PREDICTING PERFORMANCE OF AXIAL PUMP INDUCER OF LOX BOOSTER TURBO-PUMP OF STAGED COMBUSTION CYCLE BASED ROCKET ENGINE USING CFD

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ABSTRACT

For low cost, high thrust, space mission with high specific impulse and high reliability, inert weight demand to be curtailed down and thereby increasing the delivered payload. Turbopump feed system for a liquid propellant rocket engine (LPRE) has the highest power to weight ratio. Turbopumps are primarily equipped with an axial flow inducer to achieve the high angular velocity and low suction pressure in combination with increased system reliability. The performance of turbopump strongly depends on the performance of inducer. Thus, for designing a turbopump for an LPRE demands optimization of inducer geometry based on the performance of different off-design operating regimes. In this paper, steady-state CFD analysis of the inducer of the liquid oxygen (LOX) axial pump used as a booster pump for an oxygen rich staged combustion cycle based rocket engine has been presented using ANSYS® CFX. Attempts have been made to obtain the performance characteristic curves for the LOX pump inducer. The formalism has been used to predict the performance of the inducer for the throttling range varying from 80% to 113 % of nominal thrust and the different rotational velocities ranges from 4500 to 7500 rpm. The results have been analysed to find out the region of cavitation inception for different inlet pressure.

INTRODUCTION

The primary constraint on space enterprises is the high cost of escaping Earth's gravity. Therefore, for manned space mission and deep space probes, reusable launch vehicles are contemplated to be used.

- For high thrust, mission with high specific impulse, mass of the propellant tanks would be prohibitive [1].
- There should be a booster turbopump, for raising the pressure to a small amount, and to ensure the cavitation free operation at the main pump inlet [2].
- Turbopump feed systems used for high thrust ,long duration operation in oxygen-rich, staged combustion cycle based liquid propellant rocket engines to increase the power to weight ratio and to raise the performance over pressure feed systems [2].
- The performance of turbopump strongly depends on the performance of inducer.
- The LOX booster turbopump consists of an axial tip turbine driven pump in which LOX is pumped by a helical inducer is driven by a velocity compounded impulse turbine [3].
- The engines operate in a wide range of throttling condition.
- One of the steps in the design of turbopumps is to confirm the performance characteristics under varying operating conditions.

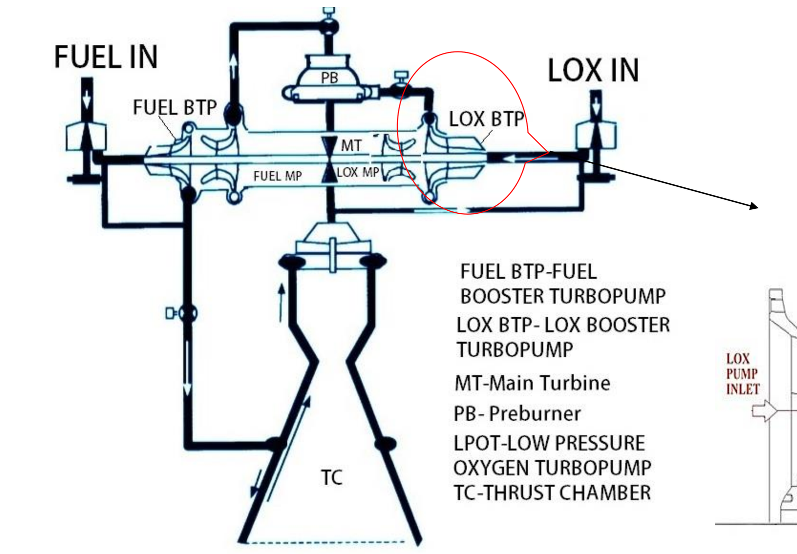
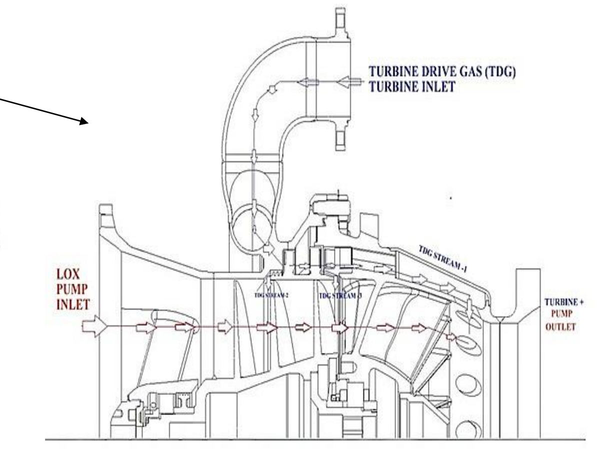


FIGURE 1. SCHEMATIC DIAGRAM OF STAGED COMBUSTION CYCLE WITH OXYGEN RICH BOOSTER TURBOPUMP



FIFIGURE 2. LOX BOOSTER TURBOPUMP ASSEMBLY

OBJECTIVE

- The Flow of axial pump inducer of turbo-pump system is highly complex due to 3D flow structure involving turbulence, recirculation, tip vortices and cavitation induced unsteadiness.
- CFD is an important tool where the flow field of the inducer can be numerically estimated for the investigation of the performance of the pump inducer [4, 5].
- In the present work, with the help of ANSYS® CFX LOX pump inducer has been analysed with the following objectives.

1) To plot performance characteristic curves of the inducer for different off design operating conditions.
2) To study the effect of variation in different process parameters like mass flow rate, rotational speed and inlet total pressure on the performance of the axial pump inducer of LOX booster turbo-pump.

METHODOLOGY

Geometry of axial pump inducer for LOX turbopump

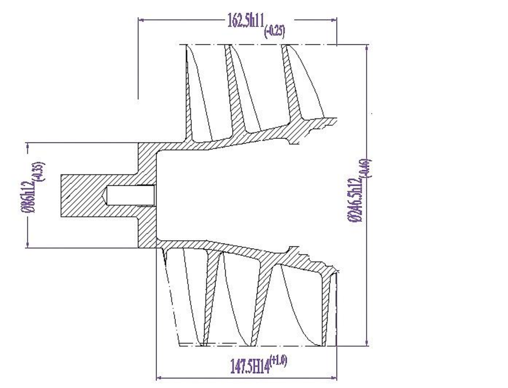


FIGURE 3. 2D fabrication drawing of the inducer for the LOX booster turbo-pump for staged combustion cycle based rocket engine.

FIGURE 4. 3D fabricated model of the inducer created in AUTODESK Inventor.

Numerical simulation methodology

Grid generation

- Unstructured , mostly tetrahedral grid for the three dimensional model has been created in Ansys® Meshing software.
- To model the cavitating region, high grid density cells with small aspect ratio has been created at the inducer leading tip for all three helical blades.
- The computational domain consists of 8.94 million nodes and 51.5 million elements. Different meshing statistics is summarised below in Table 1.

Table 1. Mesh statistics for the inducer

Domain	No. of nodes	No. of Elements	Method	Mesh Type/ Type of elements
Inducer	8947153	51580950	Patch conforming	Unstructured/ Mostly Tetrahedral

Numerical modeling

- For the steady state mathematical solution of the discretized three-dimensional, Reynolds Averaged Navier-Stokes (RANS) based two-equation zonal SST (shear stress transport) k-ω eddy viscosity used for turbulence modeling.
- High resolution advection scheme was used in all simulations.

Boundary conditions

- Subsonic inlet with stationary frame total pressure and temperature defined at the inlet with normal flow direction profiles and mass flow rate at the outlet of the axial inducer.
- Turbulence intensity level set to be medium intensity of about 5%.

- Different thermophysical parameters required to set numerical simulation for the 100% nominal thrust condition are summarised in Table 2.
- The analysis has been performed for the off-design performance prediction of LOX pump inducer for different mass flow rates and rotating speeds in which Q/Qd is from 0.80 to 1.13 and rotational speed of the axial flow inducer ranges from 4500 to 7500 rpm respectively.

Table 2. Input data required for the CFD analysis of 100% nominal thrust condition

Parameter	Input data
Inlet domain	Inducer inlet
Flow Direction	Normal to Boundary
Flow regime	Subsonic
$T_{0,1}$ [K]	91
$p_{o,1}$ [M Pa]	0.47
Mass flow rate [kg/s]	442
Design speed, N_d [rpm]	7016

RESULTS AND DISCUSSION

PERFORMANCE CHARACTERISTICS CURVEOF THE INDCUER

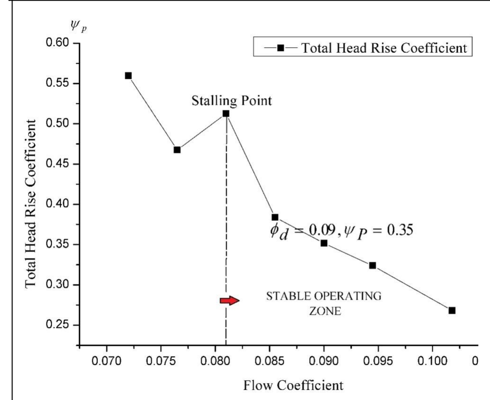


Figure 5. Total head rise coefficient vs. Flow coefficient

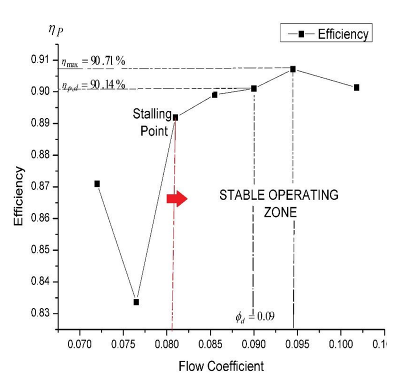


Figure 6. Efficiency vs. Flow coefficient

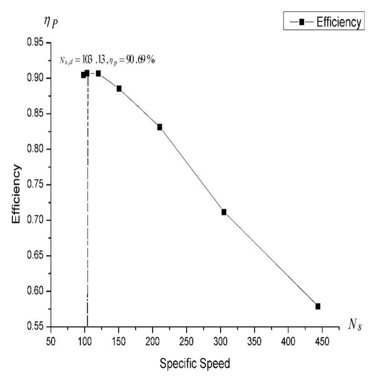


Figure 7. Efficiency vs. Specific speed

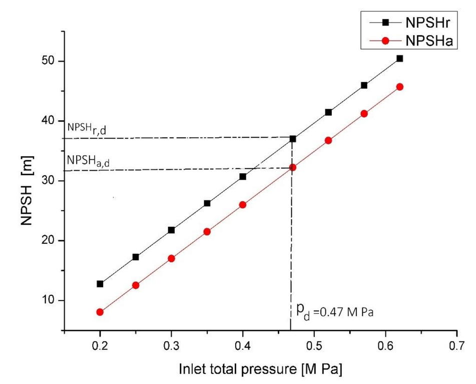


Figure 8. NPSH vs. Specific speed

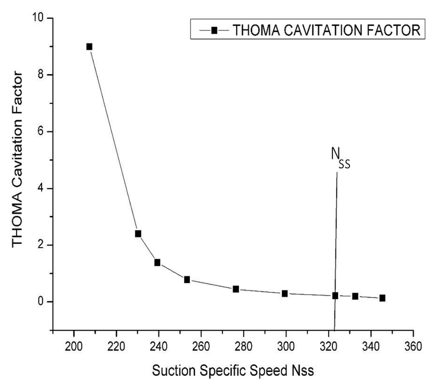


Figure 9. THOMA Factor vs. Suction specific speed

Table 3. Performance parameters for axial flow inducer at 100% nominal thrust condition

Performance parameter	Output data
N_s	103.60
N_{ss}	323.20
$N_{ss/corrected}$	344.87
ϕ	0.09
ψ_p	0.35
ψ_s	0.28
H [m]	147.92
$NPSH_a$ [m]	32.26
$NPSH_r$ [m]	36.98
σ_{cav}	0.077
σ	0.22
P_t [kW]	707.48
P_h	637.48
η_P	90.10%

- The values of various performance parameters are summarized in Table 3.
- Figure 5. , it is observed that below the designed flow rate of 90% of nominal flow coefficient, there is dip in the head. The depression in operating performance curve indicates the flow separation. This is known as stalling point of the pump.
- Figure 6. , shows that the maximum efficiency of 90.71% occurs at 95% thrust condition. The efficiency curve falls steeply below the stalling point and hence, the pump should operated at a flow rate near to the designed point for economical operation.
- Figure 7., shows that the efficiency is maximum at designed specific speed. At higher specific speed, the hydraulic losses increases, efficiency decreases and at the lower specific speeds the amount of friction and cavitation induced losses increase results in sudden reduction in efficiency.
- Figure 8., shows that the value of NPSHa < NPSHr for the design thrust value. This ensures that the pump inducer is designed to work under the influence of cavitation to achieve the high power to weight ratio for low cost liquid rocket engines.
- Figure 9., shows that above the designed suction specific speed chances of cavitation increase as the value of thoma cavitation factor decreases.

PARAMETRIC ANALYSIS OF THE INDCUER

Effect of Mass flow rate variation

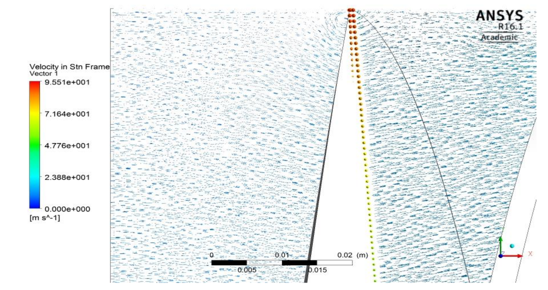


Figure 10.a Velocity vector plot for $\phi/\phi_d = 1$

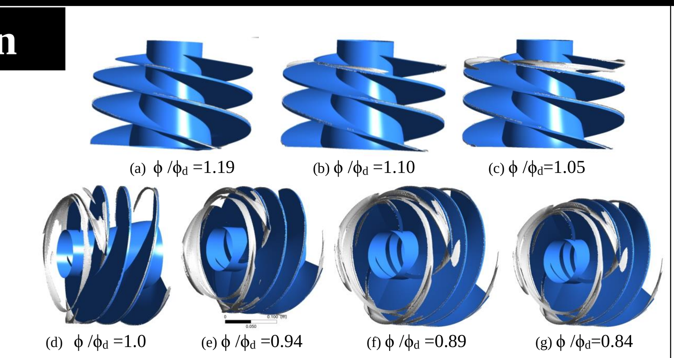


Figure 11. Vorticity contours for different throttling conditions

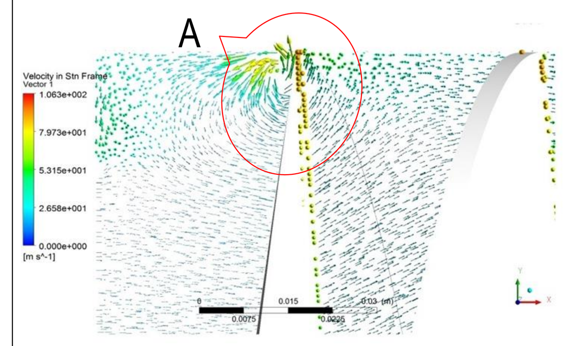


Figure 10.b Velocity vector plot for $\phi/\phi_d = 0.84$

- As the mass flow rate is reduced, there is a flow reversal at the tip of the inducer due to which vortices are formed. It can be revealed by velocity vectors shown in Figure 10. (a) and Figure 10. (b). With the decrease in mass flow rate chances of increase in backflow vortices lead to stalling of the pump due to choking as shown in Figure 11.

Effect of operating speed variation

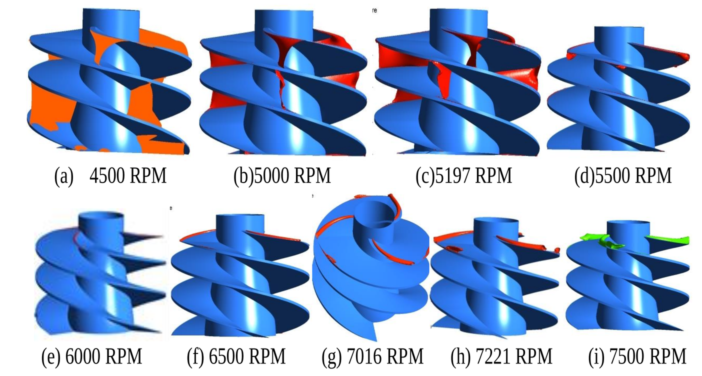


Figure 12. Iso surface corresponding to vapor pressure for the varying speed ranges from 4500 rpm to 7500 rpm.

- Figure 10 (a) to (i), show that from 4500 RPM to 5197 RPM low pressure region has engulfed the blade flow passage. This phenomenon depicts the chances of vapour lock at low speed values. As the speed is increased, this low pressure region contracts. Further increase in speed leads to tip vortex cavitation. Therefore, for the satisfactory operation, pump inducer should work in the range of 5197 RPM to 7221 RPM.

Effect of Inlet pressure variation

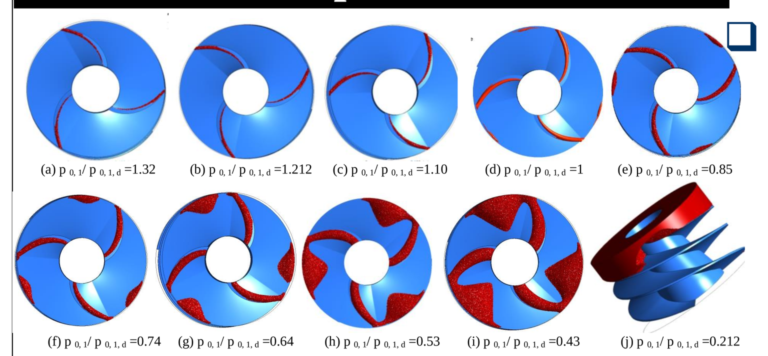


Figure 13. Iso volume contours for the absolute static pressure value equals to or less than vapor pressure for different inlet total pressure varying from 0.62 M Pa to 0.1 M Pa.

- Figure 13., shows that as inlet total pressure decreases, the inception of tip vortex cavitation occurs at the leading edge of the inducer. Further as the inlet total pressure reduces gradually cavitation grows, and the cavities fill the inlet of the inducer.

CONCLUSIONS

From the performance characteristics curves and parametric analysis of the LOX pump inducer, it has been found out that-

- The designed pump is a cavitating inducer designed to work satisfactorily under cavitating conditions for the throttling range varying from 90 % to 113 %. As the engine throttles below 90 % of the nominal thrust, abrupt depression in head curve is observed due to stalling.
- Through parametric studies of the operational parameters, it has been revealed that the pump should operate for the flow coefficient higher than φ /φd =0.94 in the speed range 5197 RPM to 7221RPM for the designed inlet pressure value.
- It has been found out that flow instabilities such as tip vortex cavitation, backflow vortices and stall occurs at the off design conditions leading to substantial performance losses.
- Need for design modifications may arise if the inducer is to be operated at wider operating range.

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Designed by Arpit Mishra.2015