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Effect of air flow distribution on soot formation and radiative heat transfer in a model liquid fuel spray combustor firing kerosene

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ABSTRACT

In the present paper, a numerical model has been developed for spray combustion in a model gas turbine combustor admitting air as co-axial primary and secondary streams. The model incorporates soot formation and radiative heat transfer and has been validated with experiments conducted on a combustor of identical geometry. The paper investigates the effect of air flow distribution, between primary and secondary streams, on flame structure, soot formation and radiative heat transfer in the combustor firing kerosene as fuel. Turbulence is modeled using realizable k–ε model and radiation is modeled using discrete ordinate method with weighted sum of gray gases model. The combustion is modeled using equilibrium presumed probability density model. The results show that an increase in the proportion of primary air flow, from 30% to 50% of the total air, results in a more compact flame with lower soot production and a better pattern factor at the combustor exit. However, the corresponding reduction in secondary air flow rate increases the combustor wall temperature. The decrease in soot in flame at higher primary air fraction reduces the incident radiative heat flux on the injector body while, the injector surface temperature remains almost unaffected due to increased convective heat transfer rate from the gas.

1. Introduction

Numerical modeling of liquid fuel spray combustion is widely used as a predictive tool for the performance analysis of gas turbine combustors and liquid fuel furnaces. Spray combustion is a complex phenomenon consisting of various physical and chemical processes, like atomization of liquid jet and movement of droplets in a gaseous field, vaporization of droplets, turbulent transport and mixing, chemical reaction, thermal radiation and pollutant formation. The prediction of the entire process depends on the accuracy of the component models, which have been employed in the whole scheme. Some of the models are quite well established in the literature. For example, the fluid flow is commonly solved with RANS based models for their computational economy, though it has been found that LES [1] and DNS [2] based models can provide valuable insight of flow in the combustors. However, the latter models are very expensive particularly in three dimensional geometries. In the RANS based models, the turbulence quantities are usually solved using two equation models with eddy viscosity concept. Different forms of the k–ε models, like standard, RNG and realizable k–ε models are commonly employed in the literature [3–5]. Hsiao and Mongia [6] and Joung and Huh [7] used standard and realizable k–ε models to predict swirling flows in confined geometries and found reasonable prediction of flow parameters. Karim et al. [8] showed that standard k–ε model is over-diffusive in highly swirling flows in comparison with realizable k–ε model. In spray combustion calculation, a suitable model is also required to predict the initial spray characteristics following breakup of the liquid fuel jet. Thereafter, the interactions between the continuous and dispersed phases are often captured using the discrete droplet model (DDM) in the Eulerian–Lagrangian formulation [9–11]. In the discrete droplet model, the liquid spray is considered to consist of a finite number of droplet classes, whose trajectories in the gas phase are tracked using suitable governing equations. The mass, momentum and energy exchanges between the two phases are computed as source terms and accounted in the gas phase governing equations.

Soot formation in combustion is important in liquid fuel spray flames. Soot particles present in the flames result in a highly luminous radiation and thereby influence the heat transfer phenomenon from the flame. As a consequence, soot in flame augments the wall and burner heating considerably. It is therefore important to precisely model the soot formation process in spray flames and study its influence on radiative heat transfer from the flame. Kerosene (or jet fuel) is widely used as fuel in aero gas turbine

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Nomenclature

A	surface area, m^2
a_k	weighting factor
C_d	coefficient of discharge
C_{drag}	drag coefficient
C_f	vapor concentration in the continuous phase
C_{f_s}	vapor concentration at the droplet surface
C_L	ligament constant
C_p	specific heat, J/kg K
C_μ	a variable, function of mean strain rate
D	diameter of the combustor, m
d	diameter, m
d_L	ligament diameter, m
d_o	mean droplet diameter, m
$d_{p_{soot}}$	mean diameter of soot particle, m
ΔH_v	latent heat of vaporization, J/kg
h	convective heat transfer coefficient
h_D	mass transfer coefficient
I	radiation intensity, W/m^2 sr
k	turbulent kinetic energy, m^2/s^2
k_w	wave number
M	soot mass concentration, kg/m^3
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
N	particle number density, $1/m^3$
N_A	Avogadro number 6.022045e+26 kmol/l
Oh	Ohnesorge number
P	pressure, N/m^2
$P(\xi)$	probability density function
ΔP	pressure differential, N/m^2
p	total partial pressure, N/m^2
Q	ratio between gas and liquid density
q	radiative heat flux, W/m^2
R	universal gas constant
Re	Reynolds number
S	source
T	temperature, K
t	liquid sheet thickness, m
U	resultant (total) velocity of fuel jet, m/s
u	velocity, m/s
We	Weber number
w_i	quadrature weight
X	mole fraction
z	path length

Greek symbols

Γ	diffusivity
ρ	density
ϕ	scalar variable
μ	dynamic viscosity
μ_t	dynamic eddy viscosity
σ	Prandtl/Schmidt number
σ_s	surface tension of the liquid
ε	rate of dissipation of turbulent K.E.
θ	spray cone half angle
ρ	density
ω_r	growth rate of sinuous wave
ν	kinematic viscosity
ξ	mixture fraction
κ	absorption coefficient
κ_k	gray gas absorption coefficient

Subscript

b	black body
$crit$	critical
d	droplet
eff	effective
f	liquid
f	fuel
g	gas
i	ith coordinate direction
inj	injection
j	jth coordinate direction
k	kth coordinate direction
l	liquid
or	orifice
p	particle
rad	radiation
ϕ	scalar variable

combustors, where a high overall air–fuel ratio is maintained in order to keep the exit gas temperature within the allowable limit for the turbine blade material. The total air is distributed in different zones, so that a stable flame can be established on the burner. The air flow distribution influences the stoichiometry in the flame zone and affects the soot formation there. The cooling of the combustor wall and the temperature uniformity of the exit gas also depend on the air flow distribution in the combustor.

Soot formation in hydrocarbon combustion is a very complex process, which initiates with the formation of precursor molecules and completes through the growth of poly aromatic hydrocarbons [12,13]. Detailed formulations using elementary reactions for the gas phase and soot [14,15] are often found to be unfeasible in the real combustor configurations (e.g. in gas turbine combustor) because of their complexities. Therefore, different semi-empirical models had been proposed by Kennedy et al. [16], Leung et al. [17], Moss et al. [18], and Brookes and Moss [19] for the prediction of soot in hydrocarbon flames, like methane or ethylene. The models compute the soot nucleation and surface growth rates based on the concentration of precursor species, which is commonly considered as acetylene in these works. Oxidation models, proposed by Lee et al. [20], Nagle and Strickland-Constable [21], and Fennimore and Jones [22] were also adopted in the soot models. Wen et al. [23] modeled soot formation in a turbulent jet diffusion flame of kerosene vapor and air. They considered two different nucleation models of soot, viz. (i) acetylene nucleation model considering acetylene as the precursor and (ii) PAH nucleation mode taking two and three ring aromatics as precursor. However, surface growth is modeled using acetylene concentration and the number of active sites on the soot particles. It was found that the PAH nucleation model contributes significant improvement in the model prediction in comparison to the experimental data. On the other hand, Moss and Aksit [24] applied the soot model, proposed by Brookes and Moss (for a methane non-premixed flame), in the laminar non-premixed flame of a surrogate kerosene fuel. They found that adjustments in the model parameters, from the values in methane–air flame, are necessary to satisfactorily reproduce the experimental measurements of soot under the change of fuel. Accordingly, they proposed two alternate models. In one of them, acetylene is considered as the precursor in nucleation and surface growth and the model parameters are changed to match the experimental results. In the other case, acetylene is considered as the precursor of soot nucleation only, while the precursor for surface growth is taken as acetylene and benzene. New model constants are evaluated for this case as well. Both the models are found to predict the soot concentration nearly equally, though the latter