Design and Analysis of a Single Stage, Impulse Gas Turbine for LOX/RP1 Gas Generator Cycle Based Rocket Engine

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Abstract*— *A gas turbine is a heat engine in which the energy of the gas is transformed into work. First, the energy in the gas expands through a nozzle and is converted into kinetic energy. Then, that kinetic energy is converted into work on rotating blades. The aim of this project is to design a Gas Turbine for a Cryogenic Rocket Engine. The project necessitates in it the conceptual, preliminary and detail design phase of the Gas Turbine configurations. Furthermore the initial design of Gas Turbine has been described. Various codes have been developed to assist in the design, parameter matching and analysis of Gas Turbines intended for use in Rocket Engines tuned to operate in a variety of performance regions. Thorough study of the Gas Generator Cycle in a liquid propelled system was completed after which the initial design and power matching of the Gas Turbine for a Cryogenic Rocket Engine was performed hence completing the initial design phase of the project after which parameter matching, optimization and analysis process are performed. Optimization required help of MATLAB to generate rigorous code to help with the iterative process of parameter matching such as flow rate and horse power, as sole purpose of this designed turbine is to get generate enough energy to drive propellant pumps while working on the gas provided from combustion chamber, while also keeping in mind the structural restraints of the turbine. Since the project was not an individual project hence different values are taken from other groups in the process of turbine design.

I. Introduction

To date rockets are the only means of access to space and interplanetary missions. Rockets are one of the most amazing endeavors man has ever undertaken for exploration of space. A big part of increasing interest in the field owes to the complexity of the subsystems and their interdependence in development of an operational rocket engine. This has introduced vacancy of constant and ever expanding research in the field. Cryogenic rockets are sophisticated systems developed to obtain higher energy from combustion systems. This is usually translated in high values of specific impulse (~350s Vac) from these rockets. The propellant combination of Liquid Oxygen (LOx) and RP-1 (Kerosene) have proved to be the cheapest propellant for typical LRE missions. Notable examples of engines designed on the combination are Russian RD- series engines and American Merlin rocket engines.

The results and trend presented here are a result of a fully integrated MATLAB program developed to aid in design of a gas generator based LRE system. The program contains routines for engine performance, Injector design, heat transfer analysis and provides manufacturing design parameters of the designed engine. The results obtained were validated against existing data in literature. The program is run in a routine to obtain results for a number of data points from 15 bar to 50 bar combustion pressure at a varying mixing ratio of 2.0 to 2.4.

II. Gas Generator Cycle

The gas generator cycle ensures continuous reliable operation with reduced complexity compared to other closed rocket engine operation cycles. This makes these engines ideal for the renewed need for access to low earth orbit and beyond for typical space missions. The gas generator cycle shown in the adjacent figure is the simplest schematic of a pump-fed system operating with liquid propellants. The system features a finite number of restarts and is appreciated for their longevity and capability for throttling and potential of delivering higher specific impulse compared to the LRE volume and complexity. The system however involves additional components such as gas generators. The pressure requirements of engines operating on this cycle lie between Expander and staged combustion cycle operated engines.

III. LOX- RP1 Propellant Engines

The combination of LOX-RP1 has been used to propel rockets for a very long time. The properties of the combination are readily available for use to researchers. The combination provides the cheapest means of propulsion to space with reliability of operation. However the RP1 propellant has a tendency of

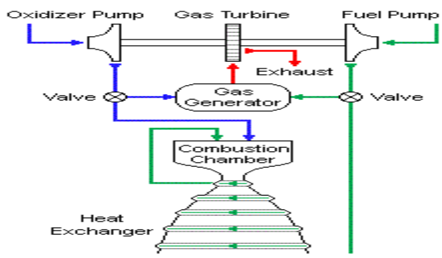

Figure 1 Gas Generator Cycle

coking under high temperature. The affect results in producing a layer of solid carbon deposits on the chamber and nozzle walls which further restrict heat flow through the chamber walls. The propellant combination produces a specific impulse of around 280 to 310 s at sea level.

IV. DEISGN METHODOLOGY

The design of a turbine for a given power requirement is relatively straightforward. Following methodology is adapted to obtain the design stator and rotor of the turbine.

Degree of Reaction:

First of all degree of reaction is set for the turbine to be designed on the basis of input parameters, output parameters and design constraints.

In our case the chosen configuration of degree of reaction is *negative* which means an Impulse Turbine is to be designed.

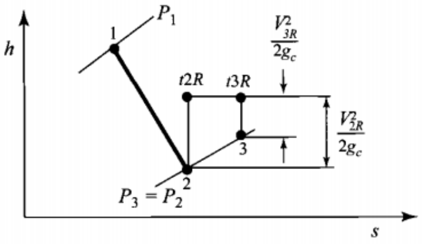

Figure 2 Impulse Stage h-s Diagram

Adiabatic Efficiency:

The adiabatic efficiency is the ratio of the actual energy output to the theoretical isentropic output for the same input total state and same exit total pressure.

$$\eta_t = \frac{\text{actual } \Delta h_t}{\text{ideal } \Delta h_t} = \frac{h_{t1} - h_{t3}}{h_{t1} - h_{t3s}}$$

Stage Loading and Flow Coefficient:

The *stage loading coefficient* is the ratio of the stage work per unit mass to the rotor speed squared,

$$\psi \equiv \frac{g_c\, \Delta h_t}{(\omega r)^2} = \frac{g_c\, \Delta h_t}{U^2}$$

The ratio of the axial velocity entering the rotor to the rotor speed is called the flow *coefficient,*

$$\Phi \equiv \frac{u_2}{\omega r} = \frac{u_2}{U}$$

Following figure shows the range of these coefficients for several types of turbines,

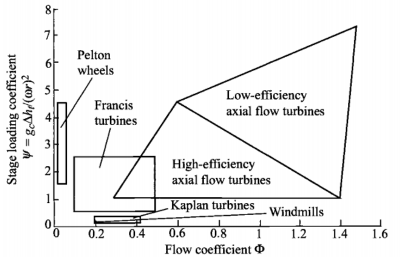

Figure 3 Stage Loading vs Flow Coefficient for various turbine types

Velocity Diagram:

Solution of Velocity Diagram provides angles for the nozzle outlet, blade inlet and outlet which helps in the process of determination of impulse turbine blade profile, thickness and breadth.

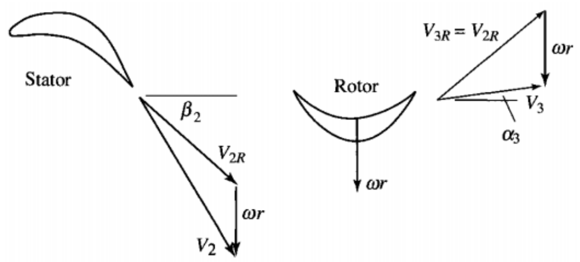

Figure 4 Velocity Diagram for Impulse Blade

Solution of the Velocity diagram is done by the following list of equations,

$$V_{\theta 1} = V_1 \cos\alpha \qquad W_2 = k_b W_1$$

$$V_{a1} = W_{a1} = V_1 \sin\alpha \ \text{(axial component)} \qquad V_{a2} = W_2 \sin\gamma$$

$$W_{\theta 1} = V_{\theta 1} - V_b \qquad W_{\theta 2} = W_2 \cos\gamma$$

$$W_1 = \sqrt{W_{a1}^2 + W_{\theta 1}^2} \qquad V_{\theta 2} = V_b + W_{\theta 2}$$

$$\beta = \tan^{-1}\frac{W_{a1}}{W_{\theta 1}} \qquad V_2 = \sqrt{V_{a2}^2 + V_{\theta 2}^2}$$

$$k_b = \left(0.892 - 6.00x10^{-5} W_1\right)^{1/2}$$

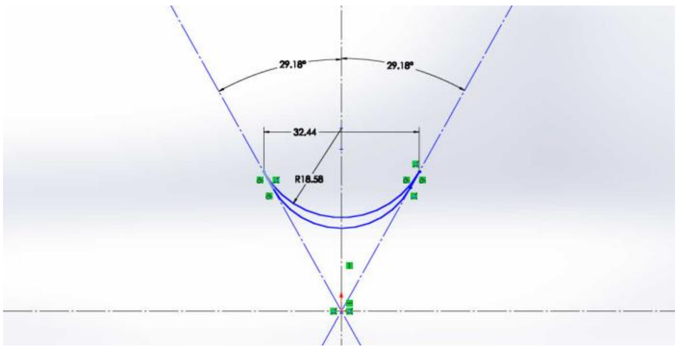

Figure 5 Actual Blade Geometry

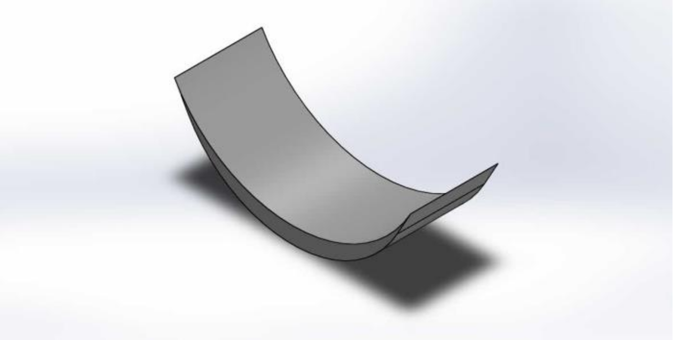

Figure 6 3D Blade

Nozzle Design:

Design of a convergent divergent nozzle, when the outlet should be at an angle of 20^o from the horizontal and the flow inside is at supersonic mach number, is very complex as it requires Methods of Characterisitcs involved which itself is very complex task hence what we did is make different configurations of nozzle and processed through CFD and choose the one with best results.

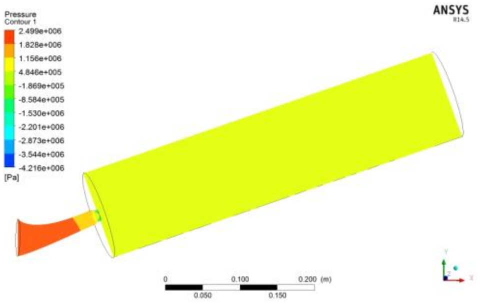

Figure 7 Nozzle CFD Analysis: Pressure Contour

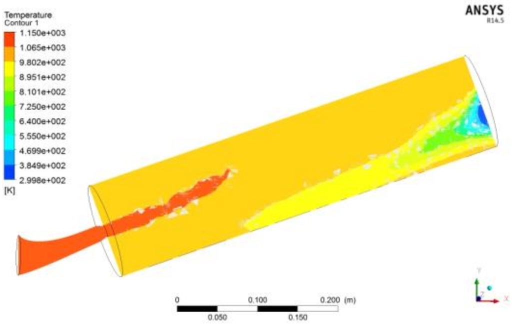

Figure 8 Nozzle CFD Analysis: Temperature Contour

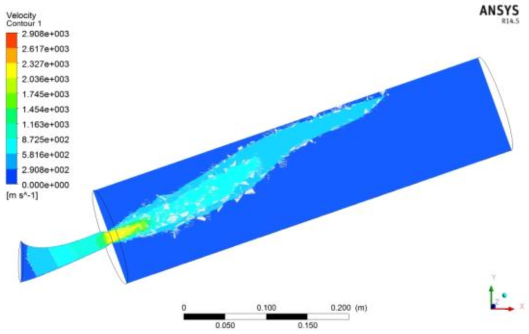

Figure 9 Nozzle CFD Analysis: Velocity Contour

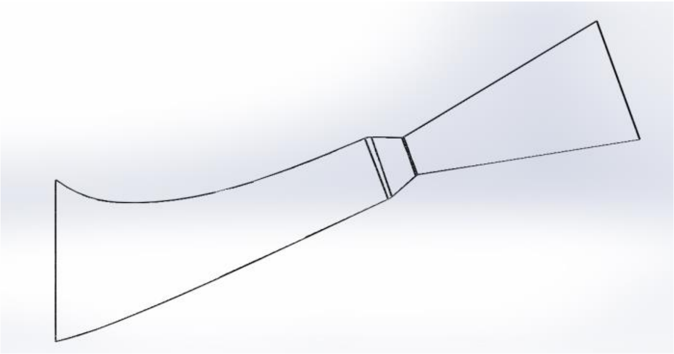

Figure 10 3D Nozzle

V. RESULTS

Parameters	Values
Nozzle	
α_1	20^o
Velocity at Exit	764 m/sec
Inlet Diameter	50 mm
Throat Diameter	12.36 mm
Outlet Diameter	39 mm
Blade	
$\beta_2 = \beta_3$	29.17^o
α_3	52.8^o
Radius	18.58 mm
Pitch	19.08 mm
Blade Efficiency	0.832
Flow Coefficient	1.045
Stage Loading	1.167
Turbine	
Mass Flow Rate	0.832 lbm/sec
Power Delivered	70.4 kW
Total Engine Efficiency	76.21%

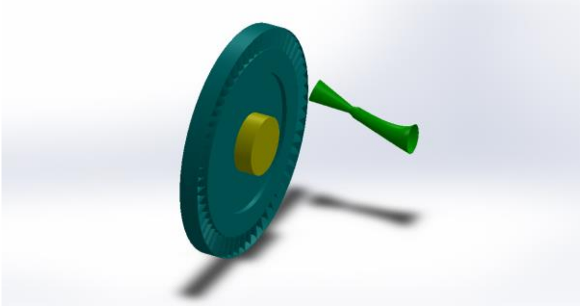

Figure 11 Final Assembly

VI. Performance Analysis

Performance analysis of turbine is done to see the change in dimension-less parameters of turbine with change in blade and flow angles.

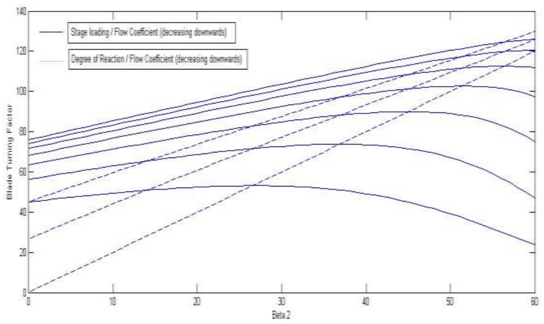

Figure 12 Turning Factor vs Blade Angle for fixed Flow Coefficient, Stage Loading and Degree of Reaction

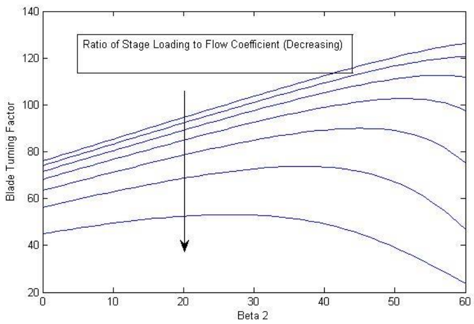

Figure 13 Turning Factor vs Blade Angle for fixed Flow Coefficient and Stage Loading

VII. Conclusion

A design methodology for obtaining the design of a gas generator cycle based LRE engine's Impulse Turbine for a proposed space mission was performed. The study takes advantage of pertinent data available in open literature to derive a fully integrated gas turbine model including design history and turbo pump feed system power requirements.

An integrated model of the problem was coded in Matlab and result trends were obtained to observe how the system behaves to the design parameters. On the basis of these trends an operation point was chosen to enable a better performance in achieving mission success. The one dimensional CFD analysis were also carried out to explore the flow characteristics inside CD nozzle at an angle. Additionally, the model developed could further facilitate research on different mass flow rate and power parameters.

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