A theoretical analysis of the influence of turbulence on radiative emission in turbulent diffusion flames of methane

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Abstract. A theoretical analysis is reported to quantify the increase of radiative emission due to turbulence for methane diffusion flames burning in air. The instantaneous thermochemical state of the reactive mixture is described by a flamelet model and a detailed chemical mechanism. Mean values of the absorption coefficient, blackbody radiation intensity and radiative emission are evaluated for different turbulence levels by assuming the pdf shape of mixture fraction. The results show that turbulent fluctuations generally contribute to reduce the Planck mean absorption coefficient of the medium, in contrast with the blackbody radiation intensity, which is significantly increased by turbulence. If the turbulence level is relatively small, the influence of turbulence on the absorption coefficient is marginal. Otherwise, fluctuations of the absorption coefficient of the medium should be taken into account. The mean radiative emission is underestimated if turbulent fluctuations are fully ignored and overestimated if only temperature fluctuations are considered, while neglecting fluctuations of the absorption coefficient of the medium, the error being generally higher in the latter case. The effects of turbulence on radiative emission are stronger in the fuel-lean region and close to stoichiometric conditions than in the fuel-rich region.

1. Introduction
Thermal radiation plays an important role in many turbulent reactive flows, particularly in industrial combustion equipment, rocket nozzles and fires. The interaction between turbulence and radiation (TRI) may significantly increase radiative emission, and influence the radiative heat source and the temperature field [1-3]. The importance of TRI has been demonstrated, and the effect of various approximations to account for TRI in the numerical solution of the radiative transfer equation has been investigated using either prescribed pdf [4-6] or pdf transport methods [7-9] to simulate turbulent flames. Despite of this, most current numerical simulations of turbulent reactive flows neglect TRI or account only for temperature fluctuations in the calculation of the mean blackbody radiation intensity. It is relatively simple to account for temperature fluctuations only, but the accuracy of this simplification may be poor. Therefore, it is important to investigate the influence of TRI in radiative emission, and how accurate is to account only for temperature fluctuations. This is the subject of the present article, which reports a theoretical analysis for turbulent diffusion flames of methane.

A simple theoretical analysis reported in [10] quantifies the influence of turbulence on the radiative energy emitted by a hot medium. It shows that, if fluctuations of the emissivity are neglected, temperature fluctuations of ±20% increase emission by 24%, while temperature fluctuations of ±30% increase emission by more than 50%. A similar analysis is presented in [11], assuming a beta pdf shape for the temperature. It confirms the findings of Cox [10], and reveals that the effect of TRI on
radiative emission is relatively insensitive to the pdf shape, varying by less than 10% for temperature fluctuations of ±20%.

A recent theoretical analysis of the importance of TRI on radiative emission for a turbulent diffusion flame of methane burning in air was reported in [3]. Chemistry was described by a single one-step, infinitely fast, irreversible global reaction. Fluctuations of the temperature and species molar fractions were taken into account. The purpose of the present work is to extend the previous analysis [3] to estimate the importance of TRI on the radiative emission for turbulent diffusion flames of methane burning in air. The flame structure is described by a flamelet model using a detailed chemical mechanism. The influence of the turbulence level is investigated. Previous works were either focused on a particular flame/combustion system or based on relatively crude theoretical analysis. The main contribution of the present paper is that it reports results concerning the importance of TRI in turbulent diffusion flames that are broadly independent of the reactive system (burner geometry, Reynolds number, stoichiometry), albeit restricted to the flamelet regime.

2. Theory

The radiative transfer equation (RTE) may be written as follows for an emitting, absorbing and non-scattering medium [12]:

\[
\frac{d I_\nu}{ds} = -\kappa_\nu I_\nu + \kappa_\nu I_{b\nu}
\]  

(1)

In this equation \( I_\nu \) is the spectral radiation intensity, \( I_{b\nu} \) the spectral blackbody radiation intensity (Planck function), \( s \) the direction of propagation, \( \kappa_\nu \) the spectral absorption coefficient of the medium, and the subscripts \( \nu \) and \( b \) denote wavenumber and blackbody, respectively. Integration of this equation over the full spectrum yields

\[
\frac{d I}{ds} = -\kappa_G I + \kappa_P I_b
\]  

(2)

where the incident mean absorption coefficient, \( \kappa_G \), and the Planck mean absorption coefficient, \( \kappa_P \), are defined as

\[
\kappa_G = \int_0^\infty \kappa_\nu I_\nu d\nu / \int_0^\infty I_\nu d\nu
\]  

(3)

\[
\kappa_P = \int_0^\infty \kappa_\nu I_{b\nu} d\nu / \int_0^\infty I_{b\nu} d\nu
\]  

(4)

The time-averaged form of equation (2) is written as

\[
\frac{d \bar{I}}{ds} = -\kappa_G \bar{I} + \kappa_P \bar{I}_b
\]  

(5)

where the overbar denotes a time-averaged value.

The TRI is generally taken into account using the optically thin fluctuation approximation [13], which neglects the correlation between the radiation intensity and the absorption coefficient of the medium, i.e., \( \kappa_G \bar{I} = \bar{\kappa}_G \bar{T} \). Therefore, the main contribution to TRI comes from the radiative emission, i.e., from the second term on the right side of equation (5). In order to investigate the importance of TRI in this term, the following quantities are defined:

\[
R_k = \kappa_P (\bar{T}, \bar{x}_i) / \bar{\kappa}_P
\]  

(6)
In these equations, $\overline{T}$ stands for the mean temperature and $\overline{x_i}$ for the mean molar fraction of species $i$. Equations (6), (7) and (8) quantify the absorption coefficient self-correlation, the temperature self-correlation and the absorption coefficient–blackbody radiation intensity correlation. Equation (9) yields the overall influence of TRI on the radiative emission term of the RTE. All the ratios defined in equations (6) to (9) are equal to unity in the absence of turbulent fluctuations. The TRI becomes increasingly more important as they depart from unity.

It is worth to stress that the impact of TRI on the above correlations does not directly depend on the optical thickness of the medium. In fact, radiative emission only depends on local properties, and this allows the present analysis, which is independent of the turbulent reactive flow details, to be carried out. Several previous studies have investigated the influence of the optical thickness of the medium on TRI, which may affect the temperature and incident radiation fields, and the heat fluxes to the boundaries. However, the radiative emission does not depend on the optical thickness of the medium, being only directly influenced by the local mean and rms of mixture fraction, and local fraction of radiative heat loss.

Turbulent diffusion flames of methane burning in air are considered in the remainder of this work. The instantaneous thermochemical state of the reactive mixture is described by a flamelet model using the GRI 3.0 mechanism [14] and determined from the numerical solution of the flamelet equations [15]. These equations yield the temperature and the chemical composition of the reactive mixture as a function of mixture fraction and scalar dissipation rate, in the absence of turbulent fluctuations. Flame Master code [16] was used to solve the flamelet equations for scalar dissipation rates, $\chi$, ranging from near equilibrium to near flame quenching conditions.

The radiative source term was not included in the flamelet equations, since it yields unrealistic results in the case of steady flamelets, as discussed in [17]. Temperature flamelet profiles for non-adiabatic conditions were generated from the temperature flamelet adiabatic profiles by assuming that the local fraction of radiative heat loss, $X_R$, which is prescribed, is independent of mixture fraction, $z$ [18]. The fraction of radiative heat loss is defined as

$$X_R = \frac{(h_{ad} - h)}{h_{ad} - \sum_i y_i h_i^{\infty}}$$

(10)

where $h_{ad}$ and $h$ are the enthalpy of the mixture for adiabatic and non-adiabatic conditions, respectively, $h_i^{\infty}$ is the standard enthalpy of formation, $y$ the mass fraction of a species and subscript $i$ identifies the species under consideration. The enthalpy of the mixture for adiabatic conditions is a linear function of mixture fraction, being equal to the enthalpy of the air for $z = 0$ and to the enthalpy of the fuel for $z = 1$. Fixing the fraction of radiative heat loss, the enthalpy of the mixture for non-adiabatic conditions is determined from equation (10), and the non-adiabatic temperature is calculated from the enthalpy and the chemical composition using the caloric equation of state for values of mixture fraction ranging from 0 to 1. The mass fractions of the species are assumed to be independent of the fraction of radiative heat loss [19]. Further details on the generation of non-adiabatic temperature flamelet profiles are given in [5].

The Planck mean absorption coefficient of the absorbing species (CO$_2$, H$_2$O, CO and CH$_4$) is determined as a function of temperature by curve fits [20] to the narrow band model implemented in the RADCAL computer code [21]. The Planck mean absorption coefficient of any species in the
reactive mixture depends on the temperature, molar fraction, and pressure. Both the temperature and the molar fraction of the species are related to the mixture fraction and the scalar dissipation rate using the flamelet data.

The pdf shape of mixture fraction is assumed to be a clipped Gaussian. The pdf is defined from the mean value and the rms of mixture fraction. The mean value of any variable in equations (6)-(9) is evaluated from integration over the mixture fraction range (0 to 1) of the instantaneous value of that variable, expressed as a function of mixture fraction, weighted by the pdf of mixture fraction, i.e.,

$$\bar{\phi} = \int_0^1 \phi(z) \, pdf(z) \, dz \quad (11)$$

where $\phi$ stands for the quantity under consideration. As an example, in the case of the radiative emission, $\phi(z) = \kappa_P(T(z, \chi, X_R) x_i(z, \chi)) I_i(T(z, \chi, X_R))$. Fluctuations of the scalar dissipation rate and local fraction of radiative heat loss are not considered.

3. Results and Discussion

Standard calculations have been performed for diffusion flames of methane burning in air, at atmospheric pressure, for scalar dissipation rate $\chi = 1 \, s^{-1}$ and fraction of radiative heat loss $X_R = 10\%$. A previous investigation has shown that the influence of the turbulent scalar fluctuations on the radiative emission is approximately independent of the scalar dissipation rate and fraction of radiative heat loss [22].

Figure 1(a) shows the temperature and the H$_2$O and CO$_2$ molar fraction profiles as a function of mixture fraction, as determined by solving the flamelet equations for adiabatic conditions, and then modifying the temperature profile to account for the prescribed fraction of radiative heat loss. The vertical dashed line indicates the stoichiometric mixture fraction ($z_{st} = 0.055$), while the solid vertical line marks a change in the scale. The maximum temperature occurs for a slightly rich mixture, $z = 0.065$.

The Planck mean absorption coefficient of the mixture is displayed in figure 1(b). Three curves are shown, depending on whether radiation from CO and CH$_4$ is considered or not. The radiation from CO has a minor impact, but that from CH$_4$ plays an important role in the fuel-rich region of the flame. The Planck mean absorption coefficient of the species under consideration decreases with the increase of temperature (except for CO and CO$_2$ and temperatures lower than about 600 K), and it is directly proportional to the molar fraction of the species. It turns out that the influence of temperature is dominant for 0.015 < $z$ < 0.43, and therefore $\kappa_P$ decreases with the increase of temperature in this range. For very lean mixtures, namely for $z < 0.015$, the influence of the molar fraction of the absorbing species on $\kappa_P$ is greater than that of temperature, and so $\kappa_P$ decreases as $z$ tends to 0. Similarly, the decrease of the molar fraction of combustion products for very rich mixtures, namely for $z > 0.43$, explains the decrease of $\kappa_P$ as $z$ tends to unity if radiation from CH$_4$ is ignored. However, if radiation from CH$_4$ is taken into account, $\kappa_P$ continues to increase as $z$ approaches unity, since the high molar fraction of CH$_4$ compensates for the decrease of H$_2$O and CO$_2$ molar fractions.

The turbulence level in a diffusion jet flame, quantified here by $\text{rms}(z)/\overline{z}$, typically increases monotonically in radial direction from the centreline to the flame edge. Values of $\text{rms}(z)/\overline{z}$ up to 0.9 have been considered in the present work. In the fuel-rich region, fluctuations up to $\text{rms}(z)/\overline{z} = 0.3$ are commonly found, but higher fluctuations, even stronger than $\text{rms}(z)/\overline{z} = 0.9$, may occur at the flame edge due to intermittency (see, e.g., the experimental data for turbulent diffusion flames available in [23]). It can be mathematically demonstrated that $\text{rms}(z) \leq \overline{z} (1 - \overline{z})^{1/2}$. Accordingly, there is an upper limit of $\overline{z}$ for a given turbulence level, i.e., only values of $\overline{z}$ lower than that limit may occur for a prescribed turbulence level. That limit decreases with the increase of the turbulence level, e.g., the limit is equal to 0.917 for $\text{rms}(z)/\overline{z} = 0.3$ and 0.552 for $\text{rms}(z)/\overline{z} = 0.9$. 
Figure 2 shows the mean temperature as a function of mean mixture fraction and turbulence level. The maximum mean temperature occurs for values of mean mixture fraction in the range 0.06-0.07, which are slightly above the stoichiometric mixture fraction for methane. As the turbulence level increases, the mean temperature decreases, except for fuel-rich flames and values of mean mixture fraction greater than a certain threshold, which depends on the turbulence level. The reason for this behaviour lies on the shape of the temperature–mixture fraction profile (convex for lean and moderately rich mixtures, and concave elsewhere, as shown in figure 1a) and on the Gaussian pdf of mixture fraction.

The total mean radiative emission, given by the second term on the right side of equation (5), is shown in figure 3 as a function of $\overline{z}$ and $\text{rms}(z)/\overline{z}$. The mean radiative emission decreases with the increase of turbulence intensity for stoichiometric and for moderately fuel-lean or fuel-rich mixtures. In the case of very lean (typically $\overline{z} < 0.01$) or very rich mixtures, the mean radiative emission becomes much smaller than the maximum mean radiative emission. In those cases, even though the influence of turbulent fluctuations may be large, the contribution to total flame emission is quite small, and so it is not worth to consider TRI.

Figure 4(a) shows the Planck mean absorption coefficient evaluated at mean temperature and mean species molar fractions, $\kappa_p(\overline{T}, \overline{x}_i)$, as a function of $\overline{z}$ and $\text{rms}(z)/\overline{z}$. In the range where the influence of $T$ on $\kappa_p$ is dominant, i.e., for moderately fuel-lean or fuel-rich mixtures, turbulence yields a decrease of the mean temperature, and therefore an increase of $\kappa_p(\overline{T}, \overline{x}_i)$. However, for very rich mixtures, the influence of turbulence on $\kappa_p(\overline{T}, \overline{x}_i)$ is the opposite due to the role of CH$_4$ for such mixtures. Figure 4(b) shows the mean value of the Planck mean absorption coefficient, $\overline{\kappa}_p$, as a function of the mean mixture fraction and turbulence level. The profile of $\kappa_p(\overline{T}, x_i)$ displayed in figure 1(b) exhibits a local maximum at $z = 0.017$ and a local minimum at $z = 0.068$. Turbulence smooths out these extremes, in such a way that $\overline{\kappa}_p$ decreases in the vicinity of $z = 0.017$ and increases in the vicinity of $z = 0.068$. In the case of highly fuel-rich mixtures, turbulence causes a decrease of $\overline{\kappa}_p(\overline{T}, x_i)$.

Figure 5 shows the values of $R$, $R_b$, $R_{dlb}$ and $R_{miss}$ as a function of mixture fraction for different levels of turbulent fluctuations. Figure 5(a) shows that turbulent fluctuations generally contribute to reduce the mean value of the Planck mean absorption coefficient of the medium, yielding $\kappa_p(\overline{T}, \overline{x}_i) > \overline{\kappa}_p$, i.e., $R > 1$. This is a direct consequence of the dependence of $\kappa_p(\overline{T}, x_i)$ and $\overline{\kappa}_p$ on $\overline{z}$, which was discussed above. If the turbulence level is relatively small, such that $\text{rms}(z)/\overline{z} \leq 0.3$, then $R$ is rather close to unity, and the influence of turbulence on the absorption coefficient is marginal. Otherwise, turbulent fluctuations should be taken into account in the calculation of the absorption coefficient of the medium. This influence is more important on the fuel-lean side of the flame, where $R$ exhibits a local maximum, and becomes progressively smaller as $\overline{z}$ increases.

The blackbody radiation intensity significantly increases due to turbulence yielding $I_b(\overline{T}) < I_b$, i.e., $R_b < 1$, as shown in figure 5(b), in contrast with the Planck mean absorption coefficient. Therefore, the influence of turbulence on the mean radiative emission is generally lower than that predicted by accounting for temperature fluctuations, while neglecting the fluctuations of the absorption coefficient of the medium. The influence of turbulence on the blackbody radiation intensity is stronger than that on the Planck mean absorption coefficient, and is more important on the fuel-lean side of the flame, where $R_{lb}$ has a local minimum. Even though $R_{lb}$ is also small for highly fuel-rich mixtures, decreasing with the increase of mixture fraction, high turbulence levels do not generally occur for such mixtures.

The correlation $\overline{\kappa}_p I_b$ may be either positive or negative (see figure 6), yielding $R_{dlb} < 1$ or $> 1$, respectively (see figure 5c). This figure shows that $\overline{\kappa}_p I_b$ is very small for $\text{rms}(z)/\overline{z} = 0.1$, and negative for $\text{rms}(z)/\overline{z} \leq 0.5$, except for very lean mixtures, yielding $R_{dlb} > 1$ for fluctuations of this magnitude. The negative absorption coefficient–blackbody radiation intensity correlation is explained
Figure 1. Instantaneous temperature, $H_2O$ and $CO_2$ molar fractions (a) and Planck mean absorption coefficient (b) as a function of mixture fraction.

Figure 2. Mean temperature as a function of mean and rms of mixture fraction.

Figure 3. Mean radiative emission as a function of mean and rms of mixture fraction.

Figure 4. Planck mean absorption coefficient evaluated at mean temperature and mean species molar fractions (a) and mean value of the Planck mean absorption coefficient (b) as a function of mean and rms of mixture fraction.
Figure 5. Influence of turbulent scalar fluctuations on the Planck mean absorption coefficient (a), blackbody radiation intensity (b), absorption coefficient–blackbody radiation intensity correlation (c) and radiative emission (d) as a function of mean and rms of mixture fraction.

Figure 6. Influence of turbulent scalar fluctuations on the absorption coefficient–blackbody radiation intensity correlation as a function of mean and rms of mixture fraction.

Figure 7. Ratio of the mean radiative emission evaluated by considering only temperature fluctuations to the mean radiative emission calculated by fully taking TRI into account.

by the decrease of $\kappa_p$ with the increase of temperature for moderately lean or fuel-rich mixtures. However, for large fluctuations ($\text{rms}(z)/\overline{z} \geq 0.7$), the correlation $\overline{\kappa_p I_b}$ becomes positive for fuel-lean or moderately fuel-rich mixtures, due to the significant probability of occurrence of instantaneous values of mixture fraction close to zero, for which $\kappa_p$ and $T$ are positively correlated (see figure 1).
This probability is increasingly smaller as the mean mixture fraction increases, so that \( \overline{\kappa_p I_b} \) eventually becomes negative. The correlation \( \overline{\kappa_p I_b} \) is small for low turbulence levels, i.e., \( R_{\kappa I b} \) is close to unity for \( \text{rms}(z)/\overline{z} \leq 0.3 \), as also observed for the absorption coefficient self-correlation. In the case of higher turbulence levels, it is less important than the absorption coefficient self-correlation for fuel-lean or moderately fuel-rich mixtures, and more important for very rich mixtures, as the values of \( R_{\kappa I b} \) and \( R_t \) reveal. However, it is always less important than the temperature self-correlation.

Figure 5(d) reveals that \( R_{\text{emiss}} \), which represents the ratio of radiative emission calculated by ignoring TRI to radiative emission computed by fully accounting for TRI, is generally lower than one, i.e., turbulence yields an increase of radiative emission, in agreement with previous theoretical analysis and experimental evidence. This increase may exceed 100\% (\( R_{\text{emiss}} < 0.5 \)) for high turbulence levels, which are more likely to occur at the fuel-lean side of a diffusion flame. Although \( R_{\text{emiss}} \) is also small for very fuel-rich mixtures, these have a small contribution to radiative emission in real flames, because the mean radiative emission and the turbulence level are smaller for these mixtures.

Sometimes, in order to save computing time, TRI is partially taken into account by considering temperature fluctuations, but ignoring fluctuations of \( \kappa_p \). To investigate the accuracy of this approximation, figure 7 shows the ratio of the mean radiative emission evaluated by considering only temperature fluctuations to the mean radiative emission calculated by fully taking TRI into account:

\[
R_{\text{emiss}}/R_{I_b} = \frac{\kappa_p (\overline{T}, \overline{\tau}) I_b}{\kappa_p I_b}.
\]

Large errors arise when fluctuations of \( \kappa_p \) are neglected and the turbulence level is high. Moreover, if turbulent fluctuations are neglected altogether, the radiative emission is underestimated, i.e., \( R_{\text{emiss}} < 1 \). In contrast, if only the influence of turbulent fluctuations on temperature is considered, the radiative emission is overestimated, i.e., \( R_{\text{emiss}}/R_{I_b} > 1 \).

Figure 8 shows the ratio of the absolute error of the mean radiative emission in the case of fully neglecting TRI to the corresponding error in the case of accounting only for temperature fluctuations, i.e.,

\[
\left| \frac{\kappa_p (\overline{T}, \overline{\tau}) I_b - \kappa_p I_b}{\kappa_p (\overline{T}, \overline{\tau}) I_b} \right| R_{\text{emiss}} = R_{I_b} \left| R_{\text{emiss}} - 1 \right|/\left| R_{\text{emiss}} - R_{I_b} \right|.
\]

This ratio is higher than unity for \( \overline{z} < 0.025 \), i.e., for very lean mixtures, as well as for low turbulence levels and very high fuel-rich mixtures. Elsewhere, the ratio is lower than unity, which means that the error in the calculation of the mean radiative emission is smaller when TRI is fully neglected than when accounting only for temperature fluctuations.

The results displayed in figure 8 may seem surprising, since previous simulations of turbulent diffusion flames have shown that predictions of the fraction of radiative heat loss and radiative heat fluxes are more accurate when temperature fluctuations are taken into account than when TRI is fully neglected [8, 24, 25]. A similar trend is reported in [24] for the total radiative emission. The reason for the contradiction between the present results and those in [24] is unclear as far as the total radiative emission is concerned. However, the present results are compatible with previous ones regarding the fraction of radiative heat loss and radiative heat fluxes. In fact, let us first suppose that TRI is fully ignored. Then, the radiative emission is underestimated, since \( R_{\text{emiss}} < 1 \), while the radiative absorption is overestimated, since \( R_t > 1 \). Accordingly, the radiative heat loss will be underestimated. Now, suppose that only temperature fluctuations are taken into account. Then, both the radiative emission and the radiative absorption are overestimated, since \( \kappa_p (\overline{T}, \overline{\tau}) I_b = \kappa_p I_b R_{\text{emiss}}/R_{I_b} > \kappa_p I_b \), and \( R_t > 1 \). Therefore, the error in the solution of the time-averaged RTE may be lower, because both the emission and the absorption are overestimated, and errors in the evaluation of the mean emission and mean absorption compensate to some extent. In contrast, the errors add up if TRI is fully ignored.

Figure 9 shows the absolute error of the mean radiative emission when TRI is ignored, normalized by the maximum radiative emission without turbulent fluctuations, which occurs for a slightly fuel-rich mixture (\( z = 0.059 \)): 

\[
\left| \frac{\kappa_p (\overline{T}, \overline{\tau}) I_b - \kappa_p I_b}{\kappa_p I_b} \right|_{\text{max}} = \left| R_{\text{emiss}} \right| \left| \frac{\kappa_p I_b}{\kappa_p I_b} \right|_{\text{max}}.
\]

The larger this normalized error, the greater the importance of TRI. Although \( R_{\text{emiss}} \) is lowest for \( \overline{z} < 0.01 \), radiative emission is too small for such values of \( \overline{z} \), and therefore TRI does not have any relevant
influence in radiative transfer calculations for these very lean mixtures. TRI is increasingly more important as the radiative emission increases and $R_{\text{emiss}}$ departs from unity. In the fuel-lean region, radiative emission increases and $R_{\text{emiss}}$ approaches unity as $\bar{z}$ increases. Figure 9 shows that TRI is most important for $\bar{z}$ in the range $0.03-0.04$, and becomes progressively less significant as $\bar{z}$ further increases. Although TRI tends to increase for very rich mixtures, turbulence levels are typically small for those mixtures, and therefore TRI is not relevant in the very rich region of real flames.

A few words of caution are appropriate before concluding. First, the present analysis is restricted to turbulent diffusion flames in the flamelet regime. It is not applicable to flames where extinction and re-ignition phenomena are significant. Second, it does not account for radiation from soot. This is acceptable for methane flames, which produce very little soot. Third, it is assumed that the pdf of mixture fraction is a clipped Gaussian. Although this assumption is often used in the literature, the pdf shape may slightly influence the results. However, it is unlikely to alter qualitative results and conclusions. Finally, the analysis only addresses radiative emission. It does not consider radiative absorption, and therefore does not fully characterize TRI effects in radiative transfer calculations for turbulent reactive flows. It does show, however, where TRI effects might be important.

4. Conclusions

A theoretical analysis of the influence of turbulence on radiative emission in turbulent diffusion methane flames was presented. The influence of turbulence on radiative emission is only dependent on local quantities. Therefore, it is independent of the optical thickness of the medium. The flamelet equations were solved for a range of scalar dissipation rates, and mean values of fluctuating quantities were evaluated by prescribing the pdf shape of mixture fraction. The relevance of TRI was investigated as a function of mean and variance of mixture fraction. The following conclusions are useful to identify the flame regions where turbulence influences radiative emission, and how strong that influence is, regardless of details of the combustion system and operating conditions.

The results show that turbulent fluctuations generally contribute to reduce the Planck mean absorption coefficient of the medium, in contrast with the blackbody radiation intensity, which is significantly increased by turbulence. If the turbulence level is relatively small, the influence of turbulence on the absorption coefficient is marginal. Otherwise, fluctuations of the absorption coefficient of the medium, arising from fluctuations of temperature and molar fractions of the species, should be taken into account.

The influence of turbulence on the mean radiative emission is generally lower than that predicted
by accounting only for temperature fluctuations. Moreover, if turbulent fluctuations are neglected altogether, the mean radiative emission is underestimated, while if only the influence of turbulent fluctuations on temperature is considered, the mean radiative emission is overestimated. The error in the calculation of the mean radiative emission is smaller when TRI is fully neglected than when accounting only for temperature fluctuations, in contrast with results reported in the literature for the radiative heat loss and heat fluxes in turbulent flame simulations, which show improved predictions when the influence of turbulence on temperature is considered.

The influence of turbulence on radiative emission is more relevant in the fuel-lean region and close to stoichiometric conditions than in the fuel-rich region. In the former case, although the mean temperature is lower than the maximum one, the turbulence level is high due to flame intermittency, and the effects of turbulence on radiation are more important than in the latter case.

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