

Forced Flame Response of Turbulent Liquid-Fueled Lean-Direct-Injection Combustion to Fuel Modulations

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Reported are the forced flame responses of a turbulent, liquid-fueled, swirl-stabilized, lean-direct-injection combustor to fuel modulations. Fuel modulations are achieved using a motor-driven, high-frequency, rotary fuel valve specially designed for this experiment. This valve is capable of fuel modulations up to 1 kHz. The instantaneous fuel flow rate out of a fuel injector is accurately determined from pressure measurements at one or two locations upstream of the fuel nozzle. Linear flame responses are obtained with small-amplitude fuel modulations, typically below 2.0% of the mean fuel flow rate, about 60 Hz below the acoustic resonant frequencies. The invariance in the flame transfer functions to the fuel modulation amplitude suggests that the derived flame transfer functions are linear and that the induced heat release rate oscillations mainly respond to variations in the instantaneous fuel flow rate rather than in the droplet size and distribution. Flame transfer functions at different air flow rates, equivalence ratios, and preheat temperature are examined. With fuel modulations around the acoustic resonant frequencies, forcing-induced acoustic feedback on heat release responses cannot be ignored, and the measured flame transfer functions are no longer open-loop and linear. The nonlinearity in the forced flame responses is significantly affected by acoustic damping. Extinction and entrainment of self-excited combustion oscillations by fuel modulations at the approach of the acoustic resonant frequencies are observed. Self-excited combustion oscillations can be diminished by increasing the amount of fuel modulations. Applications of the flame transfer functions to modeling and control of combustion instability and lean blowout for both liquid-fueled and gas-fueled combustion are discussed.

Nomenclature

\tilde{A}	= complex amplitude of the downstream-propagating acoustic wave, Pa
\tilde{B}	= complex amplitude of the upstream-propagating acoustic wave, Pa
c	= sound speed, m/s
\bar{c}	= mean sound speed, m/s
D_a	= Damköhler number
i	= complex symbol
k	= wave number, ω/\bar{c}
M	= mean flow Mach number, negligibly small in the present experiments, \bar{u}/\bar{c}
$\dot{m}'(t)$	= perturbations in the instantaneous fuel flow rate out of a fuel injector, kg/s
$\bar{\dot{m}}_f$	= mean fuel flow rate out of a fuel injector, kg/s
$\tilde{P}(x, t)$	= complex dynamic pressure, Pa
$\tilde{P}_0(x, t)$	= complex pressure immediately upstream of the fuel nozzle, Pa
$\tilde{P}_1(x, t)$	= complex pressure at one location upstream of the fuel nozzle, Pa
$\tilde{P}_2(x, t)$	= complex pressure at another location upstream of the fuel nozzle, Pa
$p_m(t)$	= dynamic pressure measured at 0.29 m upstream of the fuel injector, Pa
$p_0(t)$	= dynamic pressure immediately upstream of the fuel injector, Pa
\tilde{R}	= specific acoustic impedance
$\text{Re}()$	= real part of a complex quantity

S_L	= laminar burning velocity, m/s
s	= symbol of the Laplace transform
$\tilde{U}_0(t)$	= complex acoustic velocity immediately upstream of a fuel nozzle, m/s
\bar{u}	= mean velocity, m/s
$W_N(s)$	= transfer function between pressure measurements and prediction immediately upstream of the fuel nozzle
x_m	= pressure measurement location, 0.29 m upstream of the fuel nozzle, m
Z	= symbol of the Z transform
α	= thermal diffusivity, m^2/s
$\frac{\Delta P}{\Delta x}$	= mean pressure drop across the fuel nozzle, Pa
δ_L	= laminar flame thickness, m
$\bar{\rho}$	= mean density, kg/m^3
τ	= residence time, s
τ_c	= chemical reaction time, s
τ_v	= evaporation time, s
ϕ	= equivalence ratio

I. Introduction

COMBUSTION instability and lean blowout (LBO) are two major technical challenges for both gas-fueled and liquid-fueled dry-low-emission combustion [1]. Combustion instability refers to the self-excited, large-amplitude, limit-cycle thermoacoustic oscillations caused by the positive feedback between pressure and heat release. Strong pressure pulsations shorten engine life due to enhanced heat transfer, exacerbate NO_x emissions, generate noise pollutions, and cause instrumentation failures. LBO refers to partial or global flame quenching when the equivalence ratio is decreased below certain thresholds. As the equivalence ratio approaches the lean flammability limits, a combustor's resistance to external disturbances or small deviations from the equilibrium points is considerably weakened [2]. Thus, a small external disturbance in the inlet turbulence, fuel composition, fuel flow rate, and/or air flow rate may quench the flame. LBO necessitates expensive shutdown and restarting procedures for land-based gas turbines and represents a major safety hazard for aircraft engines.

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