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Radiative heat release from premixed oxy-syngas and oxy-methane flames

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ABSTRACT

The abundant supply of coal globally and its energy content per unit mass make the use of this fuel an attractive option for power generation. However, with increasingly strict environmental regulations imposed on greenhouse gas emission technologies the future use of coal in its current form is questionable. One solution to reduce pollutant emissions is oxy-combustion with coal-derived syngas, which can provide a method of using coal efficiently with carbon capture. This paper presents a study of the radiative heat release properties from oxy-syngas and oxy-methane flames. This is relevant since the radiative properties of prospective oxy-combustion systems are not fully known. In many oxy-fuel systems the flue gas stream is recycled and premixed with the fuel and oxidizer to reduce flame temperatures. It is estimated that the radiative heat transfer from these recirculated gases will significantly increase due to the increased emission of radiation from CO_2 and H_2O in the 1.2 μm to 5 μm wavelength range, which can impact future combustor design models. Motivated by this, this work aims to provide a study of the global and spectral radiation properties of oxy-syngas combustion and how relevant variables affect radiative emissions. Theses variables include the effect of CO_2 acting as a diluent, percentage of H_2 in the fuel, firing input, and the effects of equivalence ratio on the flame's radiative heat release and spectral radiation of CO_2 and H_2O. The current study reveals that the radiative heat release factor of syngas flames decreases at higher firing inputs. It was also observed that the radiative heat factor decreased at high hydrogen concentrations. An increase in heat release factor is also measured at higher recirculation ratios of CO_2.

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1. Introduction and background

It is projected that coal will remain the main energy source globally. This is partially due to the availability, the relatively high-energy content of the fuel per unit mass, and overall low cost [1–3]. In the United States many combustion devices rely on coal; however, increasingly strict governmental regulations on greenhouse gas (GHG) emissions in the energy sector have resulted in alternative technologies that have been developed to reduce emissions including CO_2. The combustion capture of CO_2 in power plants utilizing integrated coal gasification combined cycle (IGCC) with carbon capture and sequestration (CCS) are examples of some technologies [4]. Both IGCC and CCS contribute to the reduction of CO_2 combustion emissions at the sacrifice of overall net plant efficiency. The use of oxy-combustion has potential to offset the added efficiency penalties since the flame burns at a higher temperature, which from Carnot cycle mandates a higher overall efficiency. In fact, oxy-fuel combustion has been proposed as one of the most promising CCS technologies [4,5]. Current widespread use of oxy-combustion systems is difficult since material limitations impose an upper temperature limit that the system can operate, above approximately 2000 K. To reduce the temperature, the flue stream composed mainly of CO_2 and H_2O is recirculated. Both CO_2 and H_2O have a strong emission band in the infrared spectrum [6] making it necessary to identify the radiative properties of oxy-fuel combustion in order to enhance the predictive capabilities of combustion modeling and design.

Extensive studies have been conducted on many syngas combustion parameters including the investigation of laminar flame speeds at different syngas mixture compositions with CO_2 as the diluent, the effect of pressure and preheat dependence on flame speed, even the effect of water vapor on the laminar flame speed [7–11]. Syngas studies have also been conducted on turbulent flame speeds at gas turbine relevant conditions [12], on microturbine-like combustors for on-site decentralized power generation [13], ignition delay times with a range of varying parameters have been studied in detail [14], and the development of

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Nomenclature

A_n	area normal to surface (m^2)
A_s	surface area (m^2)
F	radiative heat release factor (–)
I	spectral intensity ($W/(m^2\ sr\ \mu m)$)
LHV_{fuel}	lower heating value (J/kg)
$\dot{m}_i$	mass flow rate of i (–)
$\dot{Q}_{in}$	fuel energy input (W)
$\dot{Q}_{rad}$	radiative heat release (W)
$\dot{q}_{in}$	fuel energy input (W/m^2)
$\dot{q}_{rad}$	radiative heat release (W/m^2)
r	distance (m)
RR_i	recirculation ratio of i (–)
T_{ad}	adiabatic flame temperature (K)
t	time (s)
Greek	
ϕ	equivalence ratio (–)
λ	wavelength (μm)
Ω	solid angle (m)

reaction mechanisms for syngas combustion for gas turbine operation has been presented previously [15]. Researchers have even investigated syngas combustion for use in diesel engines [16] and implemented novel injector technologies to achieve lower NO_x emissions [17]. However, all of the aforementioned studies and several others found in literature are relevant for syngas-air combustion. Fewer authors have focused on oxy-syngas combustion and have measured the fundamental flame characteristics of this mixture. One study by Kobayashi et al. [18] investigated highly CO_2 diluted oxy-syngas turbulent flame characteristics in a high-pressure environment. The major results of this study include a report on an increase in the total radiation intensity due to the high concentrations of CO_2. Wang et al. [19] investigated the laminar burning velocities and flame characteristics of oxy-syngas CO_2 diluted mixtures. The major results from this study include the behavior of laminar flame speed with a variation in the CO_2 content in the pre-mixture. It was also found that radiation heat loss of oxy-syngas flames is significantly higher than syngas-air and hydrocarbon-air flames due to the larger presence of CO_2 in the flame. This paper looks to further contribute to this body of knowledge.

In a power generating gas turbine combustion chamber a significant proportion of the total heat flux to the combustor walls is transmitted via radiation from the flame [20]. This is because, as mentioned previously, the two main byproducts produced for this type of system are CO_2 and H_2O. Both CO_2 and H_2O are strong emitters in the infrared region at 2 and 4.38 μm for CO_2 and 1.38 and 1.87 μm for H_2O with an overlap at 2.71 μm. In a gas turbine the banded spectra from H_2O and CO_2 is strongest at temperatures below 3000 K. At higher temperatures these two byproducts are depleted by dissociation leaving CO with the strongest banded spectra at 4.7 μm [21]. In previous studies it has been shown that the radiation emitted by oxy-flames is much higher than that of syngas air and hydrocarbon air flames. When compared to turbulent premixed methane air flames radiation is observed to be significantly stronger due to the high concentrations of CO_2 in the combustion process [18,19]. Motivated by this, the present work aims to achieve a higher level of understanding of oxy-syngas and oxy-methane flames by studying the global and spectral radiation characteristics. The impact of CO_2 recirculation rate, hydrogen volumetric percentage, firing input, and equivalence ratio on the radiative properties is documented and presented in this paper.

2. Experimental methodology

2.1. Experimental setup

There are two experimental setups used for the present work. For each setup the fuel and oxygen delivery systems are the same. The tubing assembly leading up to the burner is arranged such that the fuel and oxidants mix together before entering the injection ports at the burner manifold. Since oxy-fuel flames have a higher flame speed, to prevent damage caused by flame flashback a flame arrester device and an emergency shutoff valve were placed upstream of the burner for safety. For global radiation experiments a tubular 10 mm diameter burner is used. The burner was designed and manufactured in order to withstand the high temperatures of oxy-fuel combustion and can also accommodate different burner diameters. Global radiation measurements are taken from this tubular burner setup using a non-contact radiometer with a 150° view angle and a wavelength range from 0.2 to 50 μm. The radiometer has a sensitivity of 60 mV/(kW/m^2) and a time response of 2 s. The max allowed body temperature is 121 °C. The sensor is used in conjunction with a data acquisition system set at a 60 Hz sampling rate to record the output of the radiometer.

For the spectral radiation measurements a flat flame burner is used. The flat flame burner is 60 mm in diameter and consists of inlets for the fuel–oxidizer mixture, shrouding gas, and an inlet/outlet for liquid coolant. Two plano-convex lenses are used to focus the light from the flame and transmit to a monochromator. A chopper, or beam interrupter, is positioned in front of the monochromator slit to chop the focused light at the optimal frequency required by the light detector. A cooled PbSe detector is attached at the end of the monochromator with a wavelength detection range of 0–5 μm. Spectral radiation measurements are taken from 1.2 to 5.0 μm using the PbSe detector in conjunction with a radiometry system and data acquisition system.

Fig. 1 shows a schematic diagram of the experimental setup with the tubular burner in place. This includes research grade fuel, oxidizer, and diluent with purity levels of 99.995% delivered to the burners from pressurized tanks. Shutoff and needle valves are used to regulate the flow and achieve the desired compositions. A bank of digital flow meters is used to measure the flow rate of the fuel, oxidizer, and diluent. Before experimentation flow meters were calibrated using a laser based calibrator.

2.2. Methodology

The volumetric hydrogen concentration in syngas may vary significantly. Varying concentrations of hydrogen impacts the burning characteristics of the fuel and for higher hydrogen concentrations causes an increase on the flashback tendencies of the flame during the combustion process. For this experiment syngas was assumed to be composed of H_2 and CO with varying percentages of H_2. Oxygen (O_2) was premixed with diluent CO_2. The recirculation ratio of CO_2, representing the amount of diluent recirculated in an oxyfuel system, was used to express the amount of CO_2 diluent in the oxidizer stream, Eq. (1).

$$RR_{CO_2} = \frac{\dot{m}_{CO_2}}{\dot{m}_{O_2} + \dot{m}_{CO_2}} \tag{1}$$

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