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Review

Tubular premixed and diffusion flames: Effect of stretch and curvature

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ABSTRACT

Tubular flames are ideal for the study of stretch and curvature effects on flame structure, extinction, and instabilities. Tubular flames have uniform stretch and curvature and each parameter can be varied independently. Curvature strengthens or weakens preferential diffusion effects on the tubular flame and the strengthening or weakening is proportional to the ratio of the flame thickness to the flame radius. Premixed flames can be studied in the standard tubular burner where a single premixed gas stream flows radially inward to the cylindrical flame surface and products exit as opposed jets. Premixed, diffusion and partially premixed flames can be studied in the opposed tubular flame where opposed radial flows meet at a cylindrical stagnation surface and products exit as opposed jets. The tubular flame flow configurations can be mathematically reduced to a two-point boundary value solution along the single radial coordinate. Non-intrusive measurements of temperature and major species concentrations have been made with laser-induced Raman scattering in an optically accessible tubular burner for both premixed and diffusion flames. The laser measurements of the flame structure are in good agreement with numerical simulations of the tubular flame. Due to the strong enhancement of preferential diffusion effects in tubular flames, the theory-data comparison can be very sensitive to the molecular transport model and the chemical kinetic mechanism. The strengthening or weakening of the tubular flame with curvature can increase or decrease the extinction strain rate of tubular flames. For lean H_2-air mixtures, the tubular flame can have an extinction strain rate many times higher than the corresponding opposed jet flame. More complex cellular tubular flames with highly curved flame cells surrounded by local extinction can be formed under both premixed and non-premixed conditions. In the hydrogen fueled premixed tubular flames, thermal-diffusive flame instabilities result in the formation of a uniform symmetric petal flames far from extinction. In opposed-flow tubular diffusion flames, thermal-diffusive flame instabilities result in cellular flames very close to extinction. Both of these flames are candidates for further study of flame curvature and extinction.

Contents

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Nomenclature

a	thermal diffusivity
A	surface area
c_p	specific heat
d	diameter of the opposed jet burner nozzle
D	the mass diffusivity of the deficient reactant
Da	Damköhler number: the ratio of the mixing time to the chemical reaction time
f	mixture fraction
f_1, f_2	functions
g_n	function
H	height of the tubular burner nozzle
k	stretch rate
ke	turbulent kinetic energy
k_{ext}	extinction strain rate
Ka	the Karlovitz number: the ratio of the characteristic chemical reaction time (δ/S_{b}) divided by the characteristic flow residence time (k^{-1})
L	distance between the nozzles of the opposed jet burner
Le	Lewis number: thermal diffusivity of the mixture divided by the mass diffusivity of the deficient reactant in premixed flames or thermal diffusivity of the mixture divided by the mass diffusivity of the reactant in a stream of the diffusion flame.
m	mass flow rate
P	pressure
Q	lower heating value of the deficient reactant
R	radius of the nozzles in the tubular burner or the opposed tubular burner
Re	Reynolds number
S	flame speed
T	temperature
T_{b}^0	adiabatic flame temperature of an unstretched planar flame
T_{i}	ignition temperature
T_{2i}	the average temperature for flow rate m_{2i}
U	velocity
V	nozzle injection velocity
y	mass fraction of the deficient reactant

Greek

α,β	positive empirical constants of order unity
ε	rate of turbulent kinetic energy dissipation
λ	thermal conductivity coefficient
ρ	density
ϕ	the initial mixture strength of a diffusion flame: the ratio of the fuel mole fraction in the fuel stream to the oxygen mole fraction in the oxidizer stream normalized by the stoichiometric fuel-air molar ratio
Φ	equivalence ratio of a premixed flame
χ	scalar dissipation rate
ψ	scalar variables including temperature, density, and mass fraction of different species
ω	chemical reaction rate of the deficient reactant

Superscript

0	the classic one-dimensional planar flame.

Subscript

1	the fresh mixture zone
2	the flame zone
3	the product zone
b	the burned side, equivalent to 3
ext	extinction
F	fuel stream in a diffusion flame
i	ignition
O	oxidizer stream in a diffusion flame
r	the radial coordinate
st	stoichiometric
u	the unburned side, equivalent to 1
z	the axial coordinate