Design and Fine Tuning of a Low Thrust Engine's Pintle Injector

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***Abstract*— an injector injects and keeps a check on the flow of liquid propellants into the combustion chamber, helps in atomization, and assists the propellant mixing. Pintle injector is one of its kinds among the whole category of injectors. The central, singular injection geometry of the pintle injector, results in a combustion chamber flow field that is highly unique. These dissimilarities lead to various operational features of great benefit to the design of rocket engine, its performance, and ease of testing.**

In this paper a pintle type injector is first modeled parametrically, initially on MATLAB® and later, on MATHEMATICA®. Its geometry is then optimized by varying the parameters, subjecting to maximize the throttling range and keeping the mixing ratio (oxidizer to fuel ratio) constant. Low thrust pintle engine has been assumed with thrust of 300 Newton, whereas ethanol and nitrous oxide have been taken as fuel and oxidizer respectively as this combination is almost non-toxic to human body and is readily available. Chamber pressure of 50 bars has been assumed. Mixing ratio of 4.54 has been maintained throughout, and the Sea level specific impulse obtained is around 244.5 seconds. In the second phase the model has been fine-tuned, flow rates have been adjusted according to the requirements.

Keywords—atomization; throttling range; mixing ratio; specific impulse; fine tuned.

I. Introduction

The main function of an injector is to inject and keep a check on the flow of liquid propellants into the combustion chamber, according to Sutton in [1], it helps the liquids to split up into small droplets (known as atomization), and assist the propellant mixing in a proper mixing ratio of fuel and oxidizer, which remains constant throughout the cross section of combustion chamber. The injector of a combustion chamber and the carburetor of an internal combustion engine almost perform the same task. The task of fuel injection has been done by different types of injector. Broadly injectors have been classified into two main categories; impinging and non-impinging.

Talking about Liquid Rocket Thrust Chambers Yang [2] says, pintle injector is one of its kind among the whole category of injectors that have been implemented in liquid rocket engines. It is used in bipropellant liquid rocket engines, in which one of the propellants flows down the inside of pintle and is ejected radially outwards through a series of holes or slots near the tip of the pintle while the other propellant leaves the manifold through an annular sheet around the pintle base (impinging type). As a result of the collisions of the jets, one is being ejected radially, with the thin sheet of liquid, dynamic mixing and fine droplet formation of the propellants take place. The central, singular injection geometry of the pintle injector, results in a combustion chamber flow field that is highly different from the flow fields of commonly used rocket engines. These dissimilarities lead to various operational features of great benefit to the design of rocket engine, its performance, and ease of testing.

In [3] Dressler mentions the performance of pintle injector design, says that it can deliver high combustion efficiency (typically around 96—99%) and helps in carrying out some important features, such as wide throttle range and face shutoff of the injector(both flows are completely stopped simultaneously). The pintle injector has been used in very challenging applications, due its unique capabilities, such as an 8,200 Ibf engine which throttled over a range of 19:1. Pintle injector is ideal for gelled propellant applications and has made the first flight of a gel propellant tactical missile successful. Its ease of manufacturing makes it suitable for low cost engines. The TRW pintle engine has a demonstrated heritage of being low cost, highly reliable and safe to operate.

In [4] Austin successfully fabricated a modular pintle engine and tested the design with nontoxic hypergolic bipropellants (hydrogen peroxide and a methanol fuel laced with catalyst). Rapid, reproducible ignition has been demonstrated with this propellant combination under both single- and multiple-pulse firings. Rise times of 80 ms have been observed under both single- and multi-pulse conditions. Whereas roughness in the combustion has been seen, and no organized frequency content was observed in the measurements of chamber pressure. About 10 percent combustion roughness levels are attributed to the modular nature of the engine.

Initially an engine has been assumed, mass flow rates adjusted and a pintle injector is designed according to the requirements, a specific working range is adjusted and injector is later on fine-tuned to achieve that. Details of the processes adopted are discussed comprehensively.

II. ASSUMPTIONS

A. Engine

A small liquid bipropellant pintle engine has been assumed. It has been assumed that injector is placed at the end of the reservoir, where pressure is maximum and velocity is approximately equal to zero. Specifications of the engine are given below;

TABLE I. ENGINE SPECIFICATIONS

Parameters	Specifications
Thrust	300 N
Chamber Pressure	50 bars
Injector Inlet Velocity	0 m/s
Injector Exit Velocity	20 m/s

B. Propellants

Tokudome in [5] tested several propellant pairs and found ethanol and nitrous acid very efficient functionally. It is classified as the liquid propellant pair with non-toxic, user-friendly, and storable, since N_2O and ethanol are generally used as the inhalation anesthetic and the food additive. The target of his study was to build a safe and responsive propulsion system which can be used in an upper-stage propulsion system for JAXA's next-generation solid launcher. The propellant selection for the testing was done on the basis of the following three priorities;

- Good operability (non-toxic and storable at room temperature),
- Ready availability and cost effectiveness (commercial-off-the-shelf and delivery system currently used)
- Performance and originality (space application and the world's first study).

As a result of extensive testing nitrous oxide (N_2O) and ethanol has been selected as the only propellant combination which is almost non-toxic to human body. System operability has been improved by the fact, that the propellants have extremely low toxicity. Performance comparison has been done with typical propellant combinations that are commonly used, under specific conditions. The vacuum specific impulse of nitrous oxide and ethanol is slightly lower than that of solid propulsion, and the density specific impulse can be improved by using nitrous oxide near its freezing point. The density at -80^{o} C is 50 percent higher than that at 20^{o} C, and then, the density specific impulse improvement observed is 38 percent under constant C* efficiency condition. The value is slightly higher than the Liquid oxygen and methane (LO_x/CH_4) propulsion's.

TABLE II. PROPELLANTS' SPECIFICATIONS

Parameters	Specifications
Fuel	Ethanol
Density of fuel	789 kg/m3
Oxidizer	Nitrous Oxide
Density of oxidizer	913 kg/m3
O/F	4.5
Isp	241 s

TABLE III. INJECTOR SPECIFICATIONS

Parameters	Specifications
Propellant mass flow rate	0.1251 kg/s
Fuel mass flow rate	0.0226 kg/s
Oxidizer mass flow rate	0.1025 kg/s
Pressure Drop	5 bar
Area of fuel	4.24x10^-04 m^2
Area of oxidizer	0.0015 m^2

III. METHODOLOGY

Firstly considering thrust and pressure drop across the injector, mass flow rates of the propellants are calculated. A particular injector design is selected and an initial 2D sketch is made on the CREO. The coordinates of the sketch is then transferred to the MATLAB®, where flow areas are found and adjusted from the centerline according to the mass flow rates. Parametric modeling of the design takes place in MATLAB®. Propellants (both fuel and oxidizer) flow rates are varied with the sleeve position and represented graphically. A reference fuel (internal) flow is taken and outer oxidizer flow is adjusted accordingly, keeping the operating point in the mid of the flow range. Difference in the required and obtained flow rates are calculated for both internal and external flows.

In the second stage, design is shifted to MATHEMATICA®, fine tuning is done and flow rates are matched with the required rates, by varying the geometry parameters one by one. Very fine adjustments in flow rates can only be done using this step. If any design failed to give the required flows w.r.t the sleeve position, conclusions are observed and a new design is proposed with the modifications that caused the failure of the previous design.

Author has worked on many designs, but only single case is presented in the paper, in which iterative work is done on three designs. Failure of first two designs lead to the third design, which met the requirements with reasonable accuracy.

A. Designs

A case has been presented in the paper, in which author has worked on three designs. Initial design was a simpler one whereas the second and third designs were the modified forms of the first one. 2D diagrams of pintle injectors are shown below; figure 1, 2 and 3 represents the design 1, 2 and 3 respectively. Initially design 1 was taken and flow areas were found, the centerline was considered as reference line. An operating point was set; at that point desired mass flow rates were adjusted both for the fuel and the oxidizer. Fuel flows from the area between pintle and movable sleeve; it's the internal flow, whereas oxidizer flows from the area between sleeve and the outermost section and known as external flow. All designs gave specific mass flow rates w.r.t the sleeve position, graphs have been drawn on MATLAB® to see the behavior of every injector and compare it with the required behavior, calculate the differences and minimize them as much as possible. The flow controlling areas have been considered in the designs.

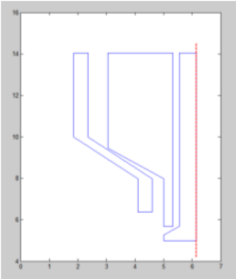

Figure 1 - Design 1

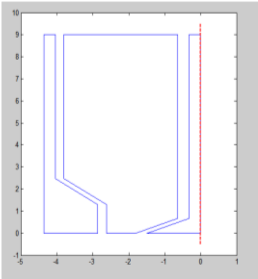

Figure 2 - Design 2

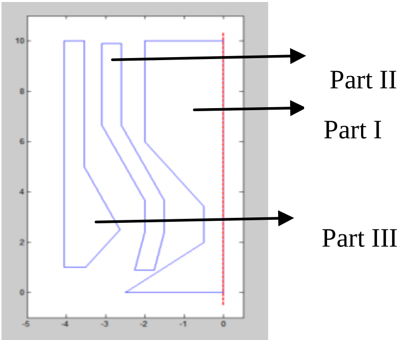

Figure 3 - Design 3

IV. INJECTOR DESIGN TOOL

A design tool is created on MATHEMATICA®. Figure 4 shows the GUI of the design tool. The GUI is user friendly and comprehendible. Tool can generally be divided into three columns; first column gives an overview of the dimensions of the pintle injector and later on provides a very brief introduction of the design tool and the developer. The second column mainly consists of 2D geometry of the pintle injector, which can be altered by altering the dimensional parameters provided in the last column, and three graphs. First and second graphs represent the mass flow rates of fuel and oxidizer respectively. Internal flow is fluid flow whereas external is the oxidizer one, both flows are varied with the sleeve position i.e. u in x-axis and y-axis constitute the mass flow rates. Last graph shows the mixing ratio of both propellants, mixing ratio is the ratio of oxidizer flow to the fuel flow. Like the other two graphs, mixing ratio in y-axis is varied with the sleeve position in x-axis.

The third column shows the dimensional parameters that are linked with the 2D geometry of the pintle injector, at the top of second column and they are basically used for varying the geometry of the injector and seeing its effects on the mass flow rates and mixing ratio.

Part I represents the geometry parameters of pintle (blue colored), Part II represents movable sleeve (orange colored) and Part III represents the outermost section (green colored). Red dotted line at the right most of the geometry diagram shows the centerline, the complete 2D geometry is revolved 360 degrees around the centerline to achieve the 3D diagram of the injector.

User can import any types of related geometry in the tool and can fine tune it. Geometry has to be initially in MATLAB® so that design import can be made possible.

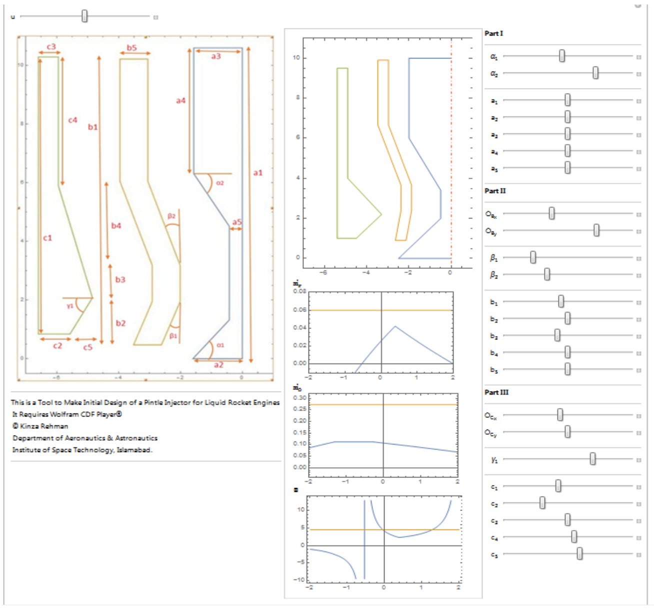

Figure 4 - Injector Design Tool

V. RESULTS AND CONCLUSIONS

A. *Injector modelling*

A pintle injector has been modeled and fine-tuned successfully, right from the initial sketch and it will be prototyped in later stage, where experimentation will take place and empirical relations will be derived.

Author has worked on various designs, which has made the general design somewhat predictable, which will further help to design pintle injector according to the required behavior.

Post design processing is very important, as required flow curves can only be achieved by tuning the designs finely in the *Injector Design Tool*.

B. *Flow nonlinearity*

Nonlinear behavior of flow has been observed during the design phase, it was one of the major issues due to which author was unable to get the required pattern of propellant flow. Figure 5 shows the flow nonlinearity w.r.t sleeve position and this behavior dominants in designing injectors for larger flows however, this behavior can be minimized by the specific contour design of the injector.

C. *Computational fluid dynamics (CFD)*

A CFD analysis of the injector has been done in order to observe the resulting flow fields inside combustion chamber and circulations patterns have been observed. The circulations patterns are responsible for the flow stability and a unique flow pattern inside combustion chamber. The impingement points of the both the propellants have been highlighted in the figure 6 and 7, showing velocity and pressure contours of the flow.

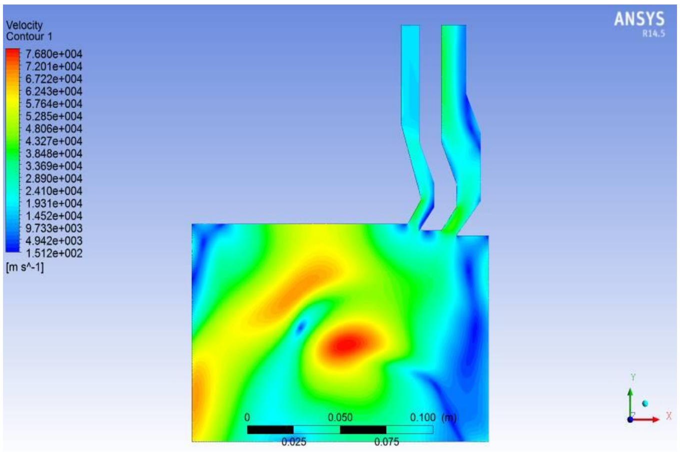

Figure 5 - Velocity Contour

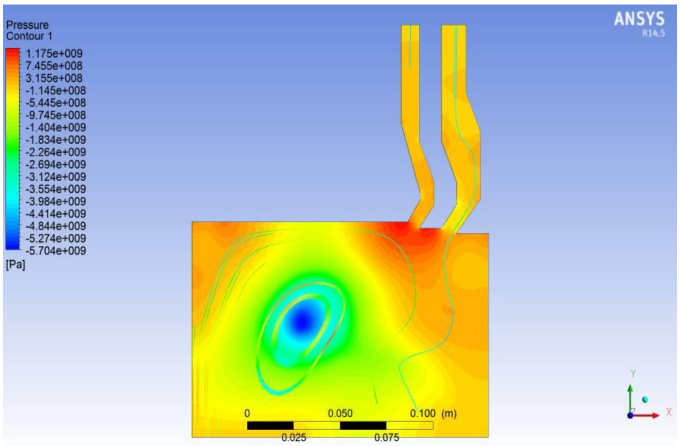

Figure 6 - Pressure Contour

ACKNOWLEDGMENT

The Author would like to thank Mr. Hafiz Zeeshan Iqbal Khan, Mr. Bilal Usmani, Mr. Atif Ali and Department of Aeronautics and Astronautics, Institute of Space Technology, Islamabad for their support and motivation during the research and design phase.

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