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Influence of thermal radiation on soot production in Laminar axisymmetric diffusion flames

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ABSTRACT

The aim of this paper is to study the effect of radiative heat transfer on soot production in laminar axisymmetric diffusion flames. Twenty-four C_1–C_3 hydrocarbon–air flames, consisting of normal (NDF) and inverse (IDF) diffusion flames at both normal gravity (1 g) and microgravity (0 g), and covering a wide range of conditions affecting radiative heat transfer, were simulated. The numerical model is based on the Steady Laminar Flamelet (SLF) model, a semi-empirical two-equation acetylene/benzene based soot model and the Statistical Narrow Band Correlated K (SNBCK) model coupled to the Finite Volume Method (FVM) to compute thermal radiation. Predictions relative to velocity, temperature, soot volume fraction and radiative losses are on the whole in good agreement with the available experimental data. Model results show that, for all the flames considered, thermal radiation is a crucial process with a view to providing accurate predictions for temperatures and soot concentrations. It becomes increasingly significant from IDFs to NDFs and its influence is much greater as gravity is reduced. The radiative contribution of gas prevails in the weakly-sooting IDFs and in the methane and ethane NDFs, whereas soot radiation dominates in the other flames. However, both contributions are significant in all cases, with the exception of the 1 g IDFs investigated where soot radiation can be ignored. The optically-thin approximation (OTA) was also tested and found to be applicable as long as the optical thickness, based on flame radius and Planck mean absorption coefficient, is less than 0.05. The OTA is reasonable for the IDFs and for most of the 1 g NDFs, but it fails to predict the radiative heat transfer for the 0 g NDFs. The accuracy of radiative-property models was then assessed in the latter cases. Simulations show that the gray approximation can be applied to soot but not to combustion gases. Both the non-gray and gray soot versions of the Full Spectrum Correlated *k* (FSCK) model can be then substituted for the SNBCK with a reduction in CPU time by a factor of about 20 in the latter case.

1. Introduction

Axisymmetric laminar diffusion flames, including normal and inverse coflows as well as flames burning in still air, constitute relevant model flame systems for obtaining insights into soot production processes. In particular they offer tractable configurations for analysis and experiments and the results can be projected onto practical turbulent flames using approximate approaches such as the laminar flamelet concept. These configurations were naturally considered in order to validate soot models [1–10] and to investigate the influence of different parameters on soot

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Nomenclature

A_S	soot surface area [m^{-1}]
C_a	agglomeration rate constant [dimensionless]
D	inner burner diameter [m]
d_S	soot particle diameter [m]
E_r	relative error [dimensionless]
f_S	soot volume fraction [dimensionless]
$f_{S,max}$	maximum soot volume fraction [dimensionless]
F_v	radially integrated soot volume fraction [m^2]
$F_{v,max}$	peak of radially integrated soot volume fraction [m^2]
G_η	incident radiation per unit wavenumber [$W\ m^{-1}$]
h	enthalpy [$J\ kg^{-1}$]
h_f	stoichiometric flame height [m]
k	absorption coefficient variable [m^{-1}]
k_B	Boltzmann constant [$J\ kg^{-1}$]
$k_{S,n1}$, $k_{S,n1}$'	soot nucleation Arrhenius reaction rates [s^{-1}]
$k_{S,sg}$	soot surface growth Arrhenius reaction rate [$m\ s^{-1}$]
l_{sp}	laminar smoke point height [m]
L_f	luminous flame height [m]
N_A	Avogadro number [$part\ mol^{-1}$]
NC_{min}	number of carbon atoms in the incipient soot particle [dimensionless]
N_S	soot number density per unit mass of mixture [$part\ kg^{-1}$]
$\dot{Q}$	heat release rate (HRR) [W]
$\dot{Q}_R$	net radiative heat loss [W]
$\dot{Q}_{R,abs}$	absorbed radiant power [W]
$\dot{Q}_{R,em}$	emitted radiant power [W]
$\dot{Q}_{R,sp}$	net radiative heat loss at the smoke point [W]
R_f	flame radius [m]
r	radial coordinate [m]
T	temperature [K]
u_r	radial velocity [$m\ s^{-1}$]
u_z	axial velocity [$m\ s^{-1}$]
V_f	flame volume [m^3]
$\dot{V}_{fuel}$	volumetric flow rate of fuel [$m^3\ s^{-1}$]
$\dot{V}_{air}$	volumetric flow rate of air [$m^3\ s^{-1}$]
W_i	molecular weight of the species i [$kg\ mol^{-1}$]
x_i	mole fraction of species i [dimensionless]
X_R	enthalpy defect parameter [dimensionless]
Y_i	mass fraction of species i [dimensionless]
z	axial coordinate [m]
χ	scalar dissipation rate [s^{-1}]
χ_R	radiant fraction [dimensionless]
χ_{abs}	fraction of the power emitted by the flame that is re-absorbed [dimensionless]
φ_i	collision efficiency factor of species i [dimensionless]
η	wavenumber [cm^{-1}]
κ	absorption coefficient [m^{-1}]
κ_η	spectral absorption coefficient [m^{-1}]
κ_P	Planck-mean absorption coefficient [m^{-1}]
ρ	density [$kg\ m^{-3}$]
τ_{R_f}	optical thickness [dimensionless]
$\dot{\omega}_n$	reaction rate for soot nucleation [$mol\ m^{-3}\ s^{-1}$]
$\dot{\omega}_{sg}$	reaction rate for soot surface growth [$mol\ m^{-3}\ s^{-1}$]
$\dot{\omega}_{N_S}$	reaction rate for soot number density [$part\ m^{-3}\ s^{-1}$]
$\dot{\omega}_{O_2}$	reaction rate for soot oxidation by O_2 [$kg\ m^{-3}\ s^{-1}$]
$\dot{\omega}_{OH}$	reaction rate for soot oxidation by OH [$kg\ m^{-3}\ s^{-1}$]
$\dot{\omega}_O$	reaction rate for soot oxidation by O [$kg\ m^{-3}\ s^{-1}$]
$\dot{\omega}_{Y_S}$	source term for soot mass fraction [$kg\ m^{-3}\ s^{-1}$]
ξ	mixture fraction [dimensionless]

Subscript

∞	ambient condition
ad	adiabatic
ag	agglomeration
mix	mixing
n	nucleation
P	Planck
R	radiation
ref	reference
sg	surface growth
sp	smoke point
S	soot
η	at a given wavenumber, or per unit wavenumber

production [11–25]. Numerical and experimental studies have shown that soot encounters radically different environments along its path in normal diffusion flames (NDFs) and inverse diffusion flames (IDFs) [11,26]. In NDFs soot forms in the annular region on the fuel-rich side of the flame sheet before being oxidized as it passes through the high-temperature oxidation zone [11]. On the other hand, in IDFs the soot particles form in a fuel-rich region at the top of the flame and escape from the flame without being oxidized [11]. IDFs were found to be characterized by combustion processes similar to those observed in underventilated fires, in which combustion is fuel rich and large amounts of CO, soot and other carbon containing species are produced and non-oxidized [26]. Most of the previously-referenced works considered buoyant laminar flames. However, the effect of buoyancy in turbulent flames is known to be locally negligible, which means the investigation of soot production in microgravity flames is of particular interest. In addition, in microgravity (0g) the elimination of buoyancy-induced flows allows the exploration of longer residence times, which lead to the enhancement of both soot growth and oxidation processes. The sooting behavior of microgravity