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Radiative Heat Transfer in Turbulent Combustion Systems

Theory and Applications

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Preface

The first author has been involved in research dealing with thermal radiation in combustion systems for the past 30 years or so and first became interested in Turbulence–Radiation interactions in the mid-1990s. When the second author joined the Penn State faculty in 1999, they both formed a team - with Haworth providing expertise in CFD, turbulence, and combustion and Modest in the field of thermal radiation. This cooperation has prospered over the years, resulting in numerous joint research grants from NSF, NASA, DoE, NETL, and AFOSR and continues fruitfully 6 years after the first author moved on to the University of California, Merced. This monograph reviews our own work, and the work of others, on the effects of radiation in turbulent reactant flows and how to deal with these effects theoretically and numerically in simulations.

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September 2015

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Nomenclature

a	Weight function for WSGG, SLW, and FSK methods
A	Area, m^2
A_{lf}	Pre-exponential factor for forward reaction l
b_{lf}	Temperature exponent for forward reaction l
C	Cross section, m^2
C^*	Nondimensional radiant power
c, c_0	Speed of light, (in vacuum), m/s
c_β	Molar concentration of species β , $\text{mol}_\beta/\text{m}^3$
c_P	Constant pressure specific heat, J/kg K
C_μ	$k - \varepsilon$ model constant
$C_\phi, C_{\phi\Delta}$	Mixing model constant for RANS/PDF (LES/PDF)
d	Spectral line spacing, cm^{-1}
Da	Damköhler number
E, E_b	Emissive power, blackbody emissive power, W/m^2
E_{lf}	Activation energy for forward reaction l , J/mol
f	k -distribution function, cm
f_v	Volume fraction
f_ϕ	Composition joint PDF
F_s	Absorption line blackbody distribution functions (ALBDF)
F_{rad}	Ratio of emitted radiation to sum of emitted radiation and convective wall heat transfer
$g_i, \mathbf{g}$	Body force component (vector), m/s^2
g	Cumulative k -distribution
G	Incident radiation, W/m^2
G	Filter function for LES, m^{-3}
h	Enthalpy, J/kg
$\Delta h_{f,\alpha}^0$	Species α formation enthalpy, J/kg
Δh_c	Lower heating value, J/kg
I	Radiative intensity, $\text{W/m}^2\text{sr}$
I_n^m	Intensity coefficient function, W/m^2
$\mathbf{J}^\alpha$	Molecular diffusive flux vector for species α , $\text{kg}_\alpha/\text{m}^2 \text{ s}$
$\mathbf{J}^h$	Molecular diffusive flux vector for enthalpy, $\text{J/m}^2 \text{ s}$

k	Turbulence kinetic energy, m^2/s^2
k	Absorption coefficient variable, cm^{-1}
k	Absorptive index
$k_{l,f}, k_{l,r}$	Forward (reverse) reaction rate for reaction l
l_t	Turbulence length scale, m
L	Geometric length, m
m	Complex index of refraction
$\dot{m}_F$	Fuel mass flow rate, kg/s
M_α	Species α chemical symbol
n	Refractive index
$\hat{\mathbf{n}}$	Unit normal vector
N	Number of gray gases, or order of P_N -approximation
N_S	Number of chemical species
p	Pressure, bar
P_n^m	Associated Legendre polynomial
Pr	Prandtl number
Pr_t	Apparent turbulence Prandtl number
$\mathbf{q}, \mathbf{q}$	Heat flux (vector), W/m^2
$\dot{Q}_{\text{rad}}$	Total radiative heat loss), W
Q	Random variable
R_c	Local cone radius, m
R_u	Universal gas constant, $= 8.3145 \text{ J}/\text{mol K}$
R	Random number
$\mathcal{R}$	TRI correlations
Re	Reynolds number
s, s'	Distance along path, m
$\hat{\mathbf{s}}$	Unit direction vector
S	Spectral line strength, or source function
$S_{\alpha, \text{chem}}$	Local mass chemical production rate for species α , $\text{kg}_\alpha/\text{m}^3 \text{ s}$
S_{rad}	Local radiation source term in energy equation, W/m^3
S_{abs}	Absorption contribution to local radiation source term, W/m^3
S_{emi}	Emission contribution to local radiation source term, W/m^3
t	Time, s
T	Temperature, K
T_A	Activation temperature, K
u	Scaling function for absorption coefficient
$u_i, \mathbf{u}$	Velocity component (vector), m/s
V	Volume, m^3
w	Quadrature weight
W_α	Species α molecular weight, $\text{kg}_\alpha/\text{mol}_\alpha$
$W_i, \mathbf{W}$	Wiener process component (vector), $\text{s}^{1/2}$
$x, \mathbf{x}$	Location (vector), m
$Y, \mathbf{Y}$	Mass fraction (vector)
Y_n^m	Spherical harmonic, sr

Greek Symbols

β	Extinction coefficient, cm^{-1}
β	Spectral line overlap parameter
Δ	LES filter scale, m
ϵ	Gas emissivity, or wall emittance
ε	Turbulence dissipation rate, m^2/s^3
η	Wavenumber, cm^{-1}
$\Delta\eta$	Narrow band wavenumber range, cm^{-1}
γ	Spectral line half-width, cm^{-1}
$\Gamma_{T\phi}$	Apparent turbulence diffusivity, $\text{kg}/\text{m s}^2$
λ	Wavelength, μm
κ	Absorption coefficient, cm^{-1}
μ_T	Apparent turbulence viscosity, $\text{kg}/\text{m s}^2$
ν', ν''	Stoichiometric coefficients
ϕ	Composition variable vector
Φ	Scattering phase function
Φ	Viscous dissipation rate, W/m^3
ω	Scattering albedo
ω, ω_Δ	Turbulence mixing frequency for RANS (LES), s^{-1}
$\dot{\omega}_\alpha$	Local molar chemical production rate for species α , $\text{kmol}_\alpha/\text{m}^3 \text{ s}$
Ω	Solid angle, sr
ρ	Density, kg/m^3
σ	Stefan–Boltzmann constant, $= 5.670 \times 10^{-8} \text{ W}/\text{m}^2 \text{ K}^4$
σ_s	Scattering coefficient, cm^{-1}
σ_ϕ	Apparent turbulence Schmidt number or Prandtl number
θ, ψ	Polar and azimuthal angles, rad
ψ	Sample space vector for random variables
τ	Gas transmissivity
τ	Optical depth
τ	Turbulence integral time scale, s
τ	Viscous stress tensor, Pa
χ_R	Radiant fraction

Subscripts

0	Reference state
abs	Absorption
b	Blackbody emission
chem	Chemical
emi	Emission
F, O, P	Fuel, oxidizer, product

g	Spectral, with cumulative k -distribution as spectral variable
i, j, k	Cartesian components
j	Narrow band
k	Spectral, with absorption coefficient as spectral variable
l	Reaction counter
max	Maximum
min	Minimum
mix	Mixture
rad	Radiative
w	Wall
α, β	Species counters
η, λ	Spectral

Overscores

$-$	Narrow-band average
$\sim$	Favre average, or spatial average narrow-band value
$\hat{\sim}$	Density-weighted filtered value

Operators

$\langle \rangle$	Mean value
$\langle \rangle_{\Delta}$	Spatially filtered value

Acronyms

ADF	Absorption distribution function
ALBDF	Absorption line blackbody distribution function
CFD	Computational fluid dynamics
CPU	Central processing unit
EGR	Exhaust gas recirculation
FSK	Full-spectrum k -distribution
FSCK	Full-spectrum correlated k -distribution
FSSK	Full-spectrum scaled k -distribution
DNS	Direct numerical simulation
DOM	Discrete ordinates method
FVM	Finite volume method
HACA	Hydrogen abstraction C_2H_2 addition
IC	Internal combustion
IDF	Inverse diffusion flame
IEM	Interaction by exchange with the mean
LBL	Line by line
LES	Large eddy simulation
NDF	Normal diffusion flame
OTFA	Optically thin fluctuation assumption
PAH	Polycyclic aromatic hydrocarbon
PDE	Partial differential equation
PDF	Probability density function
PM	Particulate matter
PMC	Photon Monte Carlo
PSDF	Particle size distribution function
RANS	Reynolds-averaged Navier-Stokes
RTE	Radiative transfer equation
SHM	Spherical harmonics method
SLW	Spectral-line weighted sum of gray gases
SNB	Statistical narrow band
SNBCK	Statistical narrow band correlated- k

TCI	Turbulence–chemistry interaction
TRI	Turbulence–radiation interaction
WSGG	Weighted sum of gray gases
WSR	Well-stirred reactor