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The influence of high flux broadband irradiation on soot concentration and temperature of a sooty flame

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ABSTRACT

This paper reports the first set of measurements of the influence of simulated concentrated solar radiation (CSR) on the soot volume fraction and temperature in a laminar non-premixed ethylene flame. Broadband irradiation that closely approximates the solar spectrum was produced with a metal-halide lamp configured in a series of three optical concentrators to achieve fluxes of up to 0.45 MW/m^2 in a focused area of 80 mm in diameter. The radiation was used to irradiate an entire Santoro-type laminar flame of 64 mm in length, where the soot volume fraction and flame temperature were measured using planar laser-induced incandescence (LII) and two-line atomic fluorescence (TLAF), respectively. The results show that the simulated concentrated solar radiation significantly influences the evolution of soot on the fuel-rich side of the flame, but does not change either the visible length or width of the flame. It causes the soot volume fraction to increase by up to 50%, the soot inception to be translated upstream by 7% of the flame length, and the consumption rate of soot in the radial direction to increase by an average value of 54% for heights greater than 10 mm above the burner. The temperature of the flame was also found to increase by up to ~100 K in most of the downstream locations.

1. Introduction

Hybrids of concentrated solar thermal energy and fossil-fuelled technologies are receiving growing attention because the combination of the two energy sources offers lower emissions of carbon and other pollutants than pure fossil fuels, lower cost than pure solar thermal energy, and continuous supply [1,2]. Various types of hybrid concepts have been proposed, e.g. preheating the feed water with the low grade solar energy [3], regenerating CO_2 solvents for the carbon capture and storage process [4], preheating the combustion air in a Brayton cycle [5–7], combining oxy-fuel combustion with solar thermal in a power cycle [8]. However, all of these concepts employ stand-alone solar receivers and combustors. There is potential to further reduce capital cost by sharing the infrastructure employed to harvest both energy sources [2]. Mehos et al. [9] proposed one approach with which to reduce heat losses from a solar receiver and a combustor in a hybrid system by mounting a combustor directly onto the back of a solar receiver. More recently, Nathan et al. [2,10,11] have been developing an alternative approach with which to fully combine a combustor and a solar cavity receiver into a single device. This offers the potential for significant savings from reduced infrastructure investment and reduced start-up and shut-down losses [2]. Importantly, this direct integration of the two energy sources also results in conditions in which the flame is directly irradiated by high flux solar radiation. However, the influence on a flame of high-flux radiation, whose spectrum approximates the solar spectrum, is poorly understood and has not been reported previously.

A flame can absorb radiation through the unburned fuel, the combustion products (such as CO_2 and H_2O) and intermediates (such as radicals, molecules and soot). Among these species, soot is the most efficient radiation receptor due to its strong absorption coefficient in a broadband spectral region from visible to near-infrared. Nevertheless, the relative significance of these different species and their role in a sooty flame is yet to be reported. Indeed, to our knowledge, the relevant investigation is that of Medwell et al. [12], who demonstrated that CO_2 laser radiation at 10.6 μm with a fluence of 4 MW/m^2 can approximately double the peak

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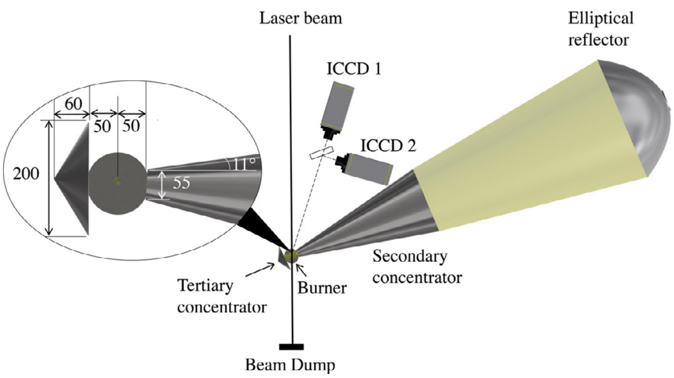

Fig. 1. A plan view of the experimental arrangement. A flame is irradiated by broadband radiation from the solar simulator. Dimensions are in millimetres (mm).

concentration of soot in a laminar ethylene/air diffusion flame, and translate the soot layer towards the oxidizing side of the flame. However, the work was undertaken with a coherent light of single excitation wavelength and irradiating on a small area of the flame (~5 mm in diameter) [12], while the CSR is broadband and would irradiate a large area of flames in a practical hybrid device. Therefore, new measurements are needed to assess the influence of radiation on a sooty flame using high-flux broadband irradiation which closely approximates the solar spectrum and irradiates the whole flame. Furthermore, the previous work by Medwell et al. [12] was performed by irradiating and measuring the upstream region of flame. Because the consumption of soot occurs mostly in the vicinity of the flame tip, the influence of irradiation on soot oxidation was not assessed. Therefore, the present work also aims to assess the influence of high-flux irradiation on soot oxidation.

Additionally, no previous measurements of both flame temperature and soot volume fraction have been reported for an irradiated flame. Measurement of both of these parameters is important because the mechanisms of soot formation and oxidation depend exponentially on flame temperature [13,14]. However, such measurements are also difficult because the introduction of high-flux, broadband radiation introduces challenges both to intrusive and to optical measurements. The use of a thermocouple is problematic because the thermocouple will be heated by irradiation to a temperature different from that of the surrounding gases. Strong broadband irradiation will also generate strong interferences to relevant optical methods [15]. However, this challenge has recently been overcome by Gu et al. [16], who developed improved capability for the two-line atomic fluorescence (TLAF) method that had previously been developed only for non-irradiated flames [17]. Therefore, this new method was adopted in the present work to measure flame temperatures.

For the reasons outlined above, the first aim of the present paper is to quantify the influence on the soot volume fraction and temperature of a sooty flame of broadband irradiation at fluxes of relevance to concentrating solar thermal energy technology. Two non-intrusive laser techniques, i.e. planar laser-induced incandescence (LII) and TLAF were used. The second aim is to provide new insight into the mechanisms responsible for any influences thus identified.

2. Methodology

2.1. High flux solar simulator

The solar simulator, illustrated in Fig. 1, consists of a 6 kW Metal Halide Lamp close-coupled with an elliptical reflector and co-aligned with a conical secondary lamp concentrator to further concentrate the radiation. A tertiary concentrator is also employed to cause the concentrated radiation to double-pass through the focal area. Details of the optical design of the solar simulator, which was perfomred using an experimentally validated Monte-Carlo ray-tracing code, are reported elsewhere [18]. The study employs a metal halide lamp as the light source of the solar simulator, whose spectrum closely matches the solar spectrum [19]. The elliptical reflector is made of aluminum alloy 1050, with a physical vapor deposition coating comprising alumina and silica, similar to that used by Petrasch et al. [20]. The secondary concentrator is cone shaped with an inlet diameter of D=500 mm, an outlet diameter of d=55 mm and a length of L=1100 mm. The tertiary concentrator is also conical with D=200 mm, d=0 and L=60 mm. Both the secondary and tertiary concentrators were made of polished stainless steel with a reflectivity of 65% and were water cooled to less than 50°C during operation, to minimize both the thermal impact of the facility on the flame and degredation of the reflecting surface.

The heat flux profile at the target area was determined with a validated Monte Carlo ray-tracing model. Firstly, the heat flux concentrated by the secondary cone was measured following the method reported previously [18,20–23]. A Lambertian plane of 250 mm × 250 mm was placed 50 mm downbeam of the secondary lamp concentrator, which is also the focal plane of the elliptical reflector with 3 m focal length. Images of the Lambertian plane were acquired using a 1600×1200 pixels Megaplus camera. The Lambertian target was then replaced with a water cooled circular foil transducer TG1000-1 (Vatell Corporation) to measure the temperature difference between the center and the circumference of the transducer, which is directly proportional to heat flux. The image of the radiation reflected by the Lambertian target was converted to a heat flux based on the measurement with the transducer. The measured heat flux map 50 mm downbeam from the secondary concentrator was then used to validate a Monte-Carlo ray-tracing model. After this, an irradiance map 50 mm downbeam of the secondary concentrator and 50 mm upbeam of the tertiary concentrator was simulated with the experimentally validated ray-tracing model [18]. This was necessary because the double path of radiation in the area between the secondary and tertiary concentrator prevents the application of the Lambertian plate.

Figure 2a presents an image of the 64 mm long laminar sooty flame employed in the current study. Figure 2b shows the irradiance map of the radiation applied to the flame, with the radiant flux peaking at 0.45 MW/m^2 and generating an average flux of 0.27 MW/m^2 in the flame area. Figure 2c presents the radial profiles of the heat flux at different heights above burners (HAB). It can be seen that the heat flux varies significantly in the axial direction, while that in the radial direction is quasi-uniform within the flame width (10 mm). The simulated heat flux for the case without the tertiary concentrator agrees with the measured results to within 5% for the peak flux and to within 13% in half width based on our previous studies [24].

2.2. Burner and flame

A laminar non-premixed ethylene flame was employed firstly becaues its high soot loading results in a strong potential for absorption of CSR and, secondly, because this flame without irradiation has been widely investigated previously [27–29]. The burner consists of a central fuel pipe with inner diameter (ID) 10.5 mm and outer diameter (OD) 12.6 mm, surrounded by an annular co-flow cylinder with an inner diameter of ID 97.7 mm and OD 101.5 mm, both made of brass. The conditioning of the co-flow gas stream was achieved with the use of stainless steel mesh, steel honey comb and glass beads. A steel honey comb was also employed in the fuel jet to ensure uniform velocity distribution at the jet exit. Industrial grade ethylene (>99.5% C_2H_4) at a flowrate of 0.184 standard litres per minute (SLM) was used for the fuel, while the air flow rate was 127.7 SLM.