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Control of radiative heat transfer in high-temperature environments via radiative trapping—Part I: Theoretical analysis applied to pressurized oxy-combustion

Fei Xia, Zhiwei Yang, Adewale Adeosun, Benjamin M. Kumfer, Richard L. Axelbaum *

Department of Energy, Environmental & Chemical Engineering, Washington University in St. Louis, St. Louis, MO 63130, USA

HIGHLIGHTS

- An approach is proposed to control wall heat flux in high temperature reacting flows.
- Effects of temperature and absorption coefficient profiles on local heat flux are studied.
- In optically dense media much radiation can be trapped with proper temperature gradient.
- Radiative trapping can occur in a pressurized system with properly designed burner.
- A method is developed to allow for a simple and convenient prediction of wall heat flux.

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ABSTRACT

Burning fuels with pure oxygen offers many benefits, including higher efficiency, a CO_2-rich flue gas that is suitable for carbon capture, and improved flame stability. However, the extremely high flame temperature that occurs during combustion in pure oxygen is typically assumed to lead to extreme levels of radiative heat flux that are beyond the tolerable limits of boiler materials. This paper presents a unique approach to control wall heat flux under extreme temperatures in particle-laden reacting flows. Fundamental studies were carried out to understand the radiative heat transfer behavior of such systems when temperature and absorption coefficient profiles are dictated by the diffusive–convective characteristics of the system, such as the case of a non-premixed combustion reactor. The results show that if the optical thickness of the particle-laden gas medium is sufficiently large, a considerable amount of emissive power coming from the high temperature sources can be trapped in the medium and the net heat flux on the wall can be managed. An average-temperature approximation (ATA) method is developed to conveniently approximate the wall heat flux when trapping of radiation occurs in an optically dense medium. The ATA method can be utilized to design systems that require manageable wall heat flux via radiative trapping under extremely high flame temperatures.

1. Introduction

Oxygen-enhanced combustion continues to receive considerable attention [1,2]. Applications can be found in industrial heating processes, such as glass melting, calcining, and metal heating and melting [1,3,4], in the chemical industry, such as producing ammonia, methanol, and ethanol from coal gasification [5], and in power industry, such as oxy-fuel combustion [6]. Benefits of burning fuels with pure oxygen include: (1) increased temperature and thermal efficiency; (2) a CO_2-rich flue gas suitable for carbon capture, utilization, and storage (CCUS); (3) elimination of thermal NOx emissions; and (4) improved flame stability [1,2,7,8]. However, the flame temperatures resulting from fuel and oxygen combustion, when not tempered by nitrogen that is normally available in air, can be quite high, with adiabatic flame temperatures approaching 3500 °C [9]. These flame temperatures, especially when in the presence of particles, e.g., char, ash or soot, will lead to extremely high emissive powers, because of the fourth-power dependence of emissive power on temperature. Without appropriate control, the resulting heat flux would be well above the acceptable levels for reactor wall materials. Radiation from particles may also result in fast preheating of particles and gas, affecting ignition and flame propagation in premixed systems [10,11]. Thus, the

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* Corresponding author. Tel.: +1 314 935 7560; fax: +1 314 935 5464.
E-mail address: axelbaum@wustl.edu (R.L. Axelbaum).

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thermal radiation in high temperature combustion systems involving particle-laden flows is of particular concern [2,3]. Only a few studies have been conducted on solid fuel combustion in pure oxygen [2,12]. These studies have indicated that combustion at high oxygen concentration is not applicable to conventional power plants because the high heat flux that results from the high flame temperature can damage the boiler tube materials. Thus, gas temperatures are typically tempered by dilution or other means, even though this constrains system performance. For example, in oxy-fuel combustion for CCUS [6,13,14] the flame temperature in the boiler is controlled by mixing the oxygen generated by the air separation unit (ASU) with a large amount of recycled flue gas. One of the primary challenges delaying full-scale implementation of this technology is the significant increase in the cost of electricity, which is due, in large part, to a substantial reduction in plant efficiency and increase in capital costs. The need to recycle a large quantity of flue gas (typically around 70%) is one reason for the efficiency reduction. Reducing the recycled flue gas (RFG) ratio (fraction of flue gas that is recycled) can improve the efficiency and reduce the cost of oxy-fuel technology [15], but it can also result in a significant increase in both the temperature of combustion and the rate of radiant heat transfer, as compared to combustion in air [16]. The resulting high heat flux to the boiler tubes may lead to tube surface temperatures that exceed safe operating limits. Several groups have investigated using lesser amounts of RFG to improve oxy-fuel technology. Becher et al. [15] reduced the RFG ratio to 50% for natural gas combustion before getting unacceptably high flame temperature. Gao et al. [17] studied the effects of reducing RFG ratio of a 1000 MWe ultra-supercritical coal fired utility power boiler using computational fluid dynamics (CFD). Extreme high wall heat flux was observed when RFG ratio was reduced below 55%.

If it were possible to avoid high wall heat flux under high flame temperature conditions, new technologies could be enabled. An example is the Staged, Pressurized Oxy-Combustion (SPOC) process [18], which involves combustion of coal in nearly pure oxygen in one stage of the process. Based on process simulation results, this process commands a plant efficiency that is as much as 6 percentage points higher than first-generation oxy-combustion plants [18]. One of the reasons for the high plant efficiency is the minimization of flue gas recycle and using fuel staging to control flue gas temperature [18,19].

Many studies of flame radiation have been conducted and they have typically involved solving radiative transfer equations, both analytically and numerically [20–23]. Nonetheless, the effects of simultaneously varying the profiles of temperature and absorption coefficient on radiative heat transfer have not been carefully examined, especially for the diffusive–convective flows that generally occur in non-premixed combustion systems. This paper examines this topic and presents a unique approach to reduce wall heat flux under extreme flame temperatures in particle-laden reacting flows.

2. Radiative trapping

To understand the potential impact that particles can have on radiative heat transfer in a combustion system, we first consider a case of pure gaseous system that is optically thin. When a small number of particles is introduced into this medium, the radiative heat transfer increases with the number of particles (strong sources of emission). When the number of particles is further increased, the medium may become optically *thick*, in which case the radiation emitted by the particles may be absorbed or scattered by other particles in the path of interest. The analysis to quantitatively predict heat transfer in such a system is more complicated, however, in most combustion applications, the medium is still optically thin and the increase in particle concentration generally results in an increase in heat transfer. If the particle concentration is further increased by, for example, pressurizing the medium, the medium can become very thick. For cases in which the optical thickness is very large the term *optically dense* can be used [24]. In this extreme condition, radiation travels only a relatively short distance before being scattered or absorbed by particles, and consequently, radiation from distant sources is significantly attenuated. Thus, in optically dense media, the heat transfer depends only on the *local* conditions in the immediate vicinity of the location of interest. In fact, if the optical thickness of the medium is greater than about 5, a diffusion-type expression can be written to express the heat transfer rate [24]. In this work, these characteristics of optically dense media are utilized to control the heat flux from a high-temperature combustion environment.

To illustrate the properties of an optically dense medium, consider a system with absorption, emission, and scattering. The change of radiative intensity I along path s is given by

$$\frac{dI}{ds} = k_a I_b - k_a I - \sigma_s I + \frac{\sigma_s}{4\pi}\int_{4\pi} I(\hat{s}_i)\Phi(\hat{s}_i,\hat{s})d\Omega_i, \tag{1}$$

where $I_b(T) = \sigma T^4/\pi$, which is the intensity of blackbody emission, σ_s is the scattering coefficient, k_a is the total absorption coefficient, Φ is the scattering phase function, and Ω is the solid angle. The first and fourth terms on the right hand side of Eq. (1) correspond to augmentation of the intensity due to local emission and scattering, respectively. The second and third terms correspond to attenuation of radiation intensity due to absorption and scattering respectively.

2.1. One-dimensional, uniform temperature and absorption coefficient

Because of the complex nature of radiative heat transfer processes, only a few simple problems have exact analytical solutions. One of them is the case with known temperature and absorption coefficient profiles in a one-dimensional plane-parallel medium when scattering is ignored [25]. To gain an initial perspective, a one-dimensional medium with a wall at the right side of the medium is used to study the effects of the absorption coefficient on radiative heat transfer, as shown in Fig. 1. Scattering is neglected to simplify the analysis. The medium is assumed to be 1 m thick, which is a relevant length scale for a combustion chamber. And the temperature of the wall is assumed to be low enough that emission from the wall can be neglected.

For the one-dimensional system where scattering is ignored, the solution to Eq. (1) is

$$I^{+}(\tau,\theta) = \frac{1}{\cos\theta}\int_0^{\tau} I_b(\tau')e^{(\tau'-\tau)/\cos\theta}d\tau', \quad 0<\theta<\frac{\pi}{2}, \tag{2}$$

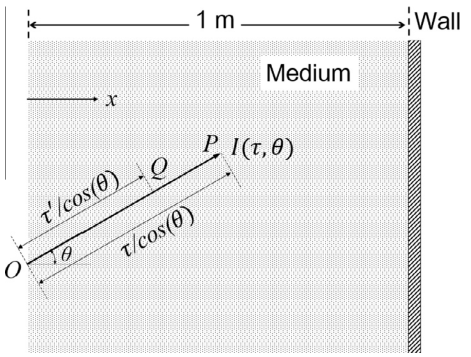

Fig. 1. A one-dimensional medium with a wall at the right side of the medium [25].