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Validation study of a turbulence radiation interaction model: Weak, intermediate and strong TRI in jet flames

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ABSTRACT

A TRI methodology developed previously for hydrogen jet flames is applied to carbon monoxide and methane jet flames. The paper demonstrates that the TRI methodology can accurately predict the spectral intensity distribution and heat flux distribution across a range of jet flames. A β probability density function (PDF) together with Reynolds averaging of the instantaneous properties along rays traversing the flames is used to prescribe the instantaneous incident intensity. Unlike most other studies in this area the model is used to predict the heat flux distribution as well as the spectral intensity. The underlying reason why hydrogen jet flames exhibit strong TRI compared to carbon monoxide and methane is also considered and shown to be a complex phenomena deserving of more research. The paper demonstrates that for the data available the heat flux distribution tends to be more sensitive to TRI than the spectral intensity distribution. Another interesting finding is that TRI can reduce as well as enhance the spectral intensity.

1. Introduction

It is well known that for some turbulent combusting systems the turbulent nature of the flow has the potential to significantly modify the radiation field. As discussed further below this is principally due to the nonlinear dependence of the Plank black body distribution on temperature and the fluctuating nature of the instantaneous temperature field. There has been significant research into TRI in turbulent hydrogen jet flames as TRI has a strong influence on the radiation field [1,2] and there has been much interest in hydrogen as an alternative green fuel to help combat the green house effect due to the increased CO_2 concentration in the atmosphere [3].

In this article a previously developed TRI methodology originally applied to hydrogen jet flames is applied to a number of jet flames with different fuels and source conditions. The fuels considered are hydrogen, methane and carbon monoxide. The performance of the model for different fuels is of interest as it is important that a TRI model can accurately predict the radiation field when TRI has a relatively weak influence (carbon monoxide) or moderate influence (methane) on the radiation field as well as when TRI is more significant (hydrogen) [1].

Over the last 3–4 decades there has been much interest in the computational modelling of turbulent flames [1–9]. The motivation for this work has been the development and evaluation of sub-models to predict different aspects of this generic flow, such as turbulence modelling [10], turbulence–chemistry interaction [11,12], depending on the fuel the modelling of soot may be of interest [13], radiation heat transfer [14,15] and turbulence–radiation interaction [1,2,16–19]. Commercial drivers for these investigations are diverse; reduction of pollution emissions such as NO_x prediction, flaring operations and consequence analysis as part of a safety case being some examples. Model sophistication has increased over the years as understanding has grown from experimental investigations, more efficient numerical techniques are developed and relatively cheap computational resources become available.

The first investigations of TRI were completed in the 1970s. Cox [17], based on a grey analysis of a turbulent homogeneous volume showed that the mean emission takes the form,

$$\overline{\varepsilon\sigma T^4}$$

where ε denotes the emissivity of the gas, σ is the Stefan–Boltzmann constant and T is the temperature. The over bar indicates the term is a Reynolds average. Due to the nonlinearity in temperature, depending on the magnitude of the fluctuations in temperature and participating species, radiation emission is significantly larger than the approximation to the mean emission based on the

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Nomenclature

$C_{p,i}$	specific heat capacity of species *i*
d	burner diameter
f	instantaneous mixture fraction
$\bar{f}$	mean mixture fraction
$\tilde{f}''^2$	variance of mixture fraction
I^-	incident intensity
$I_{b,\lambda}$	black body spectral intensity
I_λ	spectral intensity
K_a	absorption coefficient
K_λ	spectral absorption coefficient
L	length of a ray
N_R	number of control volumes in the radial direction
N_{ray}	number of rays
$N_{ray,seg}$	Number of ray segments in a ray
N_{sample}	number of samples
N_{pdf}	order of the polynomial used to fit the CPDF
P	probability density function
p_N	polynomial approximation to the CPDF
Q	approximation to the CPDF
q_{inc}	incident heat flux
r	radial coordinate
r, s	parameters in the β PDF
RD_I	measure of relative difference in intensity when including TRI or not
RE_I	relative enhancement of the integrated intensity by TRI
RD_q	relative enhancement of the heat flux by TRI
Re	Reynolds number
R_s	spatial correlation
R_t	temporal correlation
s	coordinate parameterising a pencil of radiation
T	temperature
T_{amb}	bulk air temperature
T_{adia}	adiabatic temperature
U_0	source velocity
U	axial velocity component
V	radial velocity component
z	axial coordinate
z	pseudo random number
z_L, z_U	parameters in the approximation to the CPDF

Greek symbols

Δh	enthalpy perturbation
Δs	space step in spatial correlation
Δt	time step in temporal correlation
$\Delta\Omega$	field of view of the receiver
ε	emissivity
λ	wavelength
μ_{eff}	effective dynamic viscosity
θ	angle of incidence
ρ	density
σ	Stefan Boltzmann constant
$\sigma_{\Delta h}$	turbulent Prandtl number for enthalpy perturbation
Ω	ray orientation

Subscript

adia	adiabatic property
inst	instantaneous property
RMS	root mean squared property
λ	spectral property

Superscript

$'$	fluctuating property

Over bar

$\bar{}$	Reynolds average
$\sim$	Favre average

mean temperature and emissivity evaluated from the mean participating species concentrations.

$$\bar{\varepsilon}\sigma\bar{T} \ll \overline{\varepsilon\sigma T^4}$$

This is a serious problem for most flame structure models where the mean flow fields are available for calculating the radiation source term in the conservation of energy transport equation or similar and when calculating the heat flux distributions external to the flame.

The first serious attempt to investigate TRI in jet flames, taking account of the spectral nature of flames was Faeth's group [1,2,18,19]. In [1,19], the flame structure is calculated using a parabolic Favre averaged flow model closed using a k–ε–g turbulence model. Turbulent combustion is modelled using a laminar flamelet library, combined with a clipped Gaussian PDF. In all of the simulations presented in [1,19] the primary interest is the external radiation fields rather than the internal structure of the flame, hence the influence of TRI on the flame structure is not considered and the radiation fields are calculated as a post-process to the flame structure simulation. Radiation heat loss is accounted for by adjusting the temperature flamelet to predict the measured fraction of heat radiated for each flame investigated.

Gore et al. [1] use a stochastic methodology to simulate instantaneous realisations of the spectral intensity distribution for pencils of radiation or rays with a horizontal orientation passing through the axis of the jet. The mean spectral intensity is calculated by averaging the instantaneous realisations. In Faeth's group's initial stochastic methodology the non-homogeneous path of a ray is separated into a number of segments that are assumed to be well approximated to be homogeneous and each ray segment is taken to be statistically independent. The instantaneous composition and temperature in each homogeneous ray segment is characterised by the instantaneous mixture fraction via a laminar flamelet library. The instantaneous realisation of the temperature and participating species are then input into Grosshandler's narrow band model, RADCAL [14,20] to produce the instantaneous spectral intensity distribution for a given ray orientation and receiver location. For each realisation the instantaneous mixture fraction is evaluated from a clipped Gaussian PDF using a pseudo random number generator. Faeth's group implementation of the clipped Gaussian is such that,

$$z = \frac{\tilde{f} - f_{inst}}{\tilde{f}''^2}$$

where z satisfies a Gaussian distribution with zero mean and unit standard deviation. Where the above gives physically unrealistic values of the instantaneous mixture fraction a limiter function is imposed to restrict mixture fraction to the unit interval. The clipped Gaussian PDF can reproduce the intermittency at the boundary of jets, Faeth et al. [18] but the main justification for its use is ease of implementation as they found other PDFs difficult to implement. Indeed the advantage of this approach is analytical rational approximations to the Gaussian distribution of the form,

$$f_{inst} = Q(z)$$