Droplet size distribution effects in an edge flame with a fuel spray

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ABSTRACT

The impact of the initial droplet size distribution on the behavior of an edge flame formed in the mixing layer of laminar co-flowing streams of oxidant and a spray of liquid fuel initially separated by a splitter plate is investigated for the first time. The spray is modeled using the sectional approach, and three quite different size distributions are considered having a common Sauter Mean Diameter (SMD). The nonlinear governing equations are formulated within the thermal-diffusional framework, and solved using finite differences. A parametric study discloses that despite having the same SMD the actual initial droplet size distribution influences flame location, maximum reaction rate and temperature. But more critically it can be destabilizing and lead to flame oscillations, depending on the actual initial size distribution used.

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1. Introduction

The edge flame formed in the diffusive mixing layer downstream of a splitter plate initially separating laminar co-flowing streams of oxidant and fuel is a useful configuration both at the theoretical and practical levels. In the context of *gaseous flames* (for which liquid fuel is absent) the dynamics of this sort of edge flame have been examined [1–3] in some detail. Conditions for steady states as well as the possible onset of oscillatory behavior of the edge flame were sought in an attempt to understand independent experimental evidence of such flame oscillations. The practical ramification of understanding such a phenomenon is the strong linkage between the undesirable occurrence of flame oscillations and flame extinction.

When heptane was supplied as a spray of liquid droplets in a laminar co-flowing configuration, for which a downstream diffusive mixing layer also exists, it was found experimentally [4] that noticeable flame oscillations were exhibited, in marked contrast to their gaseous equivalents which were completely steady under the same operating conditions. The authors [4] suggested various possible physical mechanisms that might be responsible for this behavior, including the coupling between heat transfer, evaporation, two-phase flow dynamics and buoyancy forces, and some opening supporting evidence was proposed. In a subsequent, more comprehensive work [5] the same flame configuration was revisited experimentally and through a well-controlled parametric investigation it was established that a small range of flame oscillation frequencies exists (1–5 Hz) and that the phenomenon was intricately linked with heat absorption by droplets for evaporation.

A simplified one-dimensional model was proposed which, despite its geometric disparity with the actual experimentally observed spray flame, was able to predict (via a linear stability analysis) an oscillation frequency in the measured range.

The dynamics of a two-dimensional edge flame with a fuel spray was investigated numerically in [6,7]. The results reinforced the proposed spray-induced heat-loss role in inducing flame oscillations. These spray flame oscillations were found to occur even when equivalent gaseous flames were completely stable. However, if operating conditions were such that an equivalent gaseous flame also oscillated the amplitudes of oscillation of the spray flames were found to be greater than those of the gas flame. A drawback of the analysis was its reliance on a mono-sectional integral description of the spray [8].

As realistic sprays are polydisperse it seems reasonable to question how the *actual* initial droplet size distribution impacts on the nature of edge flames and their dynamics. Polydisperse spray diffusion flame combustion has been considered in a number of contexts. For example, Tambour and Katoshevski [9] theoretically studied spray diffusion flames in a unidirectional shear-layer flow. They considered a flame sheet model and found that (a) sprays that contain mainly large droplets (of the order of 25–30 μm) produce smaller amounts of vapor and a cooler flame located closer to the spray stream, and (b) sprays of different initial polydispersity but having the same Sauter Mean Diameter may form flames of different shapes.

In [10] predictions of a detailed numerical model for counterflow heptane polydisperse spray diffusion flames were compared with experimental measurements and excellent agreement was achieved. Gutheil [11] numerically investigated the structure and extinction of laminar ethanol/air spray flames. Mono- and bi-disperse sprays were considered in the counterflow configu-

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Nomenclature

B	pre-exponential constant
B_j	sectional evaporation coefficient
c_p	specific heat
c_l	liquid phase specific heat
C_j	sectional evaporation coefficient
d	diameter
D	Damkoḧler number
D_T	thermal diffusivity
E	activation energy
H	Heaviside function
Le	Lewis number
N_s	total number of size sections into which droplet size distribution is divided
R	gas constant
S	spray-related source term
t	time
T	temperature
T_0, T_a	upstream and adiabatic temperatures, respectively
U_0	constant velocity of flow
x, y	axial and transverse Cartesian coordinates, respectively
x_w	axial location of maximum reaction rate
Y_F	fuel vapor mass fraction normalized by total upstream fuel mass fraction (vapor+liquid)
Y_O	oxidant mass fraction normalized by upstream value
Ze	Zeldovitz number (Eq. (8b))

Greek letters

γ	heat release parameter ($=(T_a - T_0)/T_0$)
δ	total initial liquid fuel load
δ_j	initial liquid load in size section j
Δ	evaporation frequency
$\hat{\Delta}_j$	sectional evaporation Damkoḧler number
η	ratio of latent heat of evaporation to heat of reaction
θ	non-dimensional temperature ($=(T - T_0)/(T_a - T_0)$)
λ	thermal conductivity
ν	stoichiometric coefficient
ρ	density
ϕ	initial mixture strength
$\hat{\Psi}_j$	sectional evaporation Damkoḧler number
ω	chemical source term
$\Omega_{j,i}$	spray parameters defined in Eqs. (11a) and (11b)

Subscripts

a	adiabatic
B	boiling value
d	relating to liquid fuel droplets
F	relating to fuel vapor
j	relating to droplets size section
l	relating to the liquid phase
o	relating to conditions far upstream
O	relating to oxidant

Fig. 1. Configuration for study of an edge flame with a polydisperse fuel spray: the broken line delineates the mixing layer.

appears in [12] where it was concluded that the Sauter Mean Diameter is a good approximation for the bi-disperse spray for determining the flame structure at low strain rate. In [13,14] extinction of counterflow gas and polydisperse fuel spray diffusion flames employing a polydisperse water spray in the opposing stream were studied. In both cases the difficulty in use of a Sauter Mean Diameter to characterize the sprays was demonstrated.

Mikami et al. [15] carried out an experimental investigation of polydisperse spray counterflow diffusion flames. Although they do not relate to the SMD, they did find that different burning behaviors were observed for different droplet size distributions. These differences were explained in terms of a Stokes number and the ratio of characteristic vaporization to flow times.

It is clear from this sample of references on spray diffusion flames that spray polydispersity plays an important role in determining flame behavior and characteristics. The current work addresses this issue for the aforementioned two-dimensional edge flame.

2. Governing equations

The configuration under consideration is the splitter plate, see Fig. 1. The oxidant is supplied from below the horizontal plate (which is located at $y = 0$) whereas the fuel is supplied from above it. The liquid fuel spray is introduced far upstream. However, negligible vaporization occurs until the droplets experience the fuel boiling temperature at which location appreciable vaporization commences. In the current model the droplets are assumed to be in dynamical equilibrium with their host environment *on the average* so that slip effects are negligible. This assumption is relevant for sufficiently small droplets and/or droplets located in the far-field region relative to the spray's source, for which dynamic adjustment to equilibrium with their surroundings has occurred.

The homogeneous chemical reaction, which takes place between the fuel vapor and the oxidant, is modeled by a global one-step chemical reaction *Fuel* + ν*Oxidant* → *Products* where ν is the stoichiometric coefficient. The reaction rate is assumed to be of Arrhenius type. The governing equations consist of the usual conservation laws of mass and energy balance, the balance equations for the gaseous species participating in the chemical reaction and a balance equation for the liquid fuel in the droplets. Making use of $\lambda/\rho c_p U_0$ as a unit of length and $\lambda/\rho c_p U_0^2$ as a unit of time the governing equations for the problem at hand assume

ration and a detailed description of the chemical kinetics was utilized. Smaller droplets were found to determine the width of the reaction zone and its characteristics. Larger droplets were able to traverse the stagnation plane and then reverse their path of motion. The Sauter Mean Diameter (SMD) was found to be insufficient for characterizing flame extinction when droplet reversal occurred but was suitable when reversal was absent. A previous similar more comprehensive study of the combustion in the same configura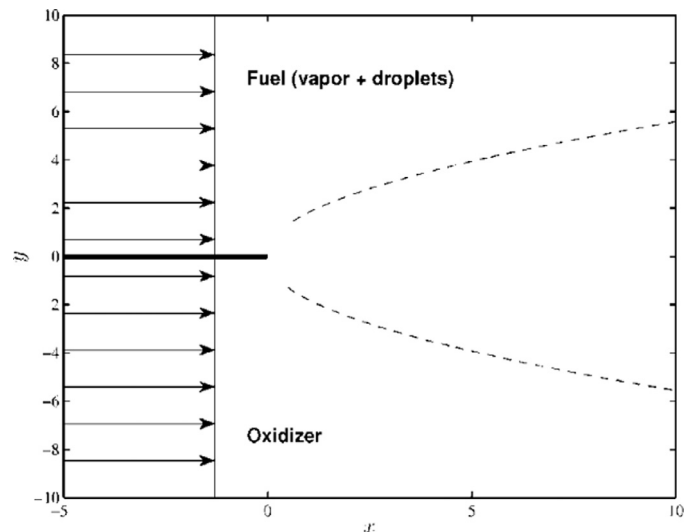tion, but for liquid oxygen/hydrogen spray flames,