Design and Mathematical Modeling of Fuel Feed System for Dual Fuel SCRAMJET

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Abstract

A Fuel Feed System (FFS) is designed to supply fuels for a Dual Fuel Scramjet engine. The system design is carried out based on the operational requirements of flow rate, pressure, duration within the envelope constraints. The scramjet engine consists of an effervescent injector with liquid hydrocarbon as the main fuel. Gaseous Hydrogen is used for pilot ignition and for emulsifying the liquid hydrocarbon. Hydrogen gas for both the requirements are met through a single source and supply system. The liquid hydrocarbon storage system consists of a standalone propellant tank with positive expulsion device and cavitating venturis. Mathematical modelling is done on the system and from the model outputs, the operational efficacy of the feed system throughout the flight duration is ensured.

Keywords: *Hypersonic flight, scramjet engine, fuel feed system, effervescent injector*

1. Introduction

SCRAMJET is a type of air-breathing engine in which the gas flow is supersonic throughout the engine including the combustion chamber. The combustion occurs at supersonic velocity. In scramjet propelled vehicles, fuel has to be carried on-board and once the vehicle reaches required Mach (Above Mach 5), Scramjet can be activated where it takes air (oxidizer) from atmosphere and propels the vehicle using supersonic combustion. Major advantage of using scramjet is that it has a higher specific impulse when compared to conventional rocket engines. Using scramjet engines, it's easy to achieve sustained hypersonic flight for air breathing rockets. A Scramjet engine is totally free from rotating or moving parts.

The major challenge in scramjet is attaining stable supersonic combustion at higher Mach numbers within the low residence time of oxidizer and fuel in chamber. Gaseous hydrogen is used as fuel in scramjet engines due to its higher calorific value, wide flammability range, higher mixing rate with oxidizer and low ignition delay. But on the other hand, GH_2 demands huge storage space due to its lower density. This results in an increase in the size of the launch vehicle which in turn increases the drag and reduces the overall payload capacity. Alternatively, using liquid hydrocarbon which has higher density impulse helps in optimizing the system design within the space constraints. Liquid hydrocarbon has to be injected at the required pressure, and atomized and mixed with ram air to have a proper and stable combustion. The operating sequence will start with a pilot ignition with GH_2 followed by the admission of emulsified liquid hydrocarbon into the engine. The flame from the pilot ignition would help sustain the combustion of the liquid. The scramjet engine under our study operates an effervescent injector. GH_2 is used to emulsify the liquid hydrocarbon flow for a better atomization. The Fuel Feed System (FFS) for scramjet should contain storage tanks for the liquid and gaseous fuels, flow controlling elements, pressure regulating devices, flow lines etc. This work concentrates on the design and mathematical modeling of the FFS.

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2. LITERATURE REVIEW

The design and mathematical modeling of the system is carried out using independent elemental models and equations mentioned in [1]. The transient analytical model in [1] has flow and thermal models for the gas bottle, fluid flow lines and flow control orifice. Additionally, a thermodynamic model for the pressure regulator is added based on [2]. The solution of flow with friction and heat transfer through the flow lines are based on [3]. Junction elements are added based on [4].

3. FUEL FEED SYSTEM DESIGN

Based on the operating requirements, the FFS is designed. There are two independent feed systems within the FFS. One with Gaseous Hydrogen and the other with the liquid hydrocarbon. Gaseous Hydrogen feed system is designed to store, regulate and deliver the gas at the specified pressure to the scramjet engine. Figure 3 shows the flow schematic of the gaseous hydrogen feed system. A dome loaded pressure regulator is used to regulate the high-pressure gaseous hydrogen to the required lower pressure. Gaseous nitrogen is used for loading the GH2 regulator dome. At the inlet to the combustion chamber, calibrated flow control orifice is used to ensure precise control on the mass flow rate.

Similarly, a liquid circuit is designed to store the liquid hydrocarbon and inject the same to the combustion chamber at the required pressure and flow rate. From Figure 4, it may be noted that a positive expulsion device is used for the tank pressurization. GN2 is filled in the gas side of the pressurization diaphragm. The liquid storage tank is of stand-alone type as there is no active pressurization circuit for the ullage gas. The liquid would flow in blow-down mode during the scramjet engine operation. Cavitating venturis are used to regulate the injection pressure of the liquid and to maintain steady flow irrespective of downstream pressure oscillations.

The major components of Fuel Feed system are as follows,

- Liquid storage tank.
- Hydrogen storage bottle.
- Hydrogen pressure regulator.
- Cavitation venturi for liquid hydrocarbon.
- Flow controlling orifices.

3.1. LIQUID STORAGE TANK

A rubber based positive expulsion device is used in the tank to ensure the continuous flow of liquid hydrocarbon from the tank bottom. Figure 1 shows a typical tank with positive expulsion device. A positive expulsion tank contains a diaphragm which separates the fuel medium from the pressurant. Fuel is stored at the bottom of the tank, whereas pressurant is stored above the diaphragm. Due to system envelope constraints, a standalone tank was used for the storage of the liquid, without an active pressurization system.

3.2. HYDROGEN STORAGE BOTTLE

Gaseous Hydrogen is required for both ignition and emulsification of the liquid hydrocarbon. Storing gaseous hydrogen at a high pressure and regulating it to lower pressure helps in designing the system within the available system envelope. A Composite spherical bottle is designed to store gaseous Hydrogen at high pressure (Figure 2).

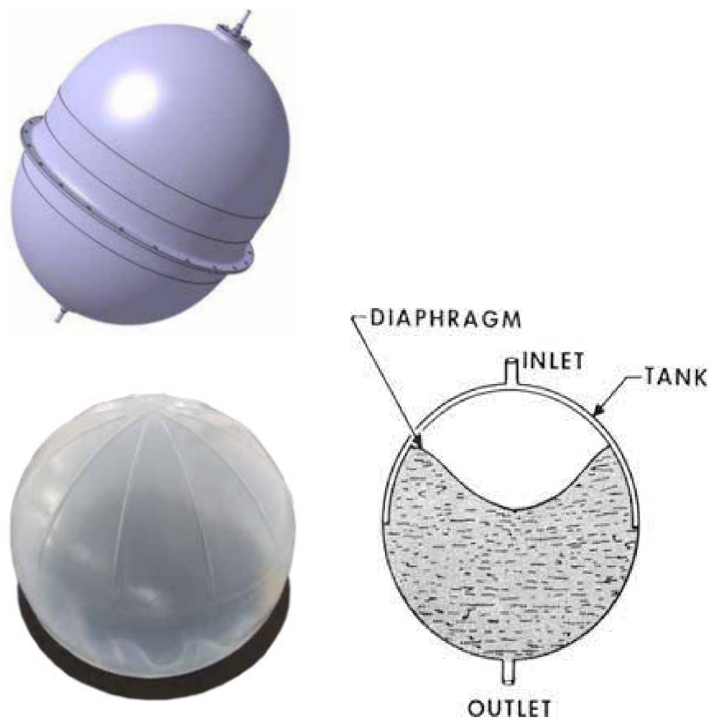

Figure 1: Positive expulsion Tank for liquid storage (Courtesy: https://www.space-propulsion.com/brochures/propellant-tanks)

Figure 2: Composite overwrapped pressure vessels for gas storage [6]

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3.3. HYDROGEN PRESSURE REGULATOR

A dome loaded pressure regulator is designed to regulate gaseous hydrogen from the storage pressure to the required injection pressure. The regulated pressure would be set considering the pressure losses in the feed system downstream to the regulator. The dome loading is supplied by Gaseous Nitrogen from a separate command system.

3.4. SEQUENCE CONTROL VALVES

The sequence of planned scramjet flight is shown below,

Sl. No	Event
1	Injection of GH_2 for pilot ignition
2	Injection of emulsified liquid hydrocarbon
3	GH_2 flow stops

The aforementioned timed sequence of operation is implemented by using sequence control valves.

3.5. FLOW CONTROL ORIFICES

The mass flow rate of GH_2 into the engines are controlled using choked orifices. The orifices avoid the coupling between the pressure oscillations inside the engine combustor and the GH_2 feed system.

3.6. CAVITATING VENTURI FOR LIQUID HYDROCARBON

A cavitating venturi is designed to deliver the liquid at the required injection pressure. The device is designed to have a pressure recovery sufficiently enough to provide the required injection pressure to the scramjet engine injectors. The cavitating venturis ensure decoupling of the liquid feed system from the engine injector and combustor.

4. MATHEMATICAL MODELLING

4.1. GASEOUS HYDROGEN FEED SYSTEM

The gaseous hydrogen feed system is modelled using 13 elements and 16 nodes. Equations on the conservation of mass, momentum and energy are simultaneously solved on all the nodes to determine the mass flow rate, pressure and temperature at each node. The details are shown in Figure 3. Three junction elements are used in the system model. The model outputs are shown from Figure 5 to Figure 8.

4.2. LIQUID SYSTEM

The liquid system is modelled using 14 elements and 17 nodes. At each node, the conservation of mass and momentum are solved to obtain the mass flow rate and pressure. The model outputs are shown from Figure 9 to Figure 12.

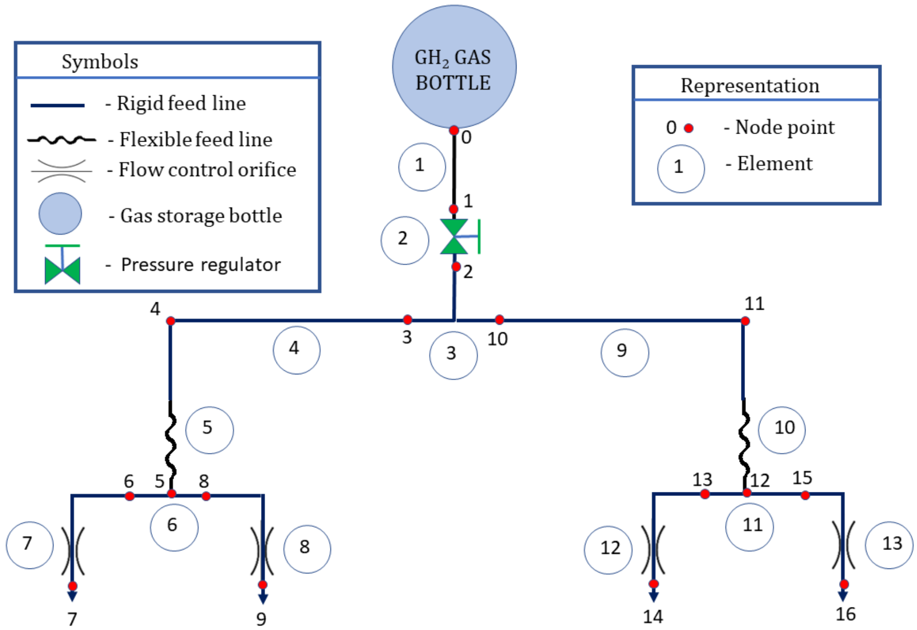

Figure 3: Mathematical model of GH2 feed system

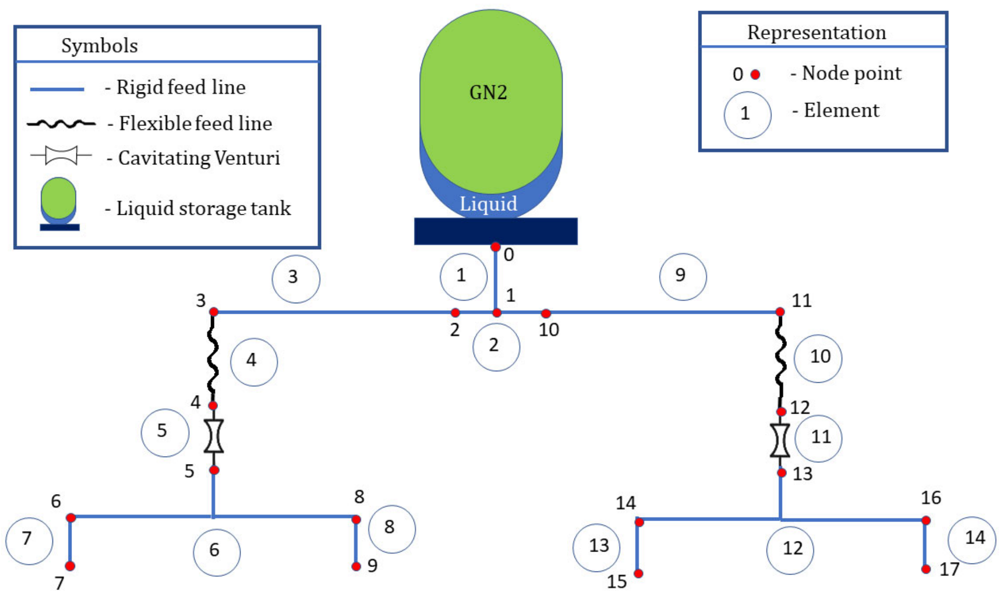

Figure 4: Mathematical model of liquid feed system

5. Result and Discussions

The temperature in the GH_2 bottle drops due to adiabatic expansion (Refer Figure 5). The flow control orifices are designed to maintain constant flow rate at constant inlet pressure and temperature. The GH_2 regulator maintains constant pressure at the inlet of the control orifices. The main flow rate and the emulsification flow rate of GH_2 increases as a result of the increase in gas density due to reduction in bottle temperature. Figure 8 shows the variation of regulator exit temperature versus time and inlet temperature. The rate of change in the emulsification flow rate reduces as the main flow is cut-off at 2 s. Calibrated flow control orifices are passive flow control systems. Steady flow rate of GH_2 in the system can be made by the using a flow control valve which is an active flow control device. But to control the flow using such a valve, a mass flow measurement device and associated instrumentation is also required, which increases the system complexity. Present system configuration is adopted since, the minimum flow rate requirement of GH_2 is met. The increase in GH_2 flow rate as shown in Figure 6 has two effects. It reduces the gas bottle pressure at a rate that is higher than expected. Also, the increased flow rate induces a higher pressure drop in the feed lines. The second problem is solved by appropriately sizing the feed lines. The first problem is solved by increasing the pressure rating of the gas bottle using a composite overwrap. Both the solutions are arrived at considering the system envelope constraints. The envelope constraint on the bend radius of the feed line from gas bottle to regulator decided the maximum line size which could be used. The maximum outer diameter of the composite gas bottle also was decided by the system envelope constraint.

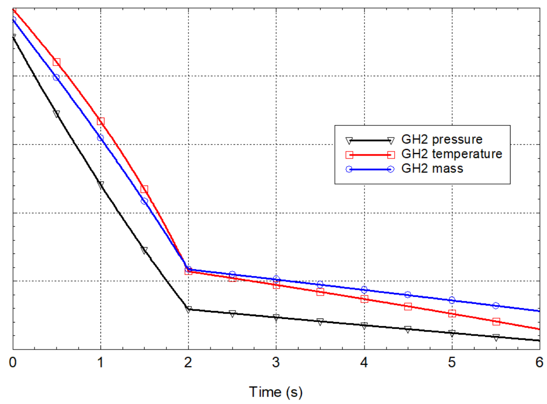

Figure 5: GH2 bottle parameters

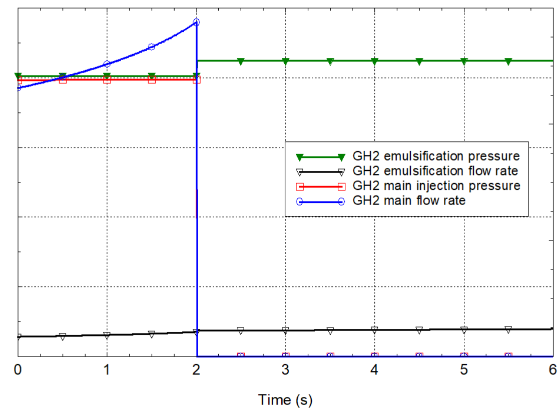

Figure 6: GH2 injection parameters

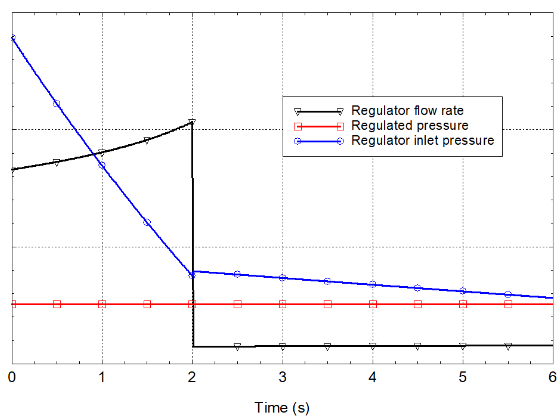

Figure 7: GH2 regulator parameters

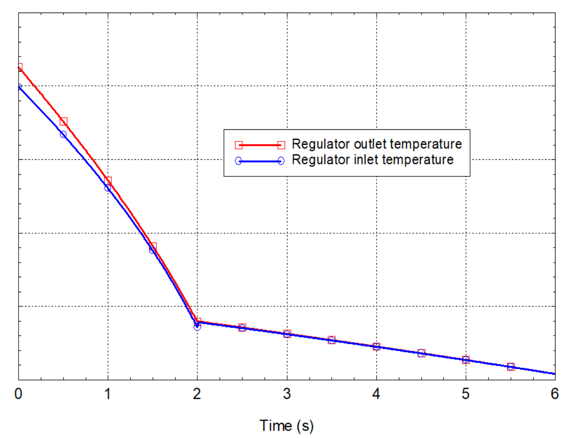

Figure 8: GH2 regulator thermodynamics

Gaseous hydrogen system model outputs

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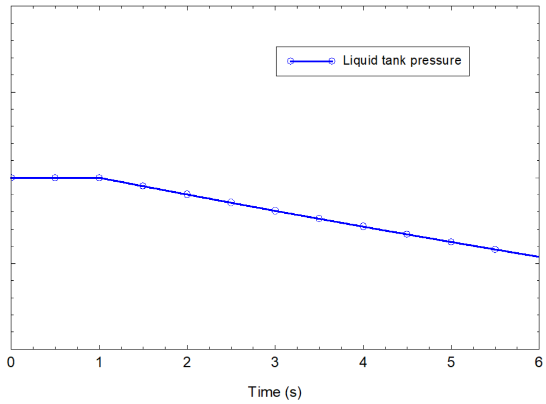

Figure 9: Liquid storage tank parameters

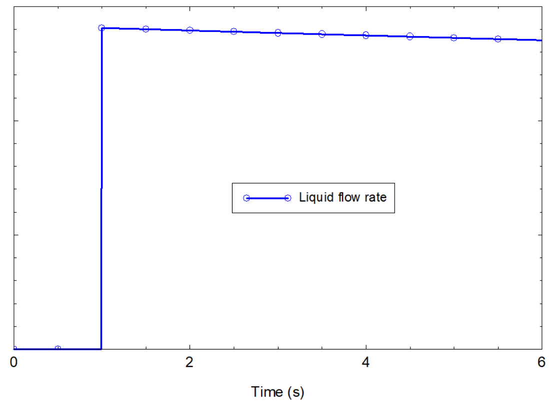

Figure 10: Liquid hydrocarbon flow rate

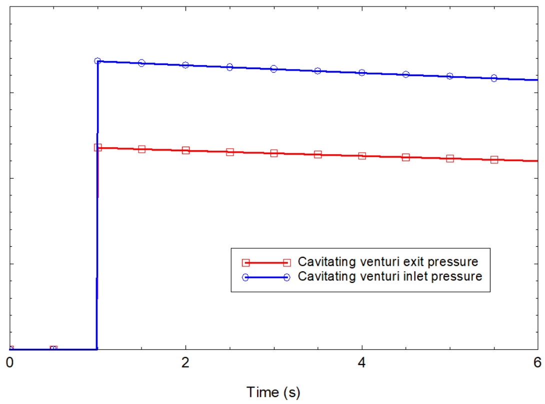

Figure 11: Cavitating venturi parameters

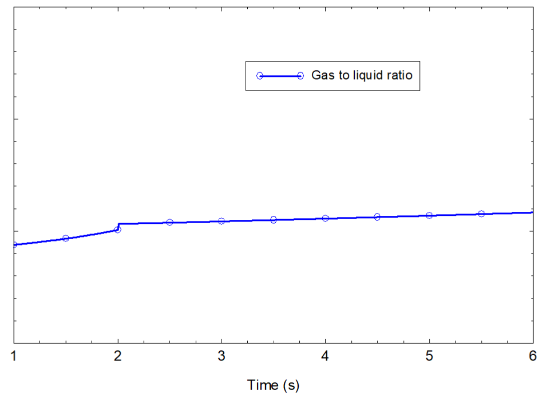

Figure 12: Gas to liquid (GLR) mass ratio

Liquid feed system model outputs

In the absence of an active pressurization system, the liquid storage tank operates in a blow-down mode. It results in reduction of the tank pressure during operation as shown in Figure 9. The reduction in tank pressure also results in a reduction in liquid hydrocarbon flow rate as shown in Figure 10. The presence of cavitating venturi in the system has two effects. The first one is mentioned earlier. The second effect is the presence of recovery factor. The recovery factor which is less than unity ensures that the variation of the venturi downstream pressure is less than that of the upstream pressure, as seen in Figure 11. Hence, the venturi also provides some damping to the upstream pressure variations. The sizing of the venturi is done to ensure the minimum liquid flow rate to the engine at the lowest inlet pressure. A standalone type propellant tank is chosen for the liquid hydrocarbon due to the system envelope constraints. The high volume of the tank ensures a variation in ullage pressure and flow rate within the acceptable limits.

The reduction in liquid flow rate and the increase in GH_2 emulsification flow rate results in an increase in Gas to Liqui Ratio (GLR) for the scramjet engine's effervescent injector. An increase in GLR results in reduction in mean droplet size [5], which results in an enhanced engine performance.

6. Conclusions

A Fuel Feed System is designed for Dual Fuel Scramjet engine using a system approach, considering operational requirements and envelope constraints. Mathematical modelling of the system shows that the throughout the operating duration, the feed system parameters are meeting the operational requirements.

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