A Study of the Dynamics of Laminar and Turbulent Fully and Partially Premixed Flames

by

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(ABSTRACT)

Environmental pollution concerns and a need to reduce NO_x and other pollutant levels in exhaust of land based gas turbines resulted in the development of lean premixed combustors. These combustors are often susceptible to thermo-acoustic instabilities, which manifest as pressure and heat release oscillations in the combustor. To be able to predict and control these instabilities, it is required that both the acoustics of the system, and a frequency-resolved response of the combustion process to incoming perturbations be understood. Presently, a system-level approach is being used to predict the thermo-acoustic instability, and it requires simple, yet accurate models which would describe the behavior of each dynamic block within the loop. This present research effort was directed towards developing reduced order models for the dynamics of laminar flat flames, swirl stabilized turbulent flames, and in evaluating the effects of the variation in fuel composition on flame dynamics.

The laminar flat flame study was conducted on instrument grade methane, propane, and ethane flames for four total flow rates from 145 cc/sec to 200 cc/sec, and five equivalence ratios from 0.5 to 0.75. The analysis was done by measuring the frequency resolved velocity perturbations, u', and the OH^* chemiluminescence, as a measure of unsteady heat release rate, q'. The experimental data showed the corresponding flame dynamics to be fourth order in nature with a pure time delay. One of the resonance was shown to represent the pulsation of the flame location caused by fluctuation in the flame speed and fluctuating heat losses to the flame stabilizer. The other resonance was correlated to the dynamics of the chemical kinetics involved in the combustion process. The time delay was correlated to the chemical time delay. The reduced order models developed indicated that at $\Phi \leq 0.65$, the chemical kinetics significantly affected the dynamics of the combustion process. Upon comparing the results of the experiments with the three fuels, it was concluded that for all equivalence ratios studied, propane flame had a higher dynamic gain than methane flames. Ethane flames exhibited a higher dynamic gain than methane flame in the frequency range of 20-100 Hz. Thus, burning of propane instead of methane increased the likelihood of the occurrence of thermo-acoustic instabilities. However, burning of ethane instead of methane in flames that were stabilized at ultra lean conditions, it was expected that stable or marginally stable systems could exhibit instabilities at a frequency other than the one at which methane flames were marginally stable.

The experimental techniques developed during the dynamic studies conducted on laminar flat flames were applied to swirl stabilized turbulent flames. Experiments were performed for $Q_{Air} = 15$ scfm and 20 scfm, $\Phi = 0.55$, 0.6, 0.65, and $S = 0.79$ and 1.19. The results of fully premixed experiments showed that the flame behaved as a 8^{th} order low pass filter. The results of the partially premixed experiment exhibited a rich spectra, which maintained its bandwidth over the entire range of frequency studied. Comparison of fully and partially premixed flames in the frequency range of 200-400 Hz, indicated that at overall lean conditions the dynamic gain of the totally premixed flames was almost an order of magnitude lower than that of the partially premixed conditions. Thus, it was concluded that combustors with fully premixed flames have a higher probability of being thermo-acoustically stable than those with partially premixed flames. Furthermore, the dynamic results of fully and partially premixed conditions showed that independent of the operating conditions, there was a sharp increase in the dynamic gain at frequencies commensurate to the longitudinal acoustic modes of the combustor. This phenomenon was attributed to the near field acoustic effects that generated evanescent waves in the radial and azimuthal direction.

To my beloved wife Neeta

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Nomenclature

A	Pre-exponential factor
A_c	Cross sectional area of flow
A_d	Dynamics of plant acoustics
A_t	Total area of the tangential inlet
c	Speed of sound
CRZ	Central re-circulation zone
C_f	Friction coefficient
C_p	Specific heat
D	Diameter
D_h	Hydraulic diameter
Ea	Activation energy
FFT	Fast Fourier Transform
FRF	Frequency response function
F_d	Dynamics of combustion process
G_x	Axial flux of the axial momentum
G_θ	Axial flux of the swirl momentum
h	Plancks constant
h_x	Local convective heat transfer coefficient
k	Thermal conductivity
L	Length
$\dot{\mathrm{m}}'$	Fluctuations in the mass flow rate

Nu_x	Local Nuselts number
ORZ	Outer re-circulation zone
p'	Fluctuation in pressure
$\bar{\mathrm{p}}$	Mean pressure
P	Total pressure
P_o	Combustor pressure
P_r	Prandlt number
q'	Fluctuations in the heat release rate
q_{net}	Net heat transfer
Q_{Air}	Total air flow rate
Q_{Total}	Total flow rate
r_e	Radius on which the tangential inlets are attached
R	Rayleigh's index
Re	Reynolds number
RR	Reaction rate
R_o	Radius of the inlet of the quarl
R_u	Unversal gas constant
S	Swirl number
S_g	Geometric swirl number
S_L	Flame speed
t	Time
T	Temperature
T_{af}	Adiabatic flame temperature
T_f	Flame Temperature
T_g	Gas temperature
T_w	Wall temperature
u'	Fluctuations in the velocity
$\bar{\mathrm{u}}$	Mean velocity

u'_a	Feedback component of the acoustic perturbation
u'_s	Externally imparted velocity perturbations upstream of the flame
u_z	Velocity in axial direction
u_θ	Velocity in tangential direction
U	Total velocity
α_g	Absorptivity of the gas
ϵ_g	Emissivity of the gas
ζ	Damping ratio
μ	Viscosity
ν	Frequency of the photon energy
ρ	Density
τ	Time delay
τ_{chem}	Time delay due to chemical kinetics
ϕ	Phase angle
ω	Frequency in radians
ω_n	Natural frequency
Φ	Equivalence ratio
Φ'	Fluctuations in equivalence ratio
Ω	Ohms