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

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Abstract

Burning fuels with pure oxygen offers many benefits, including higher efficiency, a CO₂-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.

Keywords: radiation, heat flux; radiative heat transfer; radiative trapping; high temperature.

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 CO₂-rich flue gas suitable for carbon capture, utilization, and storage (CCUS); (3) elimination of thermal NO_x 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 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

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

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.

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134 *2.1 One-dimensional, uniform temperature and absorption coefficient*

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

144

145 Figure 1.

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

$$148 \quad I^+(\tau, \theta) = \frac{1}{\cos \theta} \int_0^\tau I_b(\tau') e^{(\tau' - \tau)/\cos \theta} d\tau', \quad 0 < \theta < \frac{\pi}{2}, \quad (2)$$

149 where $I^+(\tau, \theta)$ is the radiation intensity in the positive x direction, $\tau = \int_0^x k_a dx$ is optical
150 thickness based on absorption coefficient measured from the wall ($\tau' = 0$) to the point
151 under consideration, P ($\tau' = \tau$), in the direction perpendicular to the wall; k_a is the
152 absorption coefficient in 1/m.

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In Eq (2), $I_b(\tau')d\tau'$ is the energy that is released by an infinitely thin layer of medium located at an arbitrary point Q , $I_b(\tau')e^{(\tau'-\tau)/\cos\theta}d\tau'$ is the portion of this amount of energy that arrives at point P , after being absorbed by the medium between Q and P (see Fig. 1). Therefore, integrating $I_b(\tau')e^{(\tau'-\tau)/\cos\theta}d\tau'$ over the path from points O to P gives the radiation intensity received by P due to emission from the entire medium between points O and P , considering the absorption effect of the medium itself. After integration of Eq. (2) over all angles, the heat flux at point P in the direction towards the wall can be given as

$$q^+(\tau) = 2\pi \int_0^\tau I_b(\tau') \int_0^{\frac{\pi}{2}} -e^{-\frac{\tau-\tau'}{\cos\theta}} \sin\theta d\theta d\tau', \quad (3)$$

As a first step in understanding the implications of this equation, consider the case of constant absorption coefficient and temperature for the one-dimensional medium. The temperature is assumed to be 2000 K for all cases, while five values for absorption coefficient are considered: 0.5, 0.8, 2.5, 5 and 7.5 1/m. These five values correspond to a nominal absorption coefficient for five operating conditions for coal combustion: 1) atmospheric pressure (1 bar) air-fired; 2) 1-bar oxy-fired; 3) 5-bar air-fired; 4) 10-bar air-fired; and 5) 15-bar air-fired coal combustion, respectively. The RFG ratio for the oxy-fired case is 70%. The reason that oxy-fired combustion has a higher absorption coefficient than air-fired combustion is because the partial pressures of CO_2 and H_2O in oxy-fired combustion are significantly higher than those of air-fired combustion, and triatomic gases such as CO_2 and H_2O have stronger absorption and radiation than symmetric diatomic gases such as N_2 . The strong correlation between absorption

coefficient and pressure is due to the fact that absorption coefficient in a medium is proportional to the particle number concentration in the medium.

When the temperature of the medium is constant, Eq. (2) becomes,

$$I^+(\tau, \theta) = \frac{1}{\cos \theta} \frac{\sigma T^4}{\pi} \int_0^\tau e^{(\tau' - \tau)/\cos \theta} d\tau' = \frac{\sigma T^4}{\pi} (1 - e^{-\tau/\cos \theta}), \quad 0 < \theta < \frac{\pi}{2}, \quad (4)$$

where σ is the Stefan-Boltzmann constant, T is the local temperature. This equation shows that when the optical thickness is large, I^+ approaches a saturation condition equal to the local black body emission.

Figure 2 shows the local heat flux towards the wall (positive x direction) for the 5 different absorption coefficients. As x increases from zero, the local heat flux increases, which is expected because heat is accumulated as more medium participates in emission. For the smaller absorption coefficients ($k_a \leq 2.5$ 1/m), the emission augmentation is relatively slow because the emissivity of the medium is small, and the emissive power continues to increase monotonically all the way to the wall, which is located at the right side of the medium. For the larger absorption coefficients ($k_a > 2.5$ 1/m), radiation augmentation by emission is fast but it soon reaches the saturation point where emissive power becomes constant where the constant value is equal to σT^4 (i.e., the medium behaves like a blackbody). In other words, when the absorption coefficient is large, a large amount of radiation power emitted by the left part of the medium cannot pass through the right part of the medium. This is due to the low transmissivity of the right

part of the medium. The higher the absorption coefficient, the sooner the local heat flux reaches the saturation point. Once the saturation point is reached, the local heat flux at the wall is only dependent on the local temperature of the medium. In this case, since the temperature of the medium is as high as 2000 K, the heat flux at the wall is still very high.

Figure 2.

2.2 Non-uniform temperature and absorption coefficient

Next, conditions are considered in which the temperature and absorption coefficient are not uniform. Figure 3 depicts a jet diffusion flame resulting from coal combustion, where the species, particles, and temperature distributions are dictated by the convective and diffusive transport (i.e., the system is transport limited). The high temperature zone for this jet flame is located in the central region of the furnace. The absorption coefficient is highest along the centerline because, as mentioned above, the absorption coefficient is proportional to particle number concentration, and the particle number concentration is the highest in the core of this jet flame. The temperature and absorption coefficient are smallest near the wall and increase radially as the flame is approached. Provided that the system is over-ventilated (i.e., there is excess oxygen) these characteristics are intrinsic in the jet flame structure, as is well-known from Burke-Schumann flame concepts.

Figure 3.

In order to observe the effects of non-uniform temperature and absorption coefficient on radiation behavior, four absorption profiles were considered, as shown in Fig. 4(a). The same linear temperature profile, which decreases from 2600 K to 700 K, was assumed in all cases, as shown in Fig 4(b). This high maximum temperature is relevant to the case of combustion of coal in enriched oxygen and was chosen to illustrate how radiative heat transfer can be controlled even for very high flame temperatures. The left boundary represents a high-temperature combustion zone, and the right boundary represents a cooled wall. By integrating the absorption coefficient profiles over the domain, the profiles optical thickness from the wall are obtained and plotted in Fig. 5. The optical thickness over the entire domain ranges from 0.2 to 6.4 for these cases. Thus, for the case of highest absorption coefficient, the domain is optically dense at $x = 0$ m. As the wall is approached, the optical thickness decreases until at some point transmission becomes important and the medium is no longer optically dense. Based on Beer's Law, when the optical thickness of a medium is equal to 2.3, the transmissivity of this medium is equal to 0.1 (i.e. $e^{-2.3} = 10\%$). This implies that only 10% of the radiative energy arriving from the left of this location can be transmitted towards the wall. For example, for the case with the largest absorption coefficient in Fig. 5, an optical thickness of 2.3 corresponds to the location of x equal to 0.4 m. This means that only 10% of the radiative power emitted towards the wall by the medium between 0 m and 0.4 m can pass through the medium between 0.4 m and 1 m. This also indicates that it is the radiative property of the medium between 0.4 m and 1 m that is the main contributor to the surface incident radiation at the wall, not the medium between 0 m and 0.4 m. For the less dense cases where the optical

thickness is below 2.3 throughout the domain, radiation from the entire domain is important to the radiation incident on the wall. This is the typical case for combustion.

Figure 4.

Figure 5.

To illustrate this further, Fig. 6 shows the distribution of the local heat flux in the positive x direction for all four cases. For the case with the lowest absorption coefficient, as x increases, the local heat flux increases monotonically due to continuous augmentation of radiation. Still, the increase in the local heat flux is slow because low absorption also means low emission. At the same time, since the total optical thickness of the medium is relatively small, the radiation emitted at every location in the medium is readily transmitted. Therefore, as noted above, all parts of the medium contribute to the radiative heat flux on the wall.

When the absorption coefficient is larger (e.g., $k_a(0) = 1.6 \text{ 1/m}$), both the emission and absorption by the medium become stronger. In the high temperature zone, the local heat flux is much larger compared to the case with the lowest absorption coefficient, but in the low temperature zone, the local heat flux begins to drop, because the absorption in this region is significant but emission is not because the temperature is low. Note that in this case, the heat flux at the wall is approximately doubled compared to the case of the

lowest absorption coefficient. When the absorption coefficient is much larger ($k_a(0) = 12.8 \text{ 1/m}$), the absorption in the low temperature zone becomes more extreme, and most of the radiation emitted from the high temperature zone is absorbed and cannot reach the wall. The radiative heat flux at the wall is therefore mainly attributed to radiation coming from the low temperature zone. This results in a drastically reduced heat flux at the wall, even lower than that of the case with the smallest absorption coefficient even though the peak heat flux in this case is 6 times greater than the peak heat flux in the case with the smallest absorption coefficient. The radiation energy emitted by the high temperature zone is effectively “trapped” and since only a fraction of this energy can be transmitted to the wall, the term *radiative trapping* is used here to describe this phenomenon.

Figure 6.

Figure 7 shows the surface incident radiation on the wall as a function of the total optical thickness of the medium for the linear temperature distribution shown in Fig. 4b and for linearly decreasing absorption coefficients (as in Fig. 4a). This figure demonstrates how the characteristics of radiative heat transfer in the medium change with optical thickness when there are gradients in temperature and absorption coefficient in the system. When the total optical thickness is smaller than 1, the heat transfer process is controlled by the radiation augmentation in the high temperature zone and thus, as the total optical thickness in this region increases, the emissivity of the medium increases, and the surface incident radiation on the wall increases. When the optical thickness is larger than 1,

absorption in the low temperature zone controls the process and thus the heat flux to the wall decreases as the optical thickness increases. Point A, B C in Fig. 7 correspond to a nominal optical thickness for three operating pressures for a coal combustion system: 1 bar, 5 bar and 10 bar, respectively. It can be seen that, the radiative wall heat flux in a typical 1-bar coal combustion system can be reduced by modestly elevating the operating pressure of the system.

Figure 7.

It can be concluded from the above discussions that radiative trapping can occur in a high temperature, particle-laden system when two conditions are met: the first is that the medium under consideration must have a sufficiently large optical thickness between the high temperature zone and the wall. The second condition requires that there must be a low temperature zone near the wall. High optical thickness can be achieved in pressurized systems because the particle number concentration increases with pressure for the same mass flow rate of particles and gas. As a point of reference, the medium absorption coefficient in a 15 bar pressurized coal combustion boiler can reach 7.5 1/m, corresponding to the highest absorption coefficient case in Fig. 2. The low temperature zone near the wall can be achieved by proper burner and boiler designs. For example, in a non-premixed jet flame configuration, like the case in Fig. 3, coal particles are fed through a centrally located burner and the oxidizer is fed between the fuel stream and the wall. When the momentum of the low temperature oxidizer is relatively high, a shroud of

cold gas will form along the wall, which leads to a low temperature region near the wall.

In addition, a water-cooled wall will also help to reduce the temperature in this region.

3. Average-temperature approximation (ATA) method

It has been established above that the wall heat flux that was obtained was dictated by the profiles of both the temperature and absorption coefficient. In this section, the dynamic relationship between temperature and absorption coefficient profiles on wall heat flux are studied for systems with large optical thickness. A method is described, namely the average-temperature approximation (ATA) method, to explain the radiation behavior of a diffusive-convective system with relatively large optical thickness.

Figure 8 shows idealized profiles of temperature and absorption coefficients where the high temperature zone is on the left and the low temperature wall is on the right. Two boundaries are identified by dashed lines: The boundary on the left corresponds to where the optical thickness from the wall is 2.3, which is where only 10% of the radiative energy arriving from the left of this location can be transmitted to the wall. In effect, radiative sources on the left of this location can be ignored in the calculation of wall heat flux. The boundary on the right corresponds to an optical thickness of 0.1, which means 90% of the radiative energy arriving from the left of this location can be transmitted to the wall. Since the temperature of the medium to the right side of this boundary is very low and the amount of emitters is low, the contribution of emissive power from this part can also be neglected. Therefore, the region between these two boundaries defines the zone that is the primary contributor to the wall heat flux. This region is called the

effective radiation zone, and is shown in Fig. 8 between the two boundaries marked with 10% and 90%. An average temperature location is also indicated in Fig. 8 which corresponds to an optical thickness of $(0.1+2.3)/2=1.2$. This average temperature location divides the effective radiation zone into two parts. The left part has relatively higher temperature, but the radiation power emitted by this part of medium needs to pass through a longer path length to reach wall. On the other hand, the right part of the medium has a relatively lower temperature, but the path length that the radiation emitted by this part needs to pass through is shorter. This indicates that one might be able to use the temperature and optical thickness values at the average temperature location to easily estimate the wall heat flux.

Figure 8.

According to Eq. (4), the total wall heat flux on the wall is

$$q_w = 2\pi \int_0^{\tau} I_b(\tau') \int_0^{\frac{\pi}{2}} -e^{-\frac{\tau_w - \tau'}{\cos\theta}} \sin\theta d\theta d\tau', \quad (5)$$

where τ_w is the total optical thickness of the entire domain of the medium. Making the substitution $\mu = \cos\theta$ and $\tau_w' = \tau_w - \tau'$ transforms Eq. (5) to

$$q_w = 2\pi \int_0^{\tau_w} I_b(\tau_w') \int_0^1 e^{-\tau_w'/\mu} d\mu d\tau_w', \quad (6)$$

where τ_w' is the optical thickness of the path between the local position and the wall.

The local effective wall heat flux ($q_{w,local}$, W/m²), which is the local contribution to wall heat flux per unit optical length of the medium, can be expressed as

$$q_{w,local}(\tau_w') = 2\pi I_b(\tau_w') \int_0^1 e^{-\tau_w'/\mu} d\mu = 2\sigma T^4 \int_0^1 e^{-\tau_w'/\mu} d\mu, \quad (7)$$

The function $\int e^{-\tau_w'/\mu} d\mu$ is a non-elementary integral, which means that the integral cannot be expressed in terms of elementary functions. Thus, in order to obtain a simpler expression, a new function $f_1(\tau_w') = 0.6397e^{-1.43\tau_w'}$, which was obtained from curve

fitting, is used to replace the function $f_2(\tau_w') = \int_0^1 e^{-\tau_w'/\mu} d\mu$. It should be noted that the

new function, f_1 , is a generally applicable function to one dimensional analysis of radiation equation. Since f_2 is an integral function independent of μ but dependent on τ_w' ,

a new function, f_1 can be defined that simplifies the non-elementary function as a function of τ_w' with no μ terms. So, by numerically evaluating the non-elementary

function, f_2 , in all directions, a curve fit function, f_1 , can be obtained that eliminates the need to evaluate the non-elementary integral function. Both functions are plotted in Fig. 9

and it is shown that when the optical thickness is greater than 0.3, the function f_1 agrees well with f_2 , but when the optical thickness is less 0.3, f_1 is slightly smaller than f_2 . Since the temperature and absorption coefficient levels corresponding to optical thickness less than 0.3 are both very low, this difference between f_1 and f_2 is not expected to cause significant errors in wall heat flux predictions.

Figure 9.

After replacing f_2 with f_1 , Eq. (7) becomes,

$$q_{w,local}(\tau_w') = 1.3874 \cdot \sigma \cdot T^4 \cdot e^{-1.43\tau_w'}, \quad (8)$$

In order to obtain an approximation of the wall heat flux, the average values for T and τ_w' are used in Eq. (8). Then the wall heat flux can be expressed as

$$q_w = \tau_{eff} \cdot 1.3874 \cdot \sigma \cdot \bar{T}^4 \cdot e^{-1.43\bar{\tau}_w'}, \quad (9)$$

where $\bar{T}$ is the temperature at the average temperature location, which is where optical thickness from the wall is 1.2, $\bar{\tau}_w'$ is the optical thickness between the average temperature location and the right boundary of the effective radiation zone, which is a constant 1.1 (i.e., 2.2/2), τ_{eff} is the optical thickness of the effective radiation zone, which is 2.3-0.1=2.2. Thus, the wall heat flux equation becomes

$$q_w = 3.5897 \times 10^{-8} \cdot \bar{T}^4, \quad (10)$$

The ATA method can be useful for any optically thick system, because as long as the two boundaries can be identified, the wall heat flux can be estimated from the average temperature in this zone. Although the method gives approximate prediction of radiative wall heat flux, the method is useful for design because it gives a solution that is much easier to obtain than solving the integro-differential radiative transfer equation. More importantly, the complex relationship between the radiative wall heat flux and the temperature and absorption coefficient profiles in the medium can be simply addressed by analyzing the average temperature of the effective radiation zone.

The application of the ATA method is illustrated in Fig. 10. Three different linear absorption coefficient profiles are considered for the same linear temperature profile. According to the definition of optical thickness, the area under each absorption coefficient profile indicates corresponding optical thickness. The three highlighted triangles in Fig. 10 have an equal area of 1.2, and the vertical edge of each triangle indicates the corresponding average temperature location for each absorption coefficient profile. It is clearly shown that when the absorption coefficient gradient increases, the average temperature location moves towards the wall, which results in a decrease in average temperature. The wall heat flux decreases accordingly based on Eq. (10). A comparison between the exact solution obtained by Eq. (6) and the ATA method for the three cases is shown in Table 1. The agreement is reasonably good.

Figure 10.

Table 1.

Figure 11 shows the ratio of the local effective wall heat flux to the total wall heat flux, defined by f_q . This parameter indicates the fraction of the radiative energy reaching the wall that was emitted locally from a medium of unit optical length. For this figure the temperature and absorption coefficient profiles are those of Case 1 in Table 1. f_q profiles calculated from the exact solution and the ATA method are both plotted. Fig. 11 demonstrates that Eq. (6) is a reasonable estimate of Eq. (5) in a convective-diffusive

system where temperature and absorption coefficient are both low near the wall. The difference in wall heat flux for these two curves is only 8%.

Figure 11.

In order to further evaluate the ATA method, more cases with various temperature and absorption coefficient profiles were tested. Figure 12 provides three temperature profiles and two absorption coefficient profiles. By combining these temperature and absorption coefficient profiles, six cases were created, as shown in Table 2. The wall heat fluxes calculated by the exact solution in Eq. (6) and the ATA method are also listed. The agreement between the exact solutions and the ATA method predictions is reasonably good for all the cases

Figure 12.

Table 2.

The ATA method was developed on a dimensionless basis (i.e. in terms of transmissivity or optical thickness), which means that it can be utilized as a design tool for systems that operate at very high temperature and require manageable wall heat flux via radiative trapping. For example, for a given target wall heat flux, the ATA method can provide the

average temperature that is required in the effective radiation zone (i.e. the region between optical thickness of 0.1 and 2.3). This provides important information to design burners to control the transport of reactants, particles and heat to achieve the target wall heat flux.

A new oxy-combustion approach with negligible recycle has been developed by this group to improve efficiency and cost over first-generation oxy-combustion technologies [18]. A set of unique radiant boilers has been designed based on radiative trapping to obtain manageable wall heat flux under extremely high flame temperature. The application of radiative trapping and the ATA method in the design of this new oxy-combustion technology will be presented in a subsequent paper.

Conclusions

In this paper, an approach was presented to control radiative wall heat flux in high-temperature, particle-laden flows. The effects of different temperature and absorption coefficient profiles on the local heat flux profiles were studied for a one-dimensional medium. The results show that when the medium is optically thin, the radiative wall heat flux depends on the temperature profile in the whole medium domain; when the medium is optically thick, the radiative wall heat flux is only dependent on local temperature in near-wall regions. In optically thick systems, it is possible to induce radiative trapping, which means that a large amount of the radiation power emitted by the high temperature zone can be trapped so that it does not reach the wall. For high-temperature, particle-

laden systems, radiative trapping can occur when two conditions are met: the first is that the medium under consideration must have a sufficiently large optical thickness between the high temperature zone and the wall. This can be achieved by pressurizing the system. The second condition requires that there must be a low temperature zone near the wall. This can be achieved by proper burner and boiler designs. A non-premixed jet flame configuration and a water-cooled wall can provide a low temperature zone near the wall. When radiative trapping occurs, the radiative heat flux to the wall is dictated by radiation at temperatures much lower than the peak temperature. With this method, manageable wall heat flux can be achieved under very high temperature conditions. Moreover, a new method called the average-temperature approximation (ATA) was developed to allow for a simple and convenient prediction of wall heat flux under these conditions.

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549 **Figure captions**

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

551 Figure 2. Local heat flux distributions towards the wall for a range of absorption
552 coefficients, assuming uniform temperature distribution.

553 Figure 3. Illustration of a jet diffusion flame resulting from coal combustion.

554 Figure 4. Absorption coefficient (a) and temperature profiles (b) assumed for the 1-D
555 analysis.

556 Figure 5. Optical thickness profiles.

557 Figure 6. Local heat flux towards the wall (located at $x = 1.0$) for the different absorption
558 coefficient profiles given in Fig. 4.

559 Figure 7. The surface incident radiation on the wall as a function of total optical thickness
560 of the medium. Points A, B and C correspond to a nominal optical thickness for
561 a 1-bar, 5-bar and 10-bar coal combustion system, respectively.

562 Figure 8. Temperature and absorption coefficient (k_a) profiles showing boundaries
563 (dashed lines) for low and high transmission.

564 Figure 9. Comparison between functions f_1 and f_2 .

565 Figure 10. Illustration of the method of average-temperature approximation.

566 Figure 11. f_q profile for Case 1 in Table 1.

567 Figure 12. Different temperature and absorption coefficient profiles for validation.

568

Table 1. Comparisons between exact solution and average temperature approximation method.

k_a (1/m)	Wall heat flux (kW/m ²)	
	Exact solution	ATA method
Case 1: $k_a=10(1-x)$	239	254
Case 2: $k_a=20(1-x)$	120	122
Case 3: $k_a=30(1-x)$	85	84

Table 2. Comparisons between exact solution and ATA method for different cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
T profile	A	B	C	A	A	A
k_a profile	1	1	1	2	2	2
Exact solution	80	594	230	40	369	107
ATA prediction	64	705	244	30	416	92

Figure1

Figure2

Figure3

Figure4

(a)

(b)

Figure5

Figure6

Figure7

Figure8

Figure9

Figure10

Figure11

Figure12