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EXPERIMENTAL INVESTIGATION OF HIGH FREQUENCY COMBUSTION INSTABILITY IN CRYOGENIC OXYGEN-HYDROGEN ROCKET ENGINES

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Glossary

Nomenclature

A	Area		LOx	Liquid oxygen
β^*	Reduced acoustic admittance		$\dot{m}$	Mass flow rate
c	Sound speed		M	Molecular mass, g/mol
c^*	Characteristic exhaust velocity		M_{bulk}	Bulk flow Mach number
c_p	Specific heat capacity		n	Mode index
CH_4	Methane		N	Response factor
D	Diameter		N_2	Nitrogen
η_{c^*}	Characteristic exhaust velocity efficiency		O_2	Oxygen
f	Frequency		p	Pressure
F	Thrust		p'	Acoustic pressure
g_0	Standard gravitational acceleration, 9.8 m/s^2		P_{cc}	Combustion chamber pressure
GH_2	Gaseous hydrogen		$\dot{q}$	Heat release rate
GN_2	Gaseous nitrogen		ρ	Density
GOx	Gaseous oxygen		R_p	Rayleigh index based on acoustic pressure
γ	Ratio of specific heats		R_u	Rayleigh index based on acoustic velocity
H_2	Hydrogen		ROF	Oxidiser-to-fuel mixture ratio
I	OH* emission intensity		t	Time
I_{sp}	Specific impulse		T	Temperature
J	Momentum flux ratio		u	Velocity
L	Length		u'	Acoustic particle velocity
LH_2	Cryogenic ('liquid') hydrogen		VR	Inner-to-outer-propellant injection velocity ratio
LN_2	Liquid nitrogen			

Subscripts

$bulk$	Bulk, total
cc	combustion chamber
$crit$	Critical therophysical property
d	Droplet (of LOx)
H	Hydrogen (fuel)
MN	Main (exhaust) nozzle
O	Oxygen (oxidiser)
SN	Secondary (exhaust) nozzle
x	x-axis direction
y	y-axis direction
z	z-axis direction

Acronyms

CFD	Computational Fluid Dynamics
CNRS	National Scientific Research Centre (France)
DLR	German Aerospace Center
FEA	Finite Element Analysis
IRPHE	Research Institute for Equilibrium Systems (France)
ONERA	National Aerospace Lab (France)
NASA	National Aeronautics and Space Administration

Abstract

Self-sustaining pressure oscillations in the combustion chamber, or combustion instability, is a commonly encountered and potentially damaging phenomenon in liquid propellant rocket engines (LPREs). In the high-frequency variety of combustion instability, the pressure oscillations in the combustion chamber take on the form and frequency of an acoustic resonance mode of the combustion chamber volume. The most common mode in naturally occurring instability, and also the most destructive, is the first tangential mode, with acoustic gas oscillations oriented transversally to the direction of propellant injection. The instability is driven by the coupling between acoustic oscillations and unsteady energy release from combustion. The mechanisms through which injection and combustion firstly respond to the acoustic field, and secondly feed energy back into the acoustic field have not yet been fully characterised.

Shear coaxial-type injectors are common in LPREs. Past experimental and numerical research efforts have investigated the interaction between this type of injector and transverse acoustic fields. Some experimental efforts have successfully forced transverse acoustic modes and studied their influence on shear coaxial injection under LPRE-like conditions. Acoustic forcing of coaxially injected LOx/H_2 has previously been conducted only at low pressures and injection performance levels. This work addresses the lack of experimental data available for the interaction of shear coaxial injection of LOx/H_2 with acoustics under conditions representative of industrial engines.

A new experimental rocket combustor, designated 'BKH', was developed for investigating the response of a reacting spray of coaxially injected LOx/H_2 to an acoustic field. For characterising the response, simultaneous high-speed recordings of both backlit shadowgraph and hydroxyl radical (OH*) chemiluminescence imaging have been captured through optical access windows. The operating conditions of BKH extend to conditions more representative of actual LPREs than has previously been achieved with LOx/H_2 in studies of flame-acoustic interaction. BKH was run at pressures of 40 or 60 bar, which correspond to subcritical and supercritical thermo-physical regimes for oxygen. Hydrogen injection temperature was ambient, around 290 K, or cryogenic, around 50 K. An array of multiple injectors was used to better represent real engines. A system for modulating the nozzle exhaust flow was used to induce acoustic perturbations inside the combustion chamber. Two types of perturbation were applied to the near-injection region; oscillating acoustic pressure, and oscillating transverse acoustic velocity.

BKH was used to investigate how subcritical or supercritical pressure level and ambient or cryogenic hydrogen injection temperature influence the interaction of acoustic pressure or velocity with injection and combustion processes. Shadowgraph imaging reveals up to 70% reduction in the length of the oxygen jet when subjected to acoustic velocity of amplitude approaching that of the hydrogen injection velocity. Furthermore, the mode of jet breakup changes from its natural growth-and-detachment behaviour to a 'transverse stripping' mechanism. OH* imaging reveals a corresponding decrease in the extent of the flame, and increase in emission intensity. When subjected to acoustic pressure, OH* emission from the flame was observed to fluctuate in phase with pressure. Thus, responses to both acoustic pressure and velocity have been observed in BKH, which together may form the basis of a coupling mechanism for driving natural combustion instability in LPREs.

Declaration of originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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