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Measurement of char surface temperature in a fluidized bed combustor using pyrometry with digital camera

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HIGHLIGHTS

- Pyrometry with digital camera to measure char surface temperature in FB.
- One-color pyrometry (P1C) measures temperatures both lower and higher than the bed.
- P1C used sequentially (red–green–blue) improves the classical two-color pyrometry.
- Char emissivity is needed but a rough estimate gives precise measurement.
- P1C detects precisely surface temperature gradients and evolution of char size.

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ABSTRACT

A method is presented to measure the char surface temperature during conversion in fluidized bed (FB) using a digital camera. The method applies one-color pyrometry (P1C) sequentially for the three wavelength bands (red, green, and blue) changing from one band to another automatically as a function of radiation intensity received by the sensor of the video camera. Experiments were made in a two-dimensional FB combustor ($0.18 \times 0.50 \times 0.018$ m) equipped with a window for visual observation. It is shown that the new method improves the accuracy compared to two-color pyrometry (P2C), allowing the measurement of a wider range of temperature, including temperatures lower than the bed (background). The main limitation of P1C (compared to P2C) is that the char emissivity has to be known. However, a sensitivity analysis, assuming a char emissivity variation from 0.85 to 1, reveled that the relative error in temperature is lower than 1% when the surface temperature of the char is higher than that of the bed. Then an assumed value of emissivity within this range is sufficient. However, a more precise estimate of char emissivity is needed when measuring temperatures lower than the bed temperature. Furthermore, the method enables determination of details such as surface temperature gradients and size of the particle during combustion. Overall, the technique allows determination of precise data of the fuel conversion process in FB.

1. Introduction

It is necessary to develop combustion technologies in order to reduce the CO_2 emissions to the atmosphere [1–3]. The most straightforward proposals aim at increasing the plant efficiency, removing CO_2 from the combustion gases, or changing the fuel [4,5]. Oxy-combustion stands out as favorable among all proposed technologies for CO_2 capture [6–10]. One of the main challenges of this technology is to control the combustion temperature, because it involves a high concentration of O_2 in the gas added to the boiler furnace, which could produce unacceptable temperature levels both globally in the furnace and locally in a fuel particle.

Due the importance of the combustion temperature of a fuel particle, there are many techniques dealing with temperature measurement [11]. For combustion in fluidized bed (FB) reactors, contact techniques, such as thermocouples, are used to measure the temperature of the fuel particle [11–17]. However, because of (i) its intrusive nature (the thermocouple is inserted into the interior of the particle), (ii) its influence on the fluid-dynamics and the free motion of the particle during combustion, (iii) the internal temperature is measured (not the surface one), and (iv) the fuel particle may shrink and fragment during conversion and the signal may get lost, non-contact techniques could be better options to

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Nomenclature

A	surface area, m^2
b	blue spectral band
C	first and second Planck's constants; $C_1 = 3.742 \cdot 10^8$ $(W\ \mu m^4)/m^2$, $C_2 = 1.439 \cdot 10^4$ K μm
DN	digital number provided by the software of the digital camera
e	energy emitted per unit area, and wavelength, $W/(m^2\ \mu m))$
E	energy emitted per unit area, W/m^2
f	view factor between two surfaces
j	energy emitted and reflected from a surface per unit area, and wavelength, $W/(m^2\ \mu m))$
k	general index referring to any spectral band or color
(m, n)	pixel of the sensor located at row 'm' and column 'n'
N°_{px}	pixels occupied by the char particle
r	radius of char particle
T	temperature, K

Greek letters

α	coefficient of the calibration curve or absorbance
β	calibration parameter
γ	coefficient of the calibration curve
δ	coefficient of the calibration curve
ε	emissivity
τ	transmittance
ζ	relative error of P1C RG
ζ_{ε}	relative error of P1C RG regarding with the emissivity value
$\Delta\lambda_r$	red spectral band, (0.62–0.70) μm
$\Delta\lambda_g$	green spectral band, (0.49–0.58) μm
$\Delta\lambda_b$	blue spectral band, (0.45–0.49) μm
λ_r	central wavelength of the red spectral band, 0.685 μm
λ_g	central wavelength of the green spectral band, 0.535 μm
λ_b	central wavelength of the blue spectral band, 0.47 μm
Φ	constant of proportionality between W/m^2 and $W/(m^2\ \mu m)$

Subscripts-indices

c	char
P1C	one-color pyrometry
P2C	two-color pyrometry
r, b, g	indices referring to the red (r), green (g), and blue (b) spectral bands
k, i, j	general indices referring to any spectral band or color, or surface 'i', 'j' or 'k'
o	initial
s	sand
w	homogenized surface
wnd	quartz window of the electric oven

Superscripts

–	average value
o	black behavior

Abbreviations

FBC	fluidized bed reactor
FOV	field of view of the digital camera
P1C	one-color pyrometry
P2C	two-color pyrometry
WD	working distance of the digital camera

overcome these inconveniences. Non-contact methods (optical techniques) are based on the capture and interpretation of thermal radiation emitted from the particle. The most commonly used technique is optical pyrometry [18–25], where the radiation is captured by an optical probe [18–22] or by a digital camera [23–25]. The excess-temperature of a fuel particle above the bed temperature has been measured by means of an optical probe, and even the size of the particle has been estimated [20,22]. But this technique yields widely scattered results that are difficult to interpret, because they are related to the fraction of the total field of view of the probe that is occupied by the fuel particle (depending on the distance and the particle size). The result of pyrometry by an optical probe also depends on the frequency with which the fuel particles are observed (when passing closely through the field of view). Moreover, the measured temperature is the average of the bodies present in the field of view. These weaknesses are overcome using a digital camera, if the reactor is visibly accessible from outside, because the radiation from the particle's surface is effectively separated from that of the adjacent regions, improving the accuracy of the measured temperature. The temperature field inside an FB reactor, generated during combustion of an air-propane mixture, has been measured previously by means of a digital camera [25]. Recently, this technique also has been applied to analyze how the atmosphere during oxy-combustion affects the flame temperature [26]. Even heat transfer and the temperature profiles between the solid bed-particles and the fluidizing gas have been studied by infrared cameras [27–29].

The above discussion shows that the surface temperature of a fuel particle still has not been measured in an accurate and reliable way during conversion in FB. The main objective of this paper is to demonstrate the application of pyrometry with a digital camera to determine the surface temperature of a fuel particle during combustion in FB and to discuss the capability of this technique to detect further details, such as surface temperature-gradients, particle shrinkage, and fragmentation. Experiments of char particle combustion in a two-dimensional FB, constructed by the authors [30], were conducted to support the development of the technique.

2. Measurement of temperature by pyrometry with digital camera

Pyrometry captures and interprets the thermal radiation emitted from a body whose temperature is to be measured. With a digital camera the light captured from the scene is separated into three spectral bands (red, green, and blue) by a filter placed over the sensor. When the radiation touches the sensor, each pixel generates three values, which are known as digital numbers (DN_k), measuring the radiation belonging to each red, green, and blue spectral band [31]. An image program like MATLAB generates three matrices for each image, whose elements (m,n) contain the digital numbers associated with the radiation received from the viewed scene. The sensor has a finite capability to measure radiation, and for radiation below this level the digital number assigned by a pixel is null. Furthermore, there is a maximum radiation, above which the pixel is saturated, and a maximum value is assigned (saturation) [31].

In general, the information contained in the digital numbers (the thermal radiation belonging to the red, green, and blue spectral bands) is used simultaneously to measure temperature [23–26,30,32,33]. It is not necessary to know the surface emissivity to determine the surface temperature by Eq. (1) (see Appendix) as