Injection for Liquid Rocket Engines

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Abstract

The propellant injectors are one of the dominant components of liquid rocket engines (LREs). Not only do they define the engine performance and the heat load to various sensitive parts of the combustion chamber, the integrity of the chamber and the entire launch system heavily depends on their sensitivity against combustion instabilities. The propulsion system is by far the most sensitive sub-system of a launcher since more than 50% of the world-wide launch failures are due to failures in the propulsion system.

A brief introduction into typical operating conditions and propellants of LREs is followed by the main requirements for injectors. Two classes of injectors are discussed in ore detail exploring into their advantages as well as their short-comings under different operating conditions and applications followed by a brief description of an injector design methodology. Special emphasis is given to the injector behavior during transient start-up phase of the engines and to the influence of high combustion chamber pressures which typically exceed the critical pressure of the propellants. Based on recent results of two test campaigns which focussed on near-injector phenomena during ignition and steady-state combustion, atomization, mixing and combustion are discussed.

Introduction

In order to understand the difficulties of injector design it is useful to recall the various types of engines, the propellants in use, their operating conditions and performance requirements. While the thrust levels of satellite propulsion systems and attitude control engines may vary between 0.5 N - 400 N, those of upper stage engines range from 10 kN - 180 kN and sustainer engines may even reach up to 1 MN. The currently largest booster engine, i.e. the Russian RD-170 (RD-171), has a vacuum thrust of almost 8 MN. Satellite propulsion systems mostly are mono-propellant and apply either cold gases or catalytic decomposition of a fuel (often hydrazine) and only engines with higher thrust levels are bi-propellant and apply space-storable propellants, i.e. nitrogen-tetroxide (NTO) as oxidizer and mono-methyl or un-symmetric di-methyl hydrazine (MMH, UDMH) as fuel. Typical booster engines use with a few exceptions liquid oxygen (LOX) and kerosene. The propellant mass flow rate per injector varies drastically starting from a few g/s for satellite propulsion systems up to almost 2 kg/s for boosters. Hence, the thrust per injector varies over more than 4 orders of magnitude with a peak thrust per element of about 6 kN [1,2,3,4].

Engine	**F1**	**RD-170**	**Vulcain 2**	**SSME**
Cycle	GG	SC (ox-rich)	GG	SC (fuel-rich)
Propellants	LOX/Kerosene	LOX/Kerosene	LOX/LH2	LOX/LH2
Thrust (sea level) [MN/t]	6.9 (690)	7.9 (790)	1.2 (120)	1.67/167
Chamber Pressure [MPa]	6.6	25.5	12.0	20.5
Spec. impulse (sl/v) [s]	264 / 305	311 / 337	? / 433	363 / 452
Injector Type	L-O-L doublet, (f) L-O-L triplet, (o)	co-ax (5), center gas, outer liquid swirl	co-ax, center liquid, outer gas	co-ax, center liquid, outer gas
Injection temp. (O/F) [K]	~ 100 / > 300	> 500 / > 300	~ 100 / ~ 100	~ 100 / ~ 800
Throttling capability	-	46 % - 102 %	-	67 % - 109 %
Mixture ratio [-]	2.3	2.6	6.9	6.0
Thrust/element [kN]	4.6	6.1	2.3	~ 2.8
Flow rate/element [kg/s]	1.7	1.8	0.6	~ 0.9

Table 1: Boundary conditions, propellants and injectors of large liquid rocket engines

In a gas generator engine which is the simplest pump feed system the fuel is generally used as coolant. Although the temperature pickup depends on the fluid properties it typically doesn't exceed 100 K which is sometimes not sufficient for vaporization. The oxidizer enters the injector head near its storage conditions. Staged combustion cycles are more complex since one of the propellants is fully or partially pre-burned while the remainder is mixed and injected into the combustion chamber. The key drivers of injector design aside performance and stability are engine application (thrust level) and cycle as well as propellant combination.

While the choice of propellants depends among others mostly on the thrust requirement of the engine, the propellant properties and injection conditions differ again quite drastically from all cryogenic systems such as LOX/LH2 over mixed systems such as LOX/Kerosene to all ambient temperature storable MMH/NTO systems. For all possible propellant combination there are without a few exceptions only two main classes of injectors and they employ two different physical processes for atomization of the liquid propellants. First, the impinging injector where two liquids jets are oriented towards one another to form a liquid sheet which eventually disintegrates further downstream, and, second, the shear co-ax injector where typically the central liquid jet with or without swirl is atomized by a co-axial gaseous jet.

Due to the size limits this paper focuses only on some specific issues of injectors and injection conditions of large liquid rocket engines (LRE) such as transient start-up behavior, wall heat flux and the importance of thermodynamic properties based on the experience with the American F1, the booster engine of the Saturn V, the Russian RD-170 which boosted the Energia launcher which are both LOX/Kerosene engines and the Vulcain 2, the core engine of the European Ariane 5 and the SSME, the main engines of the Space Shuttle which are both cryogenic systems. The main characteristics of these engines, their operating conditions and their injectors are characterized in table 1.

Injector requirements

Rocket engines are surely systems where combustion efficiency is a key concern and millions of dollars are spend to improve the injection system to increase the efficiency from 99.5% to 99.6 %, typical values for LOX/Hydrogen engines. Overall system performance requirements towards minimum cooling channel pressure loss and engine weight constrain the combustion chamber geometry such that typical propellant stay times are in the 10^{-3} *s* range. For almost all propellant combinations used in rocketry the chemical times scales are by far smaller than any other characteristic time in the system. For the majority of applications the combustion chamber pressure is far above the critical pressure of the propellants and therefore vaporization can be neglected. The injection problem can then be considered as a combination of mass and heat transfer between two gaseous jets having a large density ratio.

In order to improve the overall system performance the pressure drop across the injection system has to be as small as possible without significant losses in atomization and mixing efficiency. On the other hand a certain pressure loss has to be maintained in order establish the necessary de-coupling of the feed systems and propellant manifolds with the combustion chamber to prevent that pressure perturbations in the chamber cause low frequency instabilities.

The energy release rate in a LRE exceeds by far that of a nuclear power plant and thus the energy densities in LREs cause extremely high thermal loads and which impose difficult boundary conditions for cooling systems. Aside the combustion chamber walls which see especially near the throat peak loads in the order of $100\ MW/m^2$, the injector face plate and the injectors themselves may be exposed to severe heat loads which have to be avoided in order to maintain their integrity without additional cooling. Although combustion efficiency is the number one concern of the injector designer efficiency is generally traded against combustion stability (down from 93% to 91% in case of the F1 engine). The large energy densities with the resulting high heat loads make the combustion chamber walls very sensitive towards high frequency (HF) combustion instabilities. At combustion pressure levels of up to 25 MPa any HF pressure oscillations, typical frequencies are in the range between 1.5 - 3.0 kHz, may destroy the combustor walls within less than 100 acoustic cycles. Both LOX/HC and NTO/MMH systems are due to their larger chemical time scales much more sensitive to HF combustion instabilities than the more robust LOX/H2 engines although at hydrogen injection temperatures below 70 K these engines too become prone to instabilities [5,6,7,8].

The launch systems boundary conditions (maximum dynamic pressure during ascent) sometimes require that LREs have throttling capabilities which allow the engine be to work even at 50% of its nominal operating point with reasonable sufficiency. The throttling requirement for the lunar decent engine even reached a value of 10:1.

Injection Elements

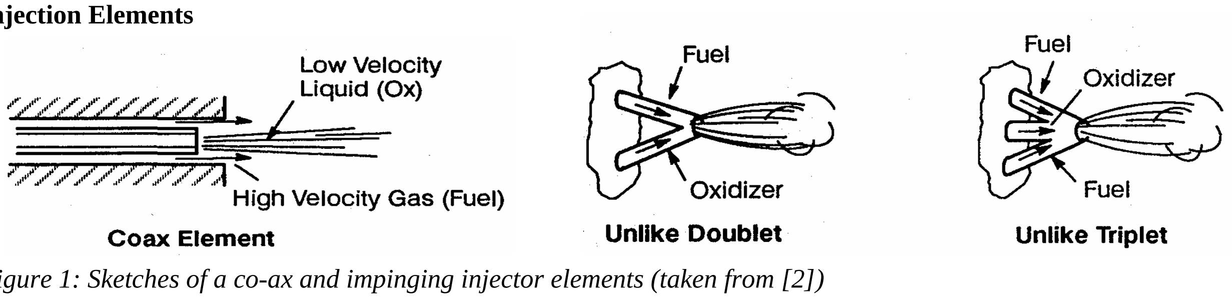

Figure 1: Sketches of a co-ax and impinging injector elements (taken from [2])

In the early days of rocketry virtually any way of propellant injection has been tried but with the exception of engines with an extremely throttling requirement (> 8:1) only two injectors types are now in commonly used in today's

LREs: co-axial elements and impinging elements with the former widely used for liquid/gas (LOX/H2) and the latter for liquid/liquid (LOX/HC or NTO/MMH) systems. Sketches of a simple shear co-ax injector and two unlike impinging elements are shown in Figure 1. Large thrust variations of LREs are mainly achieved using pintle type injection system where a moving central part partly locks the propellant injection area. Minor throttling is typically achieved designing the injectors such that even with reduced liquid velocities the atomization is still sufficient or by injecting some of the gaseous propellant into the liquid, create a two-phase flow and thus aerodynamically assist the atomization and mixing. In the case of the Russian RD-170 based engine family which operates with an oxygen-rich pre-burner staged combustion cycle where the oxidizer enters the combustion chamber as a mixture of steam and oxygen, shear co-ax injectors are applied even for an initially liquid/liquid propellant combination.

While there are only two different types of co-axial elements, the shear co-ax for cases where the velocity ratio of the propellants is sufficiently high (> 10 – 20) to ensure proper atomization and mixing and the swirl co-ax for cases where this velocity ratio requirement cannot be met and the propellant disintegration can only be achieved by an additional mechanical device or tangential injection to help self-atomize the liquid. The different impinging injector elements can again can be sub-divided into two groups, like-on-like (L-O-L) elements, the easiest of them is a L-O-L doublet which is comprised of two self impinging fuel and oxidizer doublets which each produces a spray fan which interact and react further downstream and unlike elements, the easiest of which is the unlike doublet where a single oxidizer jet meets a single fuel jet. Generally, L-O-L elements are favored for propellant combinations having similar volatility and density. While unlike doublets work best for propellants with almost equal injection area and momentum ratios, unlike triplets are used either in the fuel-oxidizer-fuel (F-O-F) or oxidizer-fuel-oxidizer (O-F-O) mode for applications where either the oxidizer or the fuel is less volatile. The choice depends upon whether the combustion is more likely to be vaporization limited or mixing limited. Typically, unlike elements tend to produce a finer spray than like elements for comparable injection conditions are of higher performance but more sensitive to combustion instabilities.

Injection Conditions

The thermodynamic boundary conditions of LRE propellants are rather unique insofar as they require either a phase change or a change in the state of super-criticality. Figure 2 gives an overview of typical thermodynamic boundary conditions of various propulsion systems with the obvious specifics of rocket engines they inject either one or both of the propellants in a trans-critical mode: supercritical with respect to pressure but sub-critical with respect to temperature. While the fluid disintegrates it goes from a sub- to super-critical state and this transition is accompanied by a change in fluid behavior properties. Hence, the typical problem of liquid atomization problem becomes within less than one second a mixing problem of two gases with a large density ratio.

The steady-state injection conditions of typical LREs are shown in figure 3 using the classical atomization (*Re – We)* parameter space. With both *Re* and *We* in the range of 10^4 - 10^5 the atomization process in a rocket engines exceeds by far that of other propulsion system. Only recently, the momentum flux ratio *J* of the propellants has been identified a key parameter for efficient atomization in rocket engine applications aside the widely used non-dimensional Weber and Reynolds-number which have been used to classify liquid jet atomization [9]. Typical high pressure LREs operate at momentum flux ratios *J* around 10.

However the most severe boundary conditions are those during engine start-up and shut down where within a few hundred milliseconds temperatures and pressures in the propellant feed system change rather quickly in the range of 1 or 2 orders of magnitude, respectively.

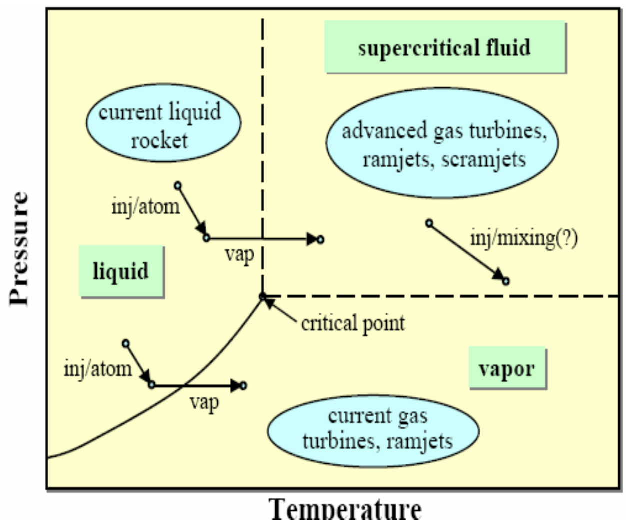

Figure 2: Thermodynamic operating conditions of typical propulsion systems (taken from [6])

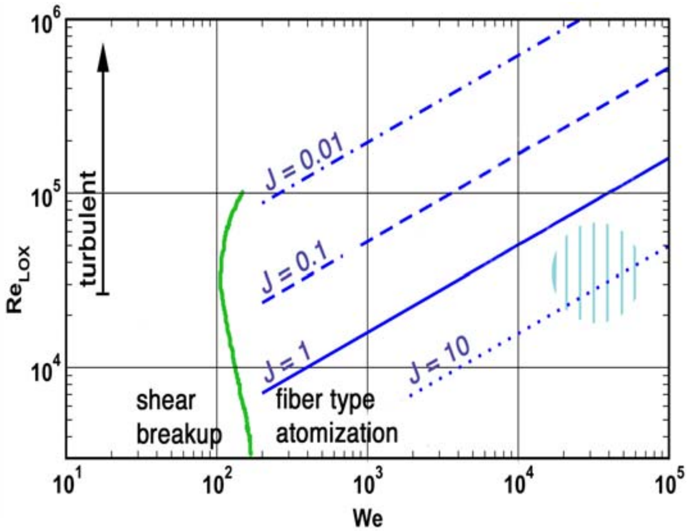

Figure 3: Aerodynamic operating conditions of rocket engines

Recent investigations [10] have demonstrated that at near critical conditions any heat transfer to the fluid doesn't yield a temperature increase but a density decrease subsequently described as quasi-boiling. Figure 4 shows for a super-critical pressure (4 MPa), density and specific heat of nitrogen (p_c = 3.4 MPa). Points A, B and C mark the injection conditions of cold nitrogen into ambient temperature nitrogen. The influence of the different injection temperature on the centerline temperature at different down-stream positions is demonstrated in Figure 5.

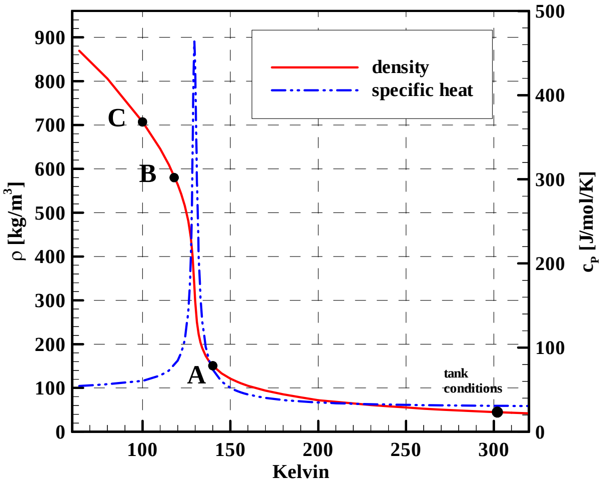

Figure 4: Fluid Properties of nitrogen

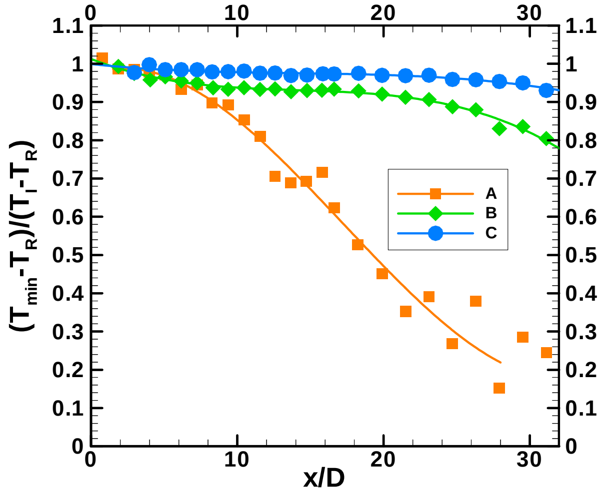

Figure 5: Centerline temperature of the LN2 jet

Design Methodology

Previously, injector design has been rather subjective. Since in almost all rocket engines manufacturers the number of different engines to be built is still small, the designers tended to stick to certain successful injection element and apply that to various applications independent of its suitability.

Atomization break-up distances together with nominal design point pressure drop and injection velocity are selected first to determine the characteristic delay time necessary to satisfy stable operation as well as margins for transients and throttling. As a starting point of propellant injection layout both co-ax and impinging injectors are designed such that their pressure drop across the injector head amounts to about 20% of the combustion chamber pressure in order to avoid coupling of chamber pressure oscillations with characteristic times of the system which would lead to combustion instabilities. Drop size distributions are then used to calculate time lags for high frequency combustion stability margins and spatial combustion profiles are evaluated to assure thermal compatibility with wall surfaces and cooling requirements [3,11]. Finally, the performance is assessed predicting the amount of large droplets which would exit the chamber with a given length without vaporization and subsequent reaction. If known, the liquid phase or liquid/gas phase mixing efficiency parameter [12]

Flame Holding

Engine designers usually aim at a flame holding directly at the injectors but with moderate heat loads to the face plate and combustion chamber walls. As long as the flame stays attached, the combustion noise is smaller and hence the system is less sensitive to instabilities. While LOX/H2 injectors usually see the flame attached to the injector lox post and a flame lift-off has never been reported so far for hydrogen injection temperatures above 100 K, LOX/kerosene and also LOX/Methane coax injectors see for a variety of injection conditions flame lift-off. Figure 6 shows for the near injector region of a coax LOX/H2 spray flame a superposition of a shadowgraph and a false color image of the spontaneous OH emission of the flame. The flame is clearly anchored in the wake of the LOX post and stretches further down in the shear layer around the cryogenic liquid [13]. Numerical studies have shown that a small recirculation region in the wake of the LOX post is most likely the key flame holding mechanism [14]. For typical injection conditions, *We* > 10^4, *Re* > 10^5 and momentum flux ratios *J* > *10*, LOX/HC injectors experience a lifted flame unless either oxidizer or fuel propellant or even both are injected at elevated temperatures. The RD-170, where the oxygen is heated in he pre-burner to about 750 K and the kerosene in the regenerative cooling circuit to more than 300 K, is a typical example for an engine cycle where both propellants are inject at high temperatures.

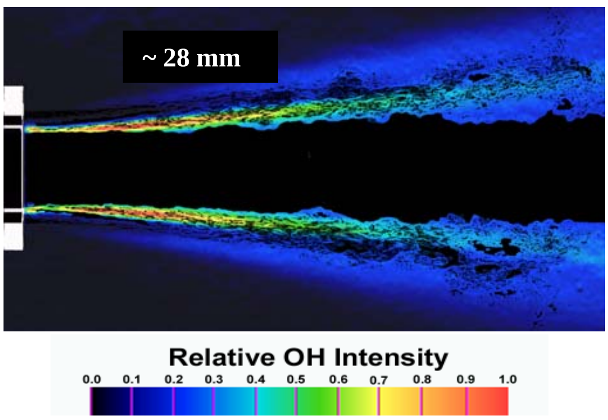

Figure 6: Superimposed shadowgraph and OH emission images of the near injector region; (shear co-ax LOX/H2, no recess and tapering)

Recent detailed DNS and LES studies have shown that the changes in properties in the near injector region are dramatic. While the speed of sound may vary by a factor of two, the local Mach number may vary even by two orders of magnitude. Similarly, the ratios of viscosity and density see variations of two and three orders of magnitude, respectively across the flame. Typical non-dimensional numbers which characterize the influence of different transport phenomena such as Prandtl, Lewis and Schmidt see changes of one, three and four orders of magnitude, respectively [15].

Transient Start-up and Ignition

The extreme changes in pressures, temperatures and fluid properties during engine start-up and ignition represent a demanding challenge for the engine designer. While the process of ignition itself only takes a few milliseconds, the process of engine start-up to steady-state conditions usually lasts a couple of seconds. During this period the injector has to generate and maintain favorable conditions for both initial ignition and subsequent flame propagation although injection and chamber pressure may change by two orders of magnitude and injection and chamber temperature may vary between 100 K - 300 K or 100 K - 3500 K, respectively. Furthermore, injection velocities for gaseous propellants typically reach sonic conditions at the beginning and will drop down by almost one order of magnitude. Hence, the velocity ratio between gas and liquid at the beginning may be more than one order of magnitude larger than that at steady-state, typically values for LOX/H2 systems would vary between 250 and 15, and obviously the aerodynamic boundary conditions for atomization vary rather drastically, too. Recent ignition investigations at low pressures have shown that the process of flame anchoring for LOX/H2 flames depends for a given combustion chamber geometry not only on the well-known non-dimensional parameters *Re*, *We*, and *J* but also on the absolute value of the momentum *I* of the co-axial hydrogen jet [16]. Figure 7 shows in the *Re – I* for a LOX/GH2 single co-ax injector marked in red where no stable flame could be maintained in the combustor, in green where the flame attaches within less than 1ms directly to the injector and third, in blue where it takes more than 10 ms for flame attachment.

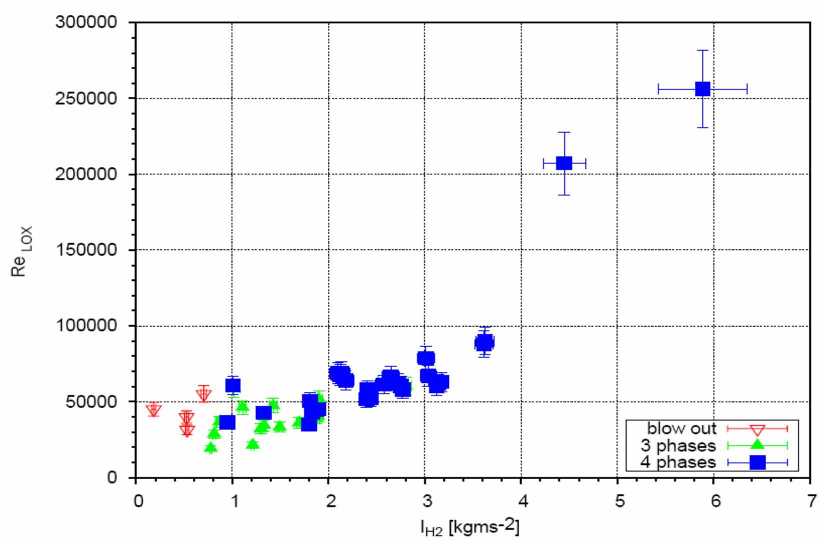

Figure 7: Chamber pressure fluctuations near the critical pressure for LOX/H2

The sensitivity of the combustion process towards transition from between sub- and super-critical propellant injection conditions has been studied intensively [17]. Various tests where the point of critical pressure has been crossed going from super- to sub-critical conditions and vice-versa. A typical result of this test campaign is given in figures 8 and 9 for a single injector LOX/GH2 high pressure combustor. While figure 8 shows the combustion chamber pressure and mixture ratio, figure 9 clearly demonstrates that the combustion noise is maximum at sub-critical conditions, experiences a distinct minimum at the critical point and slightly increases again at higher pressures shows for the same time interval the peak-to-peak pressure amplitudes.

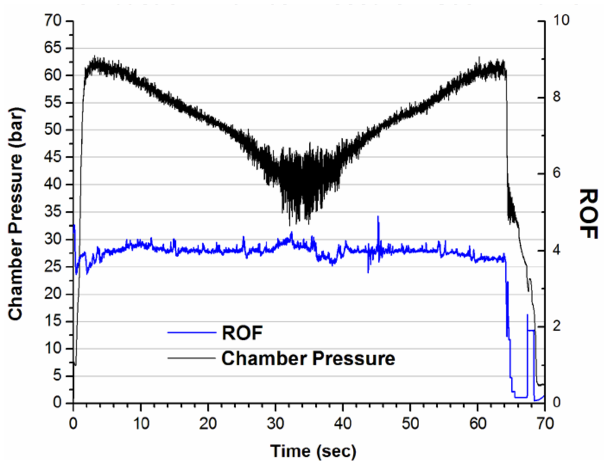

Figure 8: Combustion chamber pressure ramping and mixture ratio during ramping

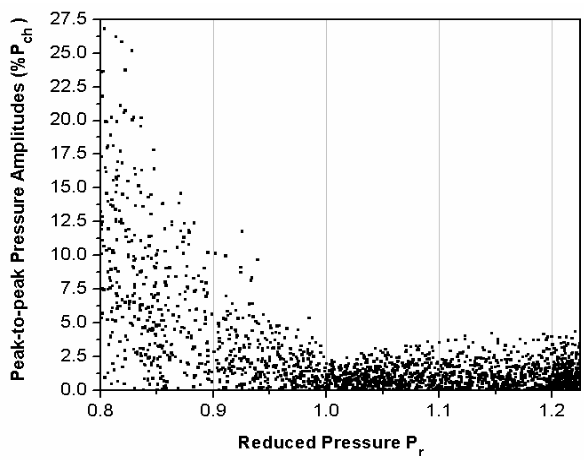

Figure 9: Combustion noise during pressure ramping tests

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