Supercritical injection, combustion and acoustic interactions in a semi-cryogenic liquid propellant rocket engine injector

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Abstract

The injector configuration and dimensions in the RD-170 engine indicated a deliberate acoustic coupling between the chamber and injector modes. It is presumed that this coupling is utilised to dissipate chamber perturbations into the propellant tanks and hence tackle the combustion instability problem. Further, it appears from the design that in order to ensure that the chamber perturbations still do not lead to combustion instability, injectors are arranged to form baffles and hence provide additional safety measures for the same. This special configuration is surprising considering the fact that the engine uses inherently stable coaxial injectors. It appears that this intentional coupling imposes the need to add a special arrangement of protruding injectors. If the above statement is true, this can be tackled by decoupling the system and hence simplifying the overall design. This paper discusses the acoustic coupling and interaction with the heat release rates due to combustion. A possible solution to decouple the systems is also proposed and discussed.

Keywords

Rocket Propulsion, Supercritical Combustion, Gas-liquid swirl Injector, Turbulence Modeling, Combustion Instability

Introduction

The RD-170 engine is considered as a stalwart in liquid propulsion systems with a peak chamber pressure of around 24 Mpa. This was the highest chamber pressure achieved until recently broken by the Raptor engine developed by SpaceX. With such a high performance engine, the methodology to tackle the ever present problem of combustion instability is very interesting. The design indicates a deliberate coupling between the tangential mode of the chamber and the longitudinal mode of the injector.

The oxidizer used in this engine is gaseous oxygen and the fuel is kerosene. The RD-170 engine uses swirl type coaxial injectors with the oxidizer in the center and the fuel taking up the annular section. The additional swirl is provided to promote better mixing of the fluids. Most liquid propulsion systems being developed now are either direct derivatives of the RD-170 or based on the design of this engine. With this engine being a benchmark for all designs, it is essential to understand the phenomenon behind its superior functionality. This study intends to shed some light on the superior stability characteristics shown by the engine and whether the utilized design is optimal or not. The proposed changes to design help us conclude that a simplication to the existing design can be achieved which will lead to easier manufacturing and reduction of cost.

Recent experiments at DLR[1] on a lab-scale cryogenic rocket engine (the BKD engine) have clearly shown that the observed combustion instability is caused by the coupling of longitudinal (L) modes of the injector with the tangential (T) modes of the combustion chamber. In the BKD engine, instability occurs whenever the 2L mode frequency of the injector matches the 1T mode frequency of the combustion chamber. But such matching of modes between injectors and chambers are deliberately introduced in some rocket engine designs (RD-170, for instance) as a method of providing damping to avoid high frequency instabilities; this arrangement is known to transmit energy from chamber oscillations through the injectors to the oxidizer dome, where it is absorbed without any reflection (like in a Helmholtz resonator, particularly when the pressure drop across the injector is high).

It can only be concluded that the matching is a source of both amplification and damping and the relative magnitudes of the two determines the stability of the engine. From this perspective, it is clear why, in spite of the excellent stability characteristics of coaxial injectors[2], baffles are provided (using a novel arrangement of protruding injectors in RD-170) - to avoid potential instabilities caused by the frequency matching between injectors and chamber, particularly during transient operation (start-up and throttling). Some results from an investigation to understand the dynamics of this coupling is reported in this paper

Flow and combustion in a model gas-centered (oxidizer)-liquid-swirl (fuel) injector of the kind used in oxidizer rich staged cycle engines with kerosene and liquid oxygen as propellants are investigated here. The transcritical injection of fuel is accounted for by the use of the Peng-Robinson cubic equation of state. The fuel is injected at 492 K and the oxidiser (partially burnt products from oxygen rich conditions in the pre-burner) at 687 K; the operating pressure of the system is 25.3 MPa (corresponding to RD-170 engine). Mean heat release rate (HRR) profiles are first calculated. Fluctuations in the heat release rate due to longitudinal mode oscillations in the injector are studied by perturbing the mean HRR profiles with standing longitudinal modes corresponding to the length and thermodynamic state of the gases in the injector. Conditions downstream of the injector are simulated by introducing domes of appropriate sizes. Results from these simulations will be presented ahead. Implications of these results for the full rocket engine are discussed. Potential design simplifications for enhanced stability are also briefly discussed. The experiments conducted in DLR on the BKD engine which is a hydrogen-liquid oxygen system indicate very similar results and hence can be used as the base to build upon for further design simplications of existing designs which can lead to superior and cost effective future designs.

All numerical simulations are run on Ansys Fluent. In order to ensure the results generated by the software are acceptable, the cold flow mixing case of hydrogen and liquid oxygen case[3] as as well as a methane oxygen combustion case[4] has been compared and validated. The results provided in [3,4] which have been generated using the AVBP and RAPTOR solvers have been recreated using Ansys Fluent. This validation is necessary as we are handling supercritical fluids here, whose thermo-chemical properties show large variations[5] with changes in their state.

Linear Acoustic Analysis

Before proceeding towards the combustion analysis of the system, a linear acoustic analysis was performed to locate the dominant frequencies associated with the system. Individual simulations were run for the injector and the chamber after which a coupled simulation was performed.

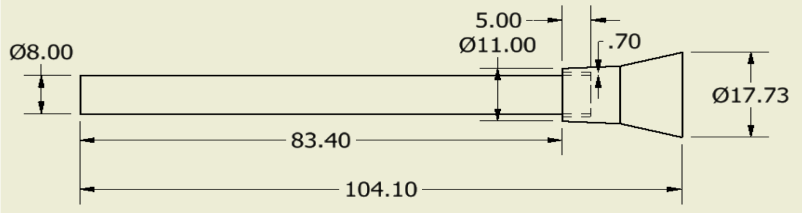

Fig 1: Injector Dimensions (all dimensions in mm)

First, the analysis was performed on a single injector. This injector is primarily used in the RD-170 engine. The first five modes of this injector are given below. The dimensions of the injector and other parts were taken from [6].

Mode	Frequency(Hz)	Type
1	1944.3	Longitudinal
2	4400.6	Longitudinal
3	6974.4	Longitudinal

4	9412.1	Longitudinal
5	11532	Longitudinal

Table 1: Longitudinal modes natural frequency of the main injector of the RD-170

As mentioned above, the lower modes are primarily longitudinal in nature, as expected. The RD-170 engine uses a special type of injector apart from the one above for the baffles. This injector has slightly varied dimensions and its acoustic analysis was also performed.

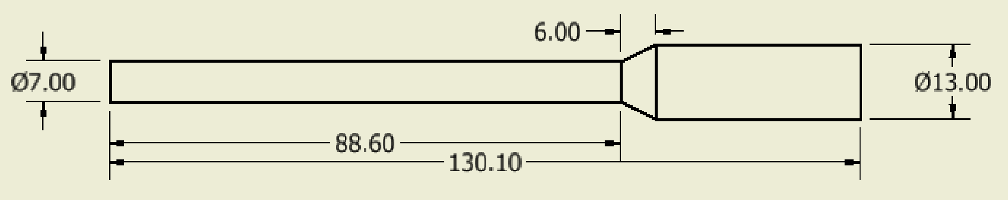

Fig 2: Baffle Injector Dimensions (all dimensions in mm)

Modes	Frequency(Hz)	Type
1	1582.4	Longitudinal
2	3932	Longitudinal
3	5819.9	Longitudinal
4	7165.5	Longitudinal
5	9422.4	Longitudinal

Table 2: Longitudinal modes natural frequency of the baffle injector of the RD-170

Yet again, the lower modes are longitudinal as expected. This modal analysis was finally performed on a case where the chamber is connected to injectors to see whether the tangential mode of the chamber couples with the longitudinal mode of the main injector.

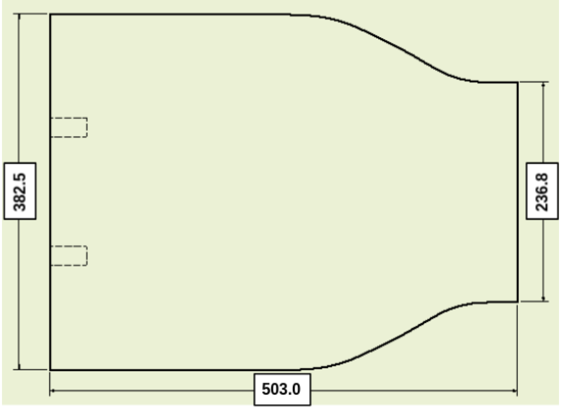

Fig 3: Main Chamber complete configuration (all dimensions in mm)

Finally we study the acoustic modes of the injector chamber setup. It must be kept in mind that not all the injectors are required to study the acoustic modes but a few injectors (three in this case) placed at appropriate locations (node, antinode and midway) are sufficient to see the coupling. The results for this study clearly show the expected coupling between the chamber and the injector.

Mode	Frequency (Hz)	Type
1	1957.5	1T
2	3191	2T

Table 3: Tangetial modes of the chamber and corressponding natural frequencies

As expected and as intended by the design, the coupling is clearly visible and also has been visualised below. The design intent behind this enforced coupling is to mitigate chamber oscillations into the propellant tanks through the injectors.

Finally, as proposed as a possible solution, 2/3rd of the injector post was used and the acoustic study was performed on the new configuration. As visualized below, the expected longitudinal mode is not coupling with the chamber's tangential mode for the same frequency as above. By coupling we mean, resonance is not observed as in the previous case, instead just some small amplitude response is seen which is expected. With the linear acoustic analysis providing good supporting grounds on the proposed design modification, the next step was to perform flow and combustion analysis to see whether the heat release rates respond to this acoustic oscillations and whether it can drive this instability.

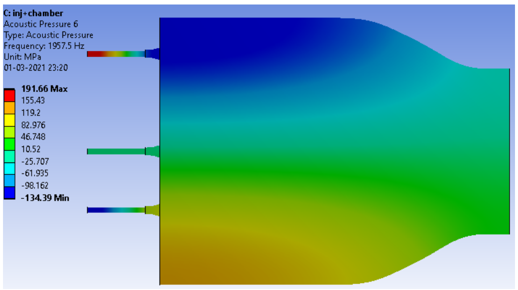

Fig 5: Tangential Mode Coupling with Injector

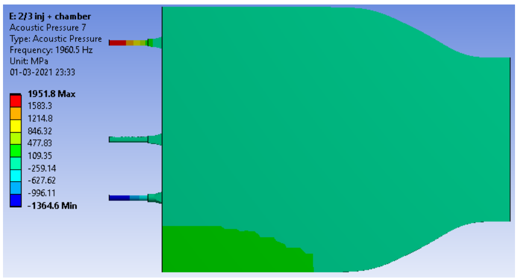

Fig 6: Reduced Injector Dimension Acoustic Analysis

Geometry and Mesh

From the acoustic analysis, we know that the longitudinal mode of the injector will potentially couple with the tangential mode of the chamber. But in order to simulate this condition, a full scale 3D simulation has to be performed. Instead of simulating a full scale engine with all the injectors included, we propose a single injector axis-symmetric simulation and couple it with the radial mode of a chamber whose dimensions are corrected accordingly. The primary objective of this paper is to study the longitudinal oscillations which occur in the main injector post. These oscillations can be captured in both 2D and 3D simulations. Now, in order to trigger these oscillations, we need a chamber whose natural frequency will match with that of the injector. In the full scale case, the first tangential mode matches with the injector, but we propose a new chamber design, whose radial mode matches with the injector. The dimensions of this new radial mode can be easily estimated to ensure this coupling exists. This simplication helps us exploit the axis-symmetric nature of the injector and chamber while ensuring that the required physics of the injector are easily captured. Also, running a 2D axis-symmetric simulation is computational cheaper than a full scale 3D simulation.

Speed of Sound	1231.3 m/s
Frequency	1957 Hz
Wavelength (mm)	629.3 mm
Radius (mm)	157.3 mm

Table 4: New combustion chamber properties and dimensions

The chamber dimensions were estimated using the speed of sound as 1231.3 m/s as this corresponds to the speed of sound with completely combusted products which are initialised in the chamber. Since this is a single injector based study, it is essential to ensure that the chamber is filled with fully combusted products. To simulate this environment, an equimolar mixture of CO_2 and H_2O was let into the chamber at a flow rate of 10 kg/s at a temperature of 3800 K. This flow rate was given to ensure that no back flow (numerically) occurs. The most critical region of the setup is the 'lip' where the oxidizer and fuel begin mixing. As expected this is a region of recirculation and also the most mesh sensitive region. Therefore it was decided to reduce the mesh sizing for this region while compensating for this increase in nodes with decreasing node count in regions where very simple flow is expected such as the injector post and regions far downstream of the injector. The mesh sizing of 7×10^{-6} m was used to discretize the lip region which is equivalent to 101 nodal points making this the area with the highest node density.

Properties	Fuel Inlet	Oxidizer Inlet
Material	Kerosene	Oxygen
Pressure	25.3 MPa	25.3 MPa
Temperature	488 K	687 K
Mass Flow Rate	0.477 kg/s	1.42 kg/s
Density	605 kg/m^3	129 kg/m^3

Table 5: Fluid Properties of fuel and oxidizer

Turbulence and Reaction Modelling

The k-epsilon realizable model was chosen for turbulence closure. This model is suitable for internal flows as in this case and is inherently more accurate than the standard k-epsilon model. The combustion reactions involved here are primarily between kerosene and oxygen. In cases such as these, with supercritical gas-like fluids involved, it is well known that the combustion is limited by the mixing of the reactants. This study is primarily focused on the effects of combustion on acoustics and hence only the heat release rate function is required. Therefore the Eddy Dissipation Model for combustion was chosen. This model uses the turbulence parameters k and epsilon to determine the rate of the reaction and hence the product concentrations and heat release. We must keep in mind that unlike most combustion reactions where the Ideal Gas Equation would suffice due to the high temperatures, here the Peng Robinson Equation of State[7] was chosen in order to estimate the densities of the incoming fuel and oxidiser correctly. The densities of these two fluids will determine the position of the flame as it directly influences the momentum carried by the fluids.

Simulation Setup and Initialization

The domain was initialized by setting all the nodal values as the values of the oxidizer inlet. This method was preferred over running an Euler simulation to obtain the initial field as the species equation cannot be initialized in this method. A cold flow steady state solution was first generated which was then used as the starting point for the transient combustion simulation. Initially first order upwind schemes were used for the discretization of flow variables, but as the solution progressed the schemes were switched to the QUICK scheme. The transient simulation was run for 10 flow times before statistics and other data (probes) required for analysis was collected. This is required to ensure that the simulation has reached a statistically steady/stationary state. As mentioned earlier, this setup has been validated by running both cold flow[3] and combustion[4] cases and validating them with literature data.

Results

The first check was to see whether the mean flame temperature is close to the adiabatic flame temperature expected (close to 3600 K) for these propellants. The mean static temperatures observed in both the cases (full injector and reduced injector) were close to 3630 K indicating that the results have satisfied the first check.

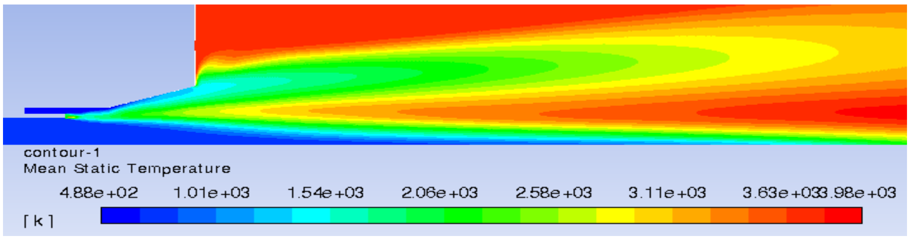

Fig 7: Full scale Injector Mean temperature

In order to analyse the pressure, axial velocity and heat release rates probes, at different locations on the domain were placed and temporal data was collected.

Name	X (m)	Y (m)
injector-inlet	0	0
injector-midpoint	0.0521	0
injector-outlet	0.1042	0
chamber-bottom	0.150	0
chamber-midpoint	0.150	0.079
chamber-top	0.150	0.158

Table 6: Probe locations on computational domain

In order to estimate the frequency of the oscillations of the field variables and see whether they match with the linear acoustic study performed earlier, the Fast Fourier Transform (FFT) was performed. The first peak observed in the FFT plot can be associated with the first mode of resonance between the systems and also indicates the coupling.

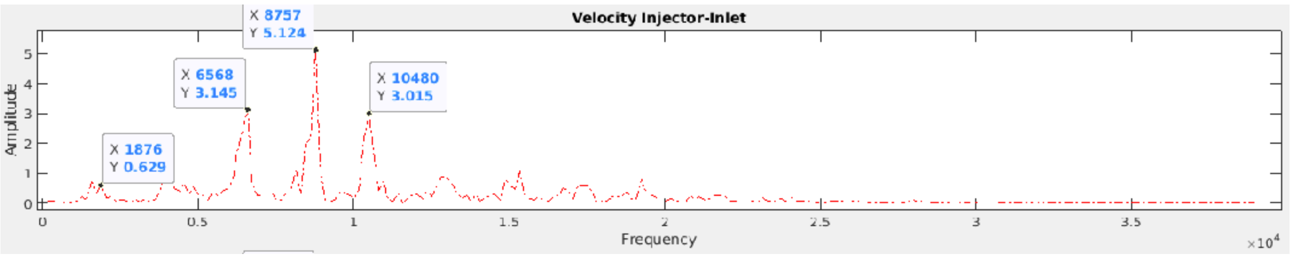

Fig 8: FFT indicating all the obtained frequencies

The amplitude of this FFT can be helpful in determining whether that particular frequency will be detrimental to the system or not. First the FFTs of the full injector case was studied and analysed followed by the reduced injector case (to ⅔ the initial injector post length). The FFT was performed on data collected from all the probe points but only a few plots are given below for representation. As seen in figure 8, frequencies higher than 4000 Hz also exist in the system. However, here we are focusing on frequencies below 4000 Hz as these are primarily responsible for the instabilities in the engine. Therefore the figures below focus on this new range.

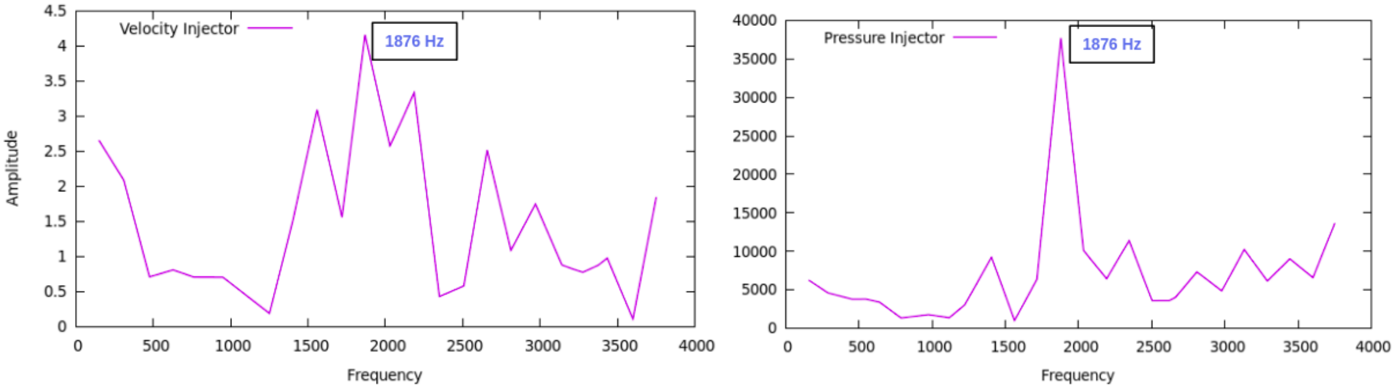

Fig 9(a): FFT of Injector Pressure(Pa) and Velocity(m/s) from from full scale injector simulation

The figures 9(a) and 9(b) clearly indicate a coupling between the acoustic modes present in the injector and the combustion chamber. The frequency of coupling is close to the expected frequency from the linear acoustic analysis.

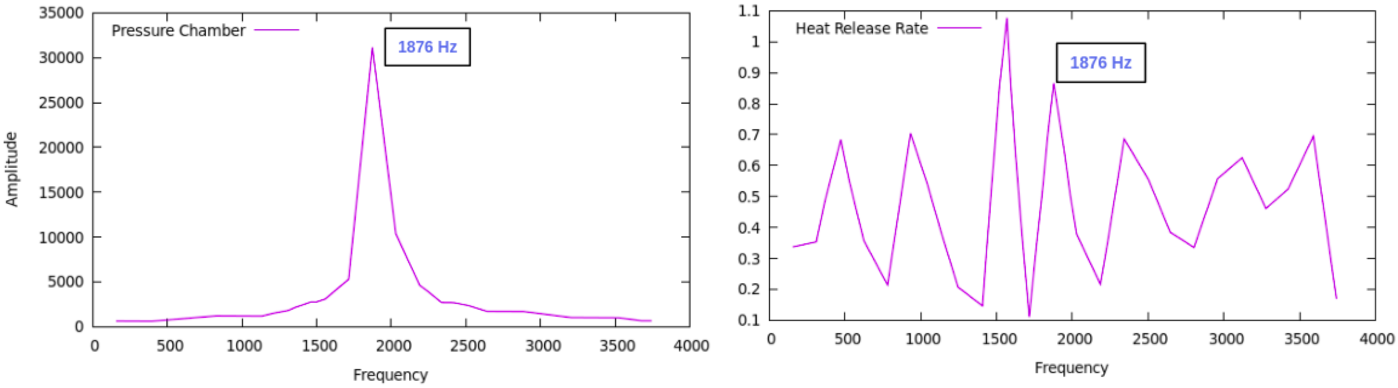

Fig 9(b): FFT of Chamber Pressure and heat release from full scale injector simulation

Even though higher frequencies seem to show higher amplitudes it is known that these frequencies are not achievable through experiments conducted. The same analysis was performed for the reduced injector to see whether the decoupling of the acoustic modes is achievable.

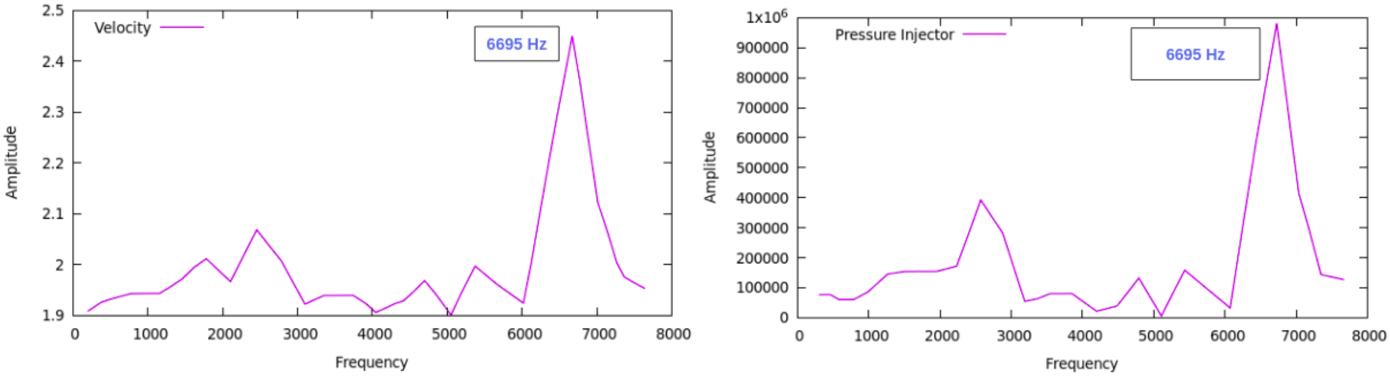

Fig 10(a): FFT of Injector Pressure(Pa) and Velocity(m/s) from reduced injector post simulation

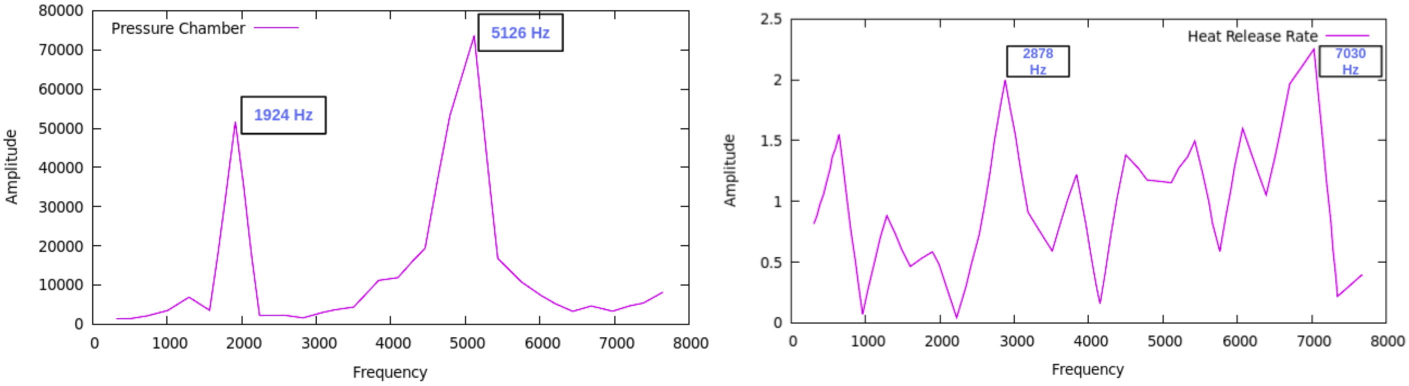

Fig 10(b): FFT of Chamber Pressure and heat release from reduced injector post simulation

The observations made from this set of simulations and analysis indicate a clear possibility to decoupling the system modes. The frequencies of the system have shifted to higher values but more importantly their amplitudes have come down indicating that this is not a natural mode coupling. This is indicative of the fact that a perturbation in the chamber might oscillate the field in the injector but the amplitudes of these variations will not be large enough to be considered a major problem from a combustion instability point of view. The heat release rate frequencies indicate that they will not drive the instability as their frequencies do not match with those of the chamber. In this case the chamber oscillations will automatically be killed by other absorptive surfaces and will not be driven due to the injector dynamics. Furthermore, the injector will not respond to the changes in the chamber, ensuring an independent system exists acoustically. And finally, with this simplification, the complex arrangement with protuding injectors could also be eliminated.

Inferences and Conclusions

This paper showcases a study on the acoustic coupling with the combustion occuring in the injector of the RD-170 engine. This engine design has relevance even today as most modern engines are derivatives of this system. The numerical method followed has been validated by generating results and comparing it with literature data. Additional importance has been given to ensure the thermochemical properties associated with the supercritical fluid combustion have been captured. A linear acoustic study has been conducted to provide an estimate of the expected frequencies occuring naturally in the system. Since the mode occuring in the injector is longitudinal, a two dimensional study of the injector is valid and in order to couple it with the chamber, the dimensions of the chamber are estimated to couple the injector's longitudinal mode with the radial mode of the chamber. The combustion study conducted on the existing injector design and the proposed reduced injector design provide data which shows the required decoupling in the system. The existing design uses baffles on the injector plate to provide stability while coupling the injector intentionally in order to provide damping. The reduction in the size of the injector post results in decoupling the system which ensures that the chamber perturbations cannot excite the injector and create a feedback loop with the combustion reaction. Since no coupling occurs, usage of appropriate absorptive material on the walls are more than sufficient to kill the chamber oscillations. Furthermore, a full scale 3D simulation (single and multiple injectors) will be run to visualize the tangential mode and validate this equivalent radial mode model. The effect of swirl will also be studied and finally an LES simulation will be conducted to study how turbulence is interacting with the acoustic modes of the injector

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