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Dual-phosphor thermometry to probe the flame particle interaction in a model packed bed

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Abstract: The flame-particle interaction in a model packed bed are probed at the pore scale using 2D lifetime imaging of thermographic phosphor coatings. A dual-phosphor approach reveals detailed temperature distributions at two temperature levels. © 2024 The Author(s)

1. Introduction

In a broad range of industrial applications, combustion of the fuel within a packed bed sustains the high temperature required for the thermal treatment of particles. The temperature of particles highly impacts the flame position and extent, while the flame position strongly influence the particle transformation, and thus the quality of products. This study uses a cylindrical packed bed to optically access the region of flame interaction with cylindrical particles. A dual-phosphor version of phosphor thermometry, which provides an augmented temperature resolution, is proposed to measure the 2D temperature distribution of cylinders surrounding a 2D premixed methane/air flame.

2. Methods

A 3D view of the the cylindrical packed bed, is shown in Fig. 1a. This configuration permits line-of-sight optical diagnostics. The burner provides a uniform flow of methane/air along the cylinder length to stabilise a 2D flame between the cylinders. The porosity of the packed bed is set to 40% similar to the industrial cases. A section view of the packed bed is shown in Fig. 1b, where the optically accessible region which includes the region where the flame stabilize between the first and second row of cylinders is visible. The telecentric chemiluminescence imaging optics, illustrated on the left side of Fig. 1d, records the location and geometry of the flame front. 2D lifetime phosphor thermometry is performed simultaneously to obtain highly resolved 2D temperature measurements on the surface of the three cylinders confining the flame, as displayed on the right part of Fig. 1d. As shown in Fig. 1c, a narrow thin strip of phosphor is coated on the perimeter of the cylinder, midway along its length. A 532 nm pulsed laser is steered into the packed bed to simultaneously excite the three phosphor coating, (Fig. 1d). A dichroic mirror reflects the beam into the packed bed and transmits the decaying luminescence of the phosphor coatings. The luminescence is collected by a high-speed camera equipped with filters to further isolate the luminescence and to reject black body radiation. A dual-phosphor approach is adopted to augment the temperature measurement resolution, as the cylinders are expected to be at very different temperatures. The top cylinder which is surrounding by combustion products is supposed to be at a higher temperature level than the bottom cylinders, which are cooled by surrounding air. In this approach, two different phosphors, each doped with Cr^{3+} , are coated on separate cylinder. As illustrated in Fig. 1c, GAP:Cr^{3+} is coated on the top cylinder, and YAG:Cr^{3+} is coated on the bottom right and left cylinders. The temperature response of the decay time of the two phosphors is shown in Fig. 2a.

The luminescence spectrum of the two phosphor is similar and therefore measurements can be done on multiple surfaces by the same receiving optics, reducing the complexity of the phosphor thermometry setup. The camera frame rate is set to 200 kHz, allowing to measure decay times as short as 10 μs . This correspond to a maximum temperature of about 650 °C for YAG:Cr^{3+} and about 950 °C for GAP:Cr^{3+} .

3. Results

The results of simultaneous surface temperature measurements and chemiluminescence imaging is shown in Fig. 2b and c. The arcs with color gradient in Fig. 2b represent the detected cylinder edges, and the color gradient on them indicates the distribution of the measured surface temperature. For a better visualisation of the temperature distribution on the top and bottom cylinder, given that they are at two distinct ranges, two color scale

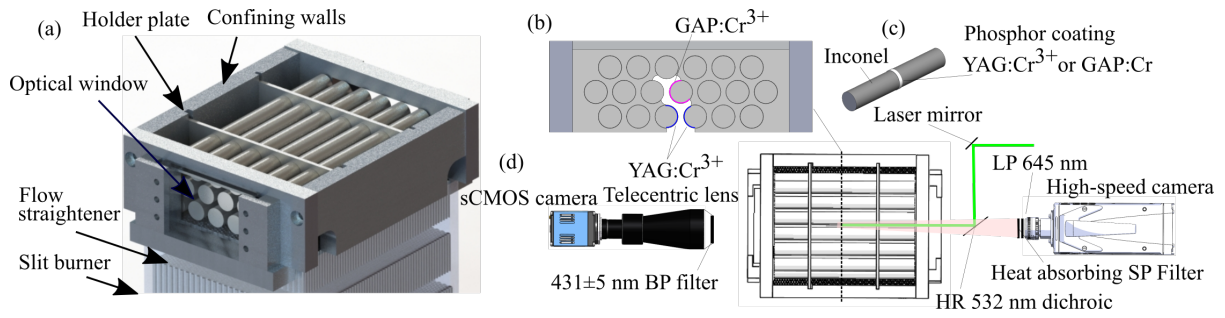


Fig. 1: A 3D view of the cylindrical packed bed (a), section view of the packed bed, YAG:Cr³⁺ coated on the bottom cylinders, GAP:Cr³⁺ coated on the top cylinder (b), narrow strip of phosphor on the perimeter of the cylinder (c), schematics of the setup to perform phosphor thermometry and chemiluminescence imaging

are used, displayed on the sides of the Fig.2b. The red arc between the cylinder edges represents the flame brush detected through the telecentric chemiluminescence imaging. Crosses indicate the location of the flame quenching point, extracted based on the chemiluminescence intensity gradient close to the right and left cylinder edge. For a more detailed visualization of the temperature profile on the left cylinder, it is plotted against the azimuthal angle θ in Fig. 2c, with red vertical line pointing out the angle at which the flame quenches. The angle θ is defined according to the blue circle on the bottom left of the Fig. 2c. The temperatures of both bottom cylinders lie in the range of 450 to 515 °C, while the temperature of top cylinder, above the flame front, lies in the range of 800 to 840 °C. Starting from the flow upstream, the surface temperature of the bottom cylinders rises monotonically from 450 °C to about 480 °C. This is followed by an abrupt temperature rise induced by the reaction. As in Fig. 2c, the maximum of surface temperature occurs at $\theta=30^\circ$ which is slightly downstream of the position of flame quenching at $\theta=25^\circ$.

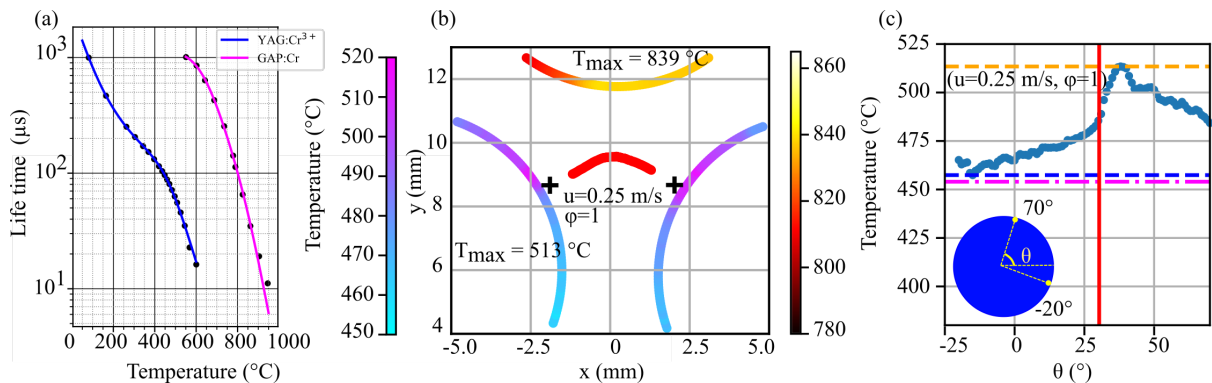


Fig. 2: Temperature response of YAG:Cr³⁺ and GAP:Cr (a), surface temperature distribution on all three cylinders, the red line delineates the reaction zone and the crosses indicate the flame sidewall quenching point (b), Azimuthal temperature distribution on the left cylinder, the red vertical line indicates the azimuthal coordinate of the quenching point in (b).

4. Conclusion

An advanced 2D phosphor thermometry method was successfully implemented to probe the thermal signature of the interaction of a flame and the cylinders surrounding it in a packed bed. By simultaneous lifetime imaging of two separate Cr³⁺-doped phosphors, it was possible to finely resolve the temperature distribution of both the side cylinders around 490°C, and the top cylinder around 820°C. Employing simultaneous telecentric imaging, the hottest region could be located as slightly downstream of the sidewall quenching point. This data can be used to validate CFD simulations with various solid-gas interface models at the wall. The interaction of a flame with hot walls is notoriously challenging to accurately model and such experimental data is therefore needed.

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