniformly taken in the effective measurement range. Each time, the temperature has to be stable for 10 minutes before a reading is taken to make sure the thermal equilibrium state has been reached. For each temperature measurement point, three readings are averaged. In the low temperature region (500 °C ~ 1100 °C), a standard platinum-rhodium10-platinum thermocouple is used for calibration; in the high-temperature zone (l100 °C ~ 1800 °C), a standard platinum-rhodium30-platinum-rhodium6 thermocouple is used for calibration.

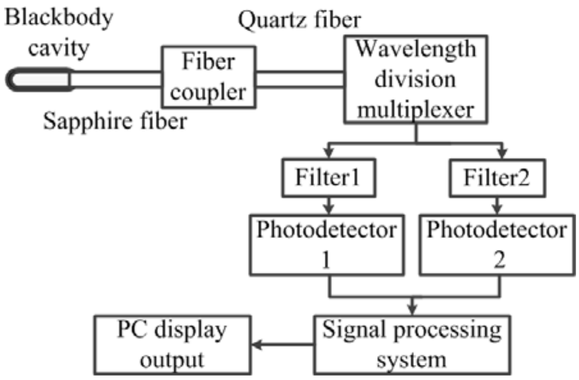

Fig. 4. Colorimetric Measurement System.

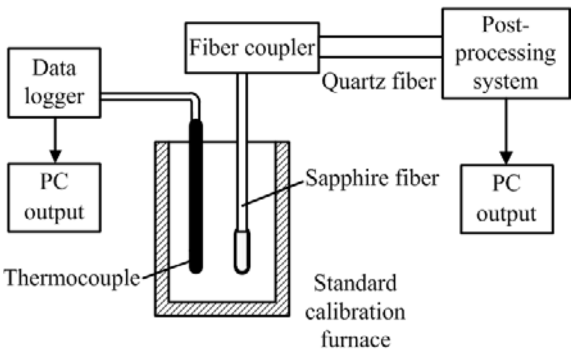

Fig. 5. Static Calibration Device.

Currently, sensor static calibration technology is relatively mature. Yan et al [15] of Aerospace forty-four designed a suitable temperature sensor calibration and test system, which consists of the acetylene flame temperature integrated test platform and the corresponding testing software to provide a stable reliable, secure and convenient platform for sensor testing. Hao et al [16-17] at North University of China designed a calibration system made of a hydroxide flame gun, infrared thermal image instrument and data acquisition card which can determine the constant K and the temperature-voltage curve more accurately. The system operation is simple, convenient and fast, it can be calibrated to a maximum temperature of above 2000 °C which will lay the foundation for accurate transient high temperature measurement.

5. Dynamic Calibrations

In many types of dynamic measurements, the temperature measured by the sensor is not the real temperature of the medium. This difference is called dynamic response error. To reduce such error, the dynamic response of the temperature sensor should be studied in the process of dynamic calibration. The thermal response characteristics of sapphire fiber sensor mainly are decided by the blackbody cavity dielectric film thickness and the thermal conductivity of the dielectric material. The dielectric material may be high temperature metal or ceramic depending on the production process. The film thickness ranges from several microns to several tens of microns. Each type of film has its own advantages, metal film blackbody cavities have fast thermal response while high temperature ceramic blackbody cavities are convenient to manufacture, have good oxidation resistance, and a thermal response, though less ideal than that of metal film cavities, that can meet the requirements of most high temperature measurement circumstances. Fig. 6 is a diagram of a sapphire fiber sensor dynamic calibration system. The system is composed of conductive quartz optical fiber, optical fiber connector, optical fiber sensors, CO_2 laser beam, mirrors, optical amplifiers, storage oscilloscopes. Fiber optic sensor's dynamic response time steps up along with the enhancement of the laser signal generated by high-power CO_2 laser beam, which passes through 45° mirror reflection, focusing on the blackbody cavity of fiber optic sensor. Then an oscilloscope records the output voltage signal changing with the laser signal and the optical fiber sensor response time can be decided.

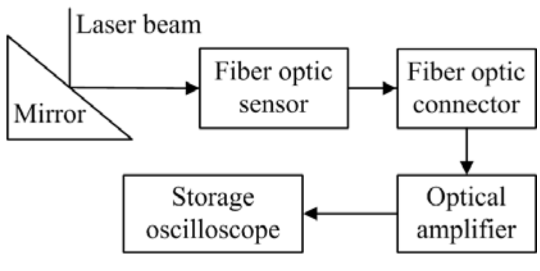

Fig. 6 Dynamic Calibration System.

Recently, the rapid development of dynamic parameter test technology has become one of the latest trends in measurement testing technology. Dynamic calibration can provide dynamic measurement traceability and also the basis for dynamic parameter measurements. P. Castellini et al [18] used laser sustained heating temperature sensor, and the sensor time constant τ is obtained by the flow medium related parameters. Researchers of North University of China [19-22] made contribution to high temperature dynamic calibration of sensors by designing and developing a transient surface temperature dynamic calibration system. This system has been successfully used to measure types of missile launch transient temperatures.

6. Conclusion

Sapphire optical temperature measurement technology has the advantages of high temperature resistance, corrosion resistance, small size, fast response, safe, easy to implement, simple remote measurement capabilities and calibration, and is not affected by electromagnetic interference over conventional temperature measurement technologies. Therefore, it has been widely applied in fields such as aviation, metallurgy, the chemical industry, energy, and other high temperature measurement areas. From the development trend of technology, sapphire optical fiber temperature measurement technology will move toward miniaturization, intelligence etc. with advances in materials technology, micro-fabrication technology, and communications technology.

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