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Review

Transverse combustion instabilities: Acoustic, fluid mechanic, and flame processes

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ABSTRACT

Thermoacoustic oscillations associated with transverse acoustic modes are routinely encountered in combustion chambers. While a large literature on this topic exists for rockets, no systematic reviews of transverse oscillations are available for air-breathing systems, such as in boilers, aircraft engines, jet engine augmentors, or power generating gas turbines. This paper reviews work on the problem for air-breathing systems, summarizing experimental, modeling, and active control studies of transverse oscillations. It then details the key physical processes controlling these oscillations by describing transverse acoustic wave motions, the effect of transverse acoustic waves on hydrodynamic instabilities, and the influence of acoustic and hydrodynamic fluid motions on the unsteady heat release. This paper particularly emphasizes the distinctions between the direct and indirect effect of transverse wave motions, by arguing that the dominant effect of the transverse acoustics is to act as the "clock" that controls the frequency and modal structure of the disturbance field. However, in many instances, it is the indirect axial flow disturbances at the nozzles (driven by pressure oscillations from the transverse mode), and the vortices that they excite, that cause the dominant heat release rate oscillations. Throughout the review, we discuss issues associated with simulating or scaling instabilities, either in subscale experimental geometries or by attempting to understand instability physics using identical nozzle hardware during axial oscillations of the same frequency as the transverse mode of interest. This review closes with a model problem that integrates many of these controlling elements, as well as recommendations for future research needs.

Contents

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Nomenclature

A_{cs}	cross-sectional area
$\widehat{B}_{i,m_h}$	complex amplitude of helical mode m_h for velocity along coordinate i
$\mathcal{A}, \mathcal{C}$	acoustic wave amplitude
D	diameter of inlet nozzle
$\mathcal{D}$	molecular diffusivity
F	flame transfer function (FTF), defined in Eq. (6)
G	level-set iso-contour variable
He	Helmholtz number, $=\omega R/c_0$
L	axial length of model annular combustor
L_θ	circumference of annular combustor based on average radius, R
L_i	axial location of interface of temperature jump
L_f	flame height
M	mach number, $=u_0/c_0$
$\dot{Q}$	global, spatially integrated, unsteady heat release rate
R	average radius of annular combustor, $=(a_1 + a_2)/2$
S	swirl number
St	Strouhal number, $=\omega L_f/u_0$
T	temperature
T_a	acoustic time period
V	combustor control volume
$\widehat{Z}_o, \widehat{Z}_{out}$	acoustic impedance at burner inflow and combustor exit, respectively
$\widehat{Z}_{tr}$	translated impedance
$\mathcal{Z}$	non-dimensional mixture fraction for non-premixed flames
$\mathcal{Z}_{st}$	stoichiometric mixture fraction, $=1/(1+\phi_{Ox})$
a_1, a_2	inner and outer radius of annular combustor respectively
c	speed of sound
d_s	nozzle/burner/injector spacing
f	frequency
h	axial length of inlet nozzle section
h_R	heat of reaction
j, n	radial and axial acoustic mode number, respectively
k,k_h	spatial wavenumber for acoustics and hydrodynamics, respectively
m_a, m_h	azimuthal mode number for acoustics and hydrodynamics, respectively
$\dot{m}_F''$	mass burning rate per unit area of flame surface
$\mathcal{n}$	*FTF* gain for thermo-acoustics model in Sec. 6
p	pressure
$\dot{q}$	unsteady heat release rate per unit volume
r	radial coordinate
u_i	velocity along coordinate direction i
s_L	laminar flame speed
s	nozzle index in annular combustor, in Fig. 2 and Sec. 6
t	time
x, y	Cartesian coordinates for transverse direction
z	axial coordinate

Greek letters

Φ	phasing between unsteady heat release and unsteady pressure
α	aspect ratio of annular combustor, $=L/R$
β	ratio of L_i/L
κ	temperature ratio between burnt and unburnt gases
ϕ	equivalence ratio
ϕ_{Ox}	stoichiometric mass ratio of oxidizer to fuel
φ	local azimuthal angle for cylindrical coordinate centered on a nozzle
λ	acoustic wavelength
μ	temporal damping coefficient in $exp(-\mu t)$
ϑ	time-varying phase for acoustic wave
ρ	density
θ	global azimuthal coordinate for annular combustor
$\tau_{(\ )}$	time-delay parameter
ω	angular frequency, $=2\pi f$
χ	flame aspect ratio, $2L_f/D$

Subscripts and superscripts

$(\ )^\circ$	stagnation value
$(\ )_u$	quantity in unburnt region
$(\ )_b$	quantity in burnt region
$(\ )_0$	time-averaged component
$(\ )_1$	unsteady first order perturbation component
$\widehat{()}$	Fourier transformed variable
$\widetilde{()}$	non-dimensionalized variable
$\overrightarrow{()}$	vector quantity
$()_r$	radial component
$()_\varphi$	azimuthal component in the nozzle coordinate system
$(\ )_z$	axial component
$()_\theta$	azimuthal component in the annular combustor coordinate system
$()_{ref}$	reference value
$()_{MBR}$	mass burning rate contribution