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Development of an Infrared Two-color Probe for Particle Cloud Temperature Measurement

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Key Words: Particle cloud, Temperature measurement, Two-color pyrometry

Abstract

The demands for reliable particle cloud temperature measurement exist in many process industries and scientific researches. Particle cloud temperature measurements depend on radiation thermometry at two or more color bands. In this study, we developed a sensitive, fast response and compact online infrared two-color probe to measure the temperature of a particle cloud in a phase of two field flow (solid-gas). The probe employs a detector contained two InGaAs photodiodes with different spectral responses in the same optical path, which allowed a compact probe design. The probe was designed to suit temperature measurements in harsh environments with the advantage of durability. The developed two-color probe is capable of detecting particle cloud temperature as low as 300°C, under dynamic conditions.

1. Introduction

Precise temperature measurements of particles and control based on these data play an important role in many applications such as pulverized coal combustors, thermal spray processes and blast furnaces(1-3). Particle temperature measurements can be categorized as single particle and particle cloud in which the pyrometer observes all particles at the same time(4). For in-flight particles, contact temperature measurement methods are not applicable, and also the effect of harsh measurement environment hampers both operational and durability of the measurement devices(4). Therefore, radiation pyrometry techniques are found to be appropriate for this type of measurement(5).

Radiation thermometers can be classified as one-color, two-color or multicolor pyrometer. In single color pyrometers, the emissivity of the particle cloud is assumed to be known, otherwise, two-color or multicolor pyrometers are favorable. Khan *et al.*(6) stated that there is no significant advantage for using more than two color bands. In two-color pyrometry, the effect of the measurement environment, as well as unknown surfaces emissivity, are lessen. Several techniques have been used to separate the incident thermal radiation into two distinct bands, such as rotating filter wheel composed of two different filters with single detector, and beam splitter with two detectors(7,8).

Although the two-color pyrometry is a well-established method for particles temperature measurement, but usually it is used in applications in which the temperature of the measured particles is relatively high and usually above 800°C. However, in some applications, the temperature of the particles is very low and can be less than 200°C. For instance, the coal particles in the upper region of a coal fired furnaces due to the gases escape from the furnace. To measure the temperature of this particle cloud, a sensitive, remote and fast response is required.

The objective of this work was to develop a sensitive, fast response, compact, durable and remotely controllable two-color probe for particle cloud temperature measurements in the range of 300 to 1000°C

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in a harsh measurement environment.

The operation principle of the developed two-color probe is based on Planck's law of spectral radiance [9]. This law states that the spectral radiance (S) of the thermal radiation that is emitted from an object when its temperature is above absolute zero is a function of the object temperature (T) and the thermal radiation wavelength (λ). For a blackbody, Wien's approximation describes the relationship between S, T, and λ as follows:

$$S_{b,\lambda}(\lambda,T) = C_1\lambda^{-5}e^{-\frac{C_2}{\lambda T}} \tag{1}$$

where C_1 and C_2 are the first and second radiation constants, respectively, for spectral radiance. For a grey body, Eq. (1) becomes

$$S_{g,\lambda}(\lambda,T) = C_1\varepsilon_\lambda\lambda^{-5}e^{-\frac{C_2}{\lambda T}} \tag{2}$$

where ε is the emissivity. Eq. (2) is the basis of one-color pyrometry, in which the temperature at a specific wavelength is measured by assuming that the emissivity is known and constant. However, for objects with unknown or changing emissivities, ratio pyrometry is more effective. In ratio pyrometry, two or more wavelengths can be used to measure the temperature. Two-color pyrometers are used to measure the spectral radiation intensities at two distinct wavelengths, λ_1 and λ_2. Applying Eq. (2) for λ_1 and λ_2,

$$S_{g,\lambda 1}(\lambda,T) = C_1\varepsilon_{\lambda 1}\lambda_1^{-5}e^{-\frac{C_2}{\lambda_1 T}} \tag{3}$$

and

$$S_{g,\lambda 2}(\lambda,T) = C_1\varepsilon_{\lambda 2}\lambda_2^{-5}e^{-\frac{C_2}{\lambda_2 T}} \tag{4}$$

Then, the temperature can be calculated from the ratio (R_g) as follows:

$$R_g = \frac{S_{g,\lambda_2}(\lambda,T)}{S_{g,\lambda 1}(\lambda,T)} = \frac{\varepsilon_{\lambda 2}\lambda_1^5}{\varepsilon_{\lambda 1}\lambda_2^5}e^{-\frac{C_2}{T}\left[\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right]} \tag{5}$$

and

$$R_b = \left[\frac{\lambda_1}{\lambda_2}\right]^5\cdot e^{-\frac{C_2}{T_{true}}\left[\frac{1}{\lambda_2}-\frac{1}{\lambda_2}\right]} \tag{6}$$

where R_b is ratio for blackbody.

The temperature (T) in Eq. (5) is known as the ratio temperature (T_{ratio}) and is related to the true temperature (T_{true}) by

$$\frac{1}{T_{true}} = \frac{1}{T_{ratio}} + \frac{\ln\left(\frac{\varepsilon_{\lambda 2}}{\varepsilon_{\lambda 1}}\right)}{C_2\left[\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right]} \tag{7}$$

if,

$$\varepsilon_{\lambda 1} = \varepsilon_{\lambda 2} \tag{8}$$

then,

$$T_{ratio} = T_{true} \tag{9}$$

In ratio pyrometry, the measured temperature is independent of unknown emissivity and presence of optical obstacles in the field of view. Therefore, ratio pyrometers are considered to be more accurate than one-color pyrometers[10].

2. Probe Design and Calibration

2.1 Probe design considerations

Generally, classical infrared radiation detection systems are configured as shown in Fig. 1. The main consideration in radiation pyrometer design is the desired temperature-measurement range. Therefore, the optical system, detector and amplifier depend on the desired temperature-measurement range[11].

In this study, the probe was designed to cover wide range of temperature measurements from 300°C to 1000°C. For this range, the peak wavelength is in the infrared range of approximately 2.3-5.1 μm according to Wien's approximation[12].

Basically, industrial environment includes dust, moisture, and high levels of carbon dioxide concentration. Therefore, the operating wavelengths should be within the atmospheric windows in which the effect of these obscurants is lower. Also, an efficient purging method should be applied to keep the optical system clean.

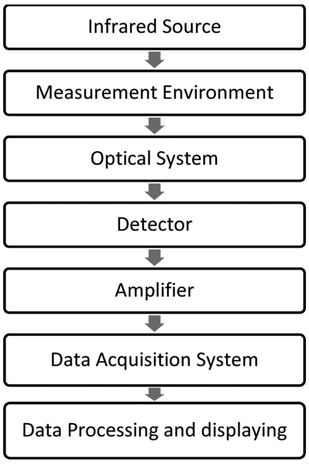

Fig. 1. General configuration of radiation pyrometer

An uncoated infrared-grade calcium fluoride (CaF_2) lens was used to collect the thermal radiation emitted by the particle cloud. In common operating conditions, CaF_2 lenses can endure temperatures of up to 800°C in dry environment. In the infrared region, CaF_2 transmits more than 90% of the incident radiation at wavelengths ranging from 1.0 μm to 5 μm. Furthermore, CaF_2 is inert when in contact with most acids, metal vapors, and gases.

The selection of the detector is the most critical aspect of two-color pyrometer design and it depends on the desired temperature measurement range. Hence, the detector should be operable at wavelengths between 1 and 4 μm. For this wavelength range, photovoltaic-type detectors possess high detectivities (D*) and fast responses. For applications in which high sensitivity is required, InGaAs detectors are used[(13)]. To determine the exact operational wavelength, the well-known fact that sensitivity decreases with increasing wavelength must be considered. The effects of the measurement environment must also be accounted for to avoid absorption or emission of thermal radiation by water vapor or gases[(12,14)]. In addition to this, the two wavelengths should be close enough to meet the requirements of the grey-body hypothesis and to decrease the possibility of severe measurement condition variations between the two wavelengths[(14)]. Consequently, a Hamamatsu two-color detector, K11908-010K, was chosen[(15)].

Usually, the detected signal is very small and need amplification. The amplifier to be used must harmonize the signal generated by the detection system, provide high sensitivity, and deliver low noise. Considering these factors, two SR570 low-noise current preamplifiers were used. This amplifier equipped with an RS-232 interface. Thus, the gain sensitivity can be efficiently controlled based on the signal intensity[(16)].

The data acquisition system which was used for sampling and digitizing signals is composed of an NI 9222 data acquisition module[(17)] mounted on an NI cDAQ 9184 Ethernet chassis[(18)]. Simultaneously, data were obtained from two k-type thermocouples using an NI 9213 module[(19)]. Those data passed through an Ethernet cable from the NI cDAQ 9184 to the PC.

2.2 Temperature-measurement software

The NI LabVIEW program was used to control all of the two-color probe components and to develop an appropriate program to obtain the signal, calculate the true temperature, and display the results[(20)]. Fig. 2 show the diagram of the measurement system.

2.3 Calibration procedure

The developed two-color pyrometer was calibrated using an OMEGA BB-4A Blackbody Calibrator which has a cavity diameter of 21.56 mm and a temperature range of 100 to 982°C. Its blackbody emissivity and temperature uncertainty are 0.99 and ±1°C, respectively. The blackbody calibrator was placed 6 m from the two-color pyrometer, and a laser was used to align them. The calibration setup is shown in Fig. 3. The blackbody temperature was set

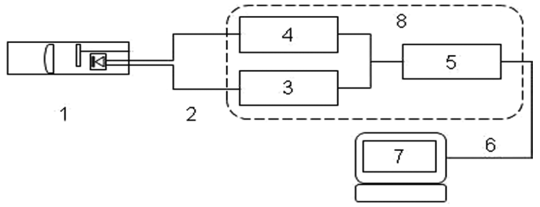

Fig. 2 Schematic diagram of the developed pyrometer : 1, Probe; 2, Coaxial connector; 3, and 4, Low noise preamplifiers; 5, Data acquisition system; 6, Optical fiber; 7, PC; 8, Control box

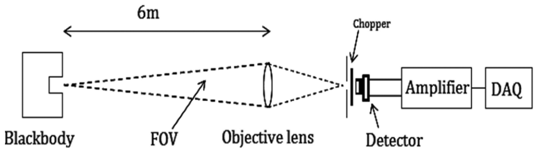

Fig. 3. Two-color probe calibration setup

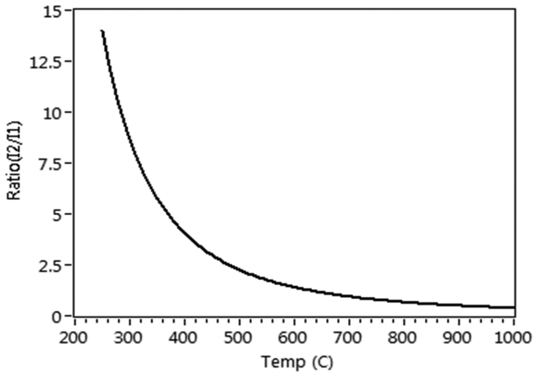

Fig. 4 Calibration curve of two-color pyrometer: $I_{\lambda2}/I_{\lambda1}$ ratio versus blackbody temperature

at 250°C to obtain the signals at λ_1 and λ_2. This procedure was repeated every 10°C starting from 250°C up to 950°C. The ratio $I_{\lambda2}/I_{\lambda1}$ was calculated for each temperature and the calibration curve was obtained by plotting the blackbody temperature versus the calculated ratio. For temperature measurements >950°C, the calibration curve equation was derived, and the ratios at temperatures >950°C were obtained. The relation between $I_{\lambda2}/I_{\lambda1}$ and the blackbody temperature is shown in Fig. 4. Also the effect of the target location on the ratio $I_{\lambda2}/I_{\lambda1}$ was studied for different temperatures. Fig. 5 shows that there is no significant difference in the measured ratio $I_{\lambda2}/I_{\lambda1}$ at different distances between the measured objects and the probe for the same object temperature.

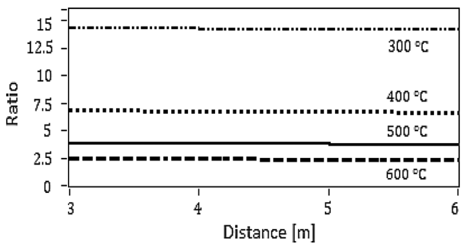

Fig. 5 The effect of the distance between the probe and measured object on the ratio $I_{\lambda2}/I_{\lambda1}$

3. Test and Measurements

3.1 Setup and data acquisition

To check the performance, the developed two-color pyrometer was installed in a blast furnace. Data was acquired simultaneously from the two-color probe and two k-type thermocouples. One of the thermocouples was used to monitor the detector temperature during operation and the other one was used to measure the temperature of the gas around the probe.

3.2 Results and discussion

The acquired raw data contained three kinds of sig-

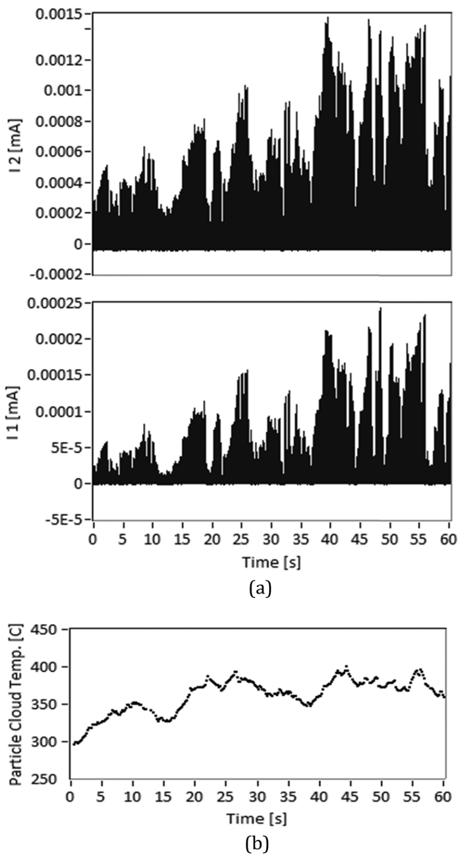

Fig. 6 (a) Absolute intensity at λ_2 and λ_1, (b) is the calculated particle cloud temperature from the detected signals in (a)

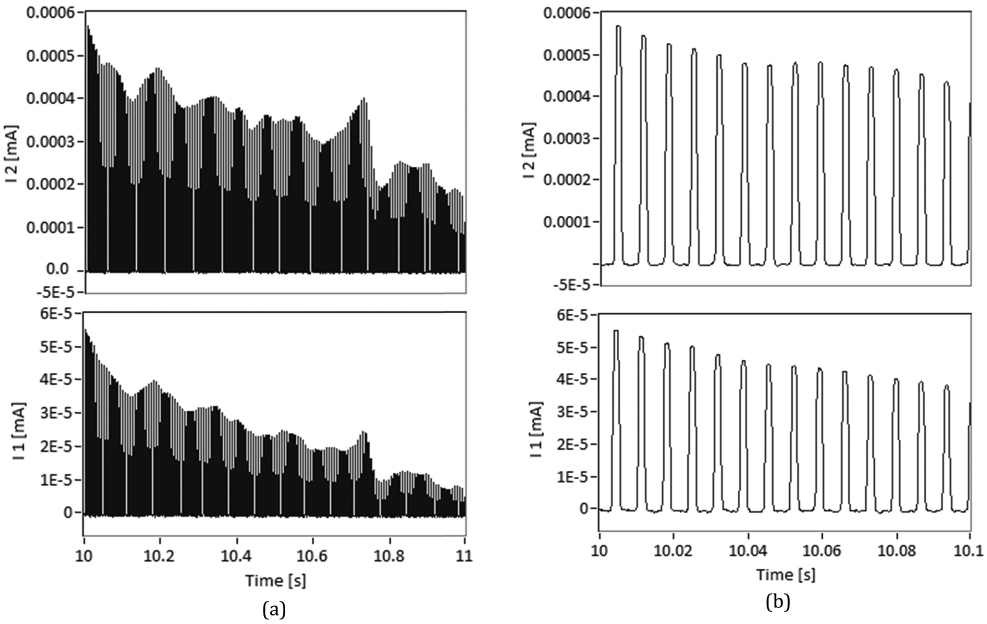

Fig. 7 Signal details within: (a) 1s and (b) 100 ms

nals. The first kind of signals is related to the thermal radiance from the particle cloud. The second one is generated from the noise. The last one is originated from amplifier gain setup. Fig. 6(a) and (b) show the absolute intensity of the acquired signal at λ_2 and λ_1 and the calculated temperature during 1 minute. Fig. 7(a) and (b) show the signal details within 1s and 100 ms.

To calculate the real temperature, the signal which is originated from thermal radiance of the hot particle cloud was identified using a wavelet based method which depends on the width and the threshold frequency to detect the peaks or valleys in the signal. The minimum and maximum amplitude of this signal ranged between 0.01 and 5 volts respectively. If the amplitude is lower than 0.01 volt or exceed 5 volts, the amplifier was automatically set to a higher or a lower gain level. Hence, a unique signal pattern occurs due to this action. The effect of noise signal is not significant at temperatures above 350°C because the signal to noise ratio (SNR) was shown to be accepted. At low temperature, a simple median filter was applied for noise cancellation. Different signals were identified and the particle cloud temperature was calculated using the ratio of the absolute intensities at the two color bands fitted to the calibration data.

As shown in Fig. 6(b), particle cloud temperature was measured down to 300°C using the developed probe. The discontinuities in the measurements are related to very low intensity or absence of particles cloud in the field of view of the probe.

4. Conclusions

An infrared two-color probe was developed to measure the temperature of a cloud of particles in a hostile environment. Temperature measurements down to 300°C obtained. This device has the ability of measuring temperature remotely with the advantage of durability. The measured temperature range of the developed probe can be prolonged by employing a cooled detector.

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References

(1) T. Joutsenoja, P. Heino, R. Hernberg, and B. Bonn, "Pyrometric Temperature and Size Measurements of Burning Coal Particles in a Fluidized Bed Combustion Reactor", Combustion and Flame, 118(4), 707~717 (1999).

(2) G. Mauer, R. Vaßen and D. Stöver, "Plasma and Particle Temperature Measurements in Thermal Spray: Approaches and Applications", J. Therm. Spray Technol., 20(3), 391~406 (2010).

(3) S. M. Godoy and F. C. Lockwood, "Development of a two-colour infrared pyrometer for coal particle temperature measurements during devolatilisation", Fuel., 77(9/10), 995~999 (1997).

(4) J. R. Fincke, D. C. Haggard and W. D. Swank, "Particle Temperature Measurement in the Thermal Spray Process," J. Therm. Spray Technol., 10(2), 255~266 (2001).

(5) Ph. Bertrand, M. Ignatiev, G. Flamant, I. Smurov "Pyrometry applications in thermal plasma processing", Vacuum A, 56, 71~76 (2000).

(6) M. A. Khan, C. Allemand and T. W. Eagar, "Noncontact temperature measurements I: interpolation based techniques", J. Rev. Sci. Instrum. A 62, 392~402 (1991).

(7) K. Crane and P. J. Beckwith, "I. R. radiation pyrometer", U.S. patent 4,470,710,11 (1984).

(8) X. Maldague and M. Dufour, "Dual imager and its applications to active vision robot welding, surface inspection, and two-color pyrometry," Opt. Eng., 28(8), 872~880 (1989).

(9) M. Planck, "On the law of distribution of energy in the normal spectrum", Ann. der Phys., 553 (1901).

(10) A. K. Ghosh, Introduction to Measurements and Instrumentation, (PHI, 2012), p. 433.

(11) Z. M. Zhang and G. Machin, "Overview of radiation thermometry", in Radiometric Temperature Measurements, Z. M. Zhang, B. K. Tsai, and G. Machin, eds. (Elsevier, 2009), pp. 1~29.

(12) D. P. DeWitt and G. D. Nutter, Theory and Practice of Radiation Thermometry (Wiley, 1988).

(13) H. W. Yoon and G. P. Eppeldauer, "Radiation thermometer designs," in Radiometric Temperature Measurements, Z. M. Zhang, B. K. Tsai, and G. Machin, eds. (Elsevier, 2010), pp. 133~159.

(14) B. Müller and U. Renz, "Development of a fast fiber-optic two-color pyrometer for temperature measurement of surfaces with varying emissivities", J. Rev. Sci. Instrum. A, 72, 3366~3374 (2001).

(15) Hamamatsu Photonics, "Two color detector K11908-010K", http://www.hamamatsu.com/resources/pdf/ssd/k11908-010k_kird1116e.pdf.

(16) Stanford Research Systems, "SR570 low-noise current preamplifier" http://www.thinksrs.com/downloads/PDFs/Manuals/SR570m.pdf.

(17) National Instruments, "NI 9222", http://www.ni.com/datasheet/pdf/en/ds-260.

(18) National Instruments, "NI cDAQ 9184", http://www.ni.com/datasheet/pdf/en/ds-427.

(19) National Instruments, "NI 9213", http://www.ni.com/datasheet/pdf/en/ds-69.

(20) National Instruments, "LabVIEW," http://www.ni.com/labview.

(21) www.omega.com/manuals/manualpdf/M3014.pdf.