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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 missions with high specific impulse and high reliability, inert weight needs to be minimized 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. Performance of the turbopump strongly depends on the performance of the inducer. Thus, for designing a LPRE turbopump, demands optimization of the inducer geometry based on the performance of different off-design operating regimes. In this paper, steady-state CFD analysis of the inducer of a liquid oxygen (LOX) axial pump used as a booster pump for an oxygen rich staged combustion cycle 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 for the different rotational velocities from 4500 to 7500 rpm. The results have been analysed to determine the region of cavitation inception for different inlet pressure.

1. Introduction

For high thrust, space missions with high specific impulse, the mass of the propellant tanks would be prohibitive [1]. This need for weight reduction and high power to weight ratio implies a requirement for the main propellant feed pumps operate at very low inlet pressure. Turbopump feed systems are used for high thrust missions with high specific impulse; long duration liquid propellant rocket engines lower the system weight and raise the performance of pressurized gas feed systems. This feed system requires relatively low pressure at the inlet and thus low propellant tank pressure that saves considerable tank weight, particularly for long duration reusable launch vehicles [2]. In this condition, in a turbo-pump, the onset of cavitation typically occurs at the inducer blade tips, in the form of blade tip vortices. Therefore, in the case of high thrust and long duration liquid propellant rocket engines, there should be a booster turbopump for raising the pressure to ensure the cavitation free operation at the main pump inlet [3]. Liquid rocket engine 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.

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A necessary step in the design process is to characterise the performance of the turbopump at different operating conditions as the engine encounters different thrust conditions during its throttling. The turbopump needs to produce the required pressure or head for operating under varying thrust conditions [4]. Hence, the pump characteristics curves are vital information for designing the pump feed system for the liquid rocket engine. The information is required to ensure a pump inducer design that yield desired performance of the pump at off design conditions. Furthermore, the cavitation due to lowering of the liquid pressure below vapour pressure limits the thermohydraulic and rotadynamic performance of the pump and often leads to vibration. This entails appropriate design decisions to alleviate the problem.

In the present work, an investigation has been carried out to find out the performance characteristics of the LOX booster pump of a staged combustion cycle based rocket engine. The effects of variation of different operational parameters versus the inlet pressure, mass flow rate and rotational speed on the operation of the pump have been studied. The information obtained from this study will be used to take necessary corrective steps in the modification of the design of the pump inducer.

2. Objectives

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 [5, 6]. In the present work, with the help of ANSYS[®] CFX, the 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 a LOX booster turbo-pump.

3. Methodology

3.1. Geometry of axial pump inducer for LOX turbopump

The LOX booster turbopump consists of an axial tip turbine driven pump in which LOX is pumped by a helical inducer driven by a velocity compounded impulse turbine [2].

The designed inducer of an axial flow configuration has 3 blades wrapped in the form of helix around the central hub. The diameter of the hub increases over the axial extent of helical blades, thereby decreasing the depth of blades between the inlet and outlet [7]. Autodesk Inventor has been used to create the 3D model of the LOX pump inducer. Figure 1 and figure 2 show the geometry of the inducer.



Figure 1. 2D fabrication drawing of the inducer



Figure 2. 3D fabricated model of the inducer created in AUTODESK Inventor.

3.2. Numerical simulation methodology

A grid independency test has been performed to obtain a grid independent solution of the computational flow field and to find a grid that is optimal in terms of accuracy and simulation time. The study is conducted under the conditions given below in table 2 and it has been observed that the computational domain should consist of 8.94 million nodes and 51.5 million elements for yielding reasonably accurate simulation results and 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. To ensure that the grid refinement near the solid boundaries fulfils the y+ criteria for low or high Reynolds number formulations in wall bounded turbulent flow, the value of non-dimensional y+ is kept in fully turbulent region as 30 < y+<60 as suggested in [8]. Different meshing statistics and quality parameters are 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	Unstructured/ Mostly Tetrahedral	
			conforming		

An implicit finite volume approach has been adopted for the solution of the discretized domain of the LOX pump inducer and to obtain the performance characteristic curves. The computational technique involves 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 turbulence model over an unstructured grid with high order upwind advection scheme. SST k- ω has been adopted as the turbulence model following the observation and recommendation provided in [6, 9, 10] wherein simulation of similar kind of machines are discussed. It is found to be applicable for the accurate prediction of flow with adverse pressure gradient and separation [11]. The zonal formulation of the SST- *k*- ω model is based on blending functions which guarantee a proper selection of *k*- ω and *k*- ε zones with a programmed near wall treatment which automatically moves from the standard low-Re formulation to wall functions, based on the grid spacing of the near-wall cell [11, 12].

3.3. Boundary conditions

At the inlet of the axial inducer, the boundary has been defined as a subsonic inlet, with stationary frame total pressure and stationary frame total temperature with normal flow direction profiles. The turbulence intensity level was set to be a medium intensity of about 5%. The mass flow rate is defined at the exit of the axial inducer. Different thermophysical parameters required to set numerical simulation for the 100% nominal thrust condition are summarised in table 2.

Parameter	Input data			
Inlet domain	Inducer inlet			
Flow Direction	Normal to Boundary			
Flow regime	Subsonic			
Stationary frame total temperature at the inducer inlet, T ₀ ,1 [K]	91			
Stationary frame total absolute pressure at the inducer inlet po,1 [M Pa]	0.47			
Mass flow rate [kg/s]	442			
Design speed, N d [rpm]	7016			
LOX density, ρ [kg/m ³]	1137.1			
Acceleration due to gravity, g $[m/s^2]$	9.81			
Absolute vapour pressure at operating temperature , p_v [M Pa]	0.11022 M Pa at 91 K			

Table 2.	Input	data required	for the C	CFD anal	ysis of	100%	nominal	thrust	condition
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The analysis has been performed for the off-design performance prediction of a LOX pump inducer for different mass flow rates and rotating speeds in which Q/Q_d is varied from 0.80 to 1.13 and the rotational speed (N) of the axial flow inducer ranges from 4500 to 7500 rpm.

4. Results and discussion

CFD analysis results for 100% nominal thrust value have been investigated by analysing the 3d flow behaviour of the axial flow inducer. The values of various performance parameters are summarized in table 3.

The value of $NPSH_{a}$, is less than the value of $NPSH_{r}$ 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 required for low cost liquid rocket engines.

4.1. Performance characteristic curves for different off-design conditions

The performance curves of a pump are represented by (1) ψ_p - ϕ curve, (2) $\eta_{_{\rm H}}$ - ϕ curve. The ψ_p - ϕ

curve is shown in figure 3. It is observed that below the designed flow rate of 90% of ϕ there is dip in

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

Performance parameter	Output data
Reynolds number, Re	1.348×10^{7}
Specific speed, N _s	103.60
Suction specific speed, N _{ss}	323.20
Corrected suction specific	344.87
speed, N _{ss} '	
Flow coefficient, ϕ	0.09
Total head rise coefficient, ψ_p	0.35
Static head rise coefficient, ψ_s	0.28
Total head developed, H [m]	147.92
NPSH _a [m]	32.26
NPSH _r [m]	36.98
Inlet cavitation number, σ_{cav}	0.077
Thoma cavitation factor, σ	0.22
Torque power, P _t [kW]	707.48
Power due to head difference,	637.48
P _h [kW]	
Hydraulic efficiency, $\eta_{\rm H}$	90.10%

the head. The depression in the operating performance curve indicates flow separation [13]. This is known as stalling point of the pump. Stall refers to a recirculating fluid zone within the pump inducer. It can be observed by substantial velocity and pressure fluctuations. These fluctuations adversely affect the pump operation and lead to structural vibrations. This causes inducer operation to become unpredictable, resulting in a total head loss and instability in pump operation [14].

Figure 4 shows the η_{μ} - ϕ curve. It is observed that the maximum efficiency of 90.71% occurs at

95% thrust condition. At design condition the efficiency is 90.14%. The efficiency curve falls steeply below the stalling point, and hence, the pump should be operated at a flow rate near to the designed point for economical operation [15] and should operate away from the region of instability.





Figure 3. Overall performance characteristic curve: Head rise coefficient, ψ_p vs. Flow coefficient, ϕ

Figure 4. Hydraulic efficiency, $\eta_{_{\rm H}}$ vs. Flow coefficient, ϕ curve

Figure 5 shows that the efficiency versus specific speed curve for designed flow coefficient (i.e. for $\phi_d=0.35$). It is observed that the efficiency is maximum at designed specific speed. At higher specific speeds, the hydraulic losses increase, efficiency decreases and at lower specific speeds friction losses, leakage and cavitation losses increase resulting in sudden reduction in efficiency and leading to sudden failure of the pump inducer [16].

Figure 6 depicts the thoma cavitation number variation with suction specific speed for different rotational speed at design flow coefficient. If the inducer is operated above its suction specific speed limit, excessive cavitation will occur and pump will not deliver the desired head-rise.



Figure 5. Hydraulic efficiency (η_{H}) Vs. Specific speed (N_s) for designed flow coefficient, ϕ_d =0.354

Figure 6. Thoma Cavitation Number Vs. Suction Specific Speed at design flow coefficient, $\phi_d = 0.354$

4.2. Effect of variation of operational parameters on the pump performance To study the effect of different operational parameters on the performance variation of the axial flow inducer, a parametric analysis has been performed.

4.2.1. Effect of Mass flow rate variation. From figure 7, it has been observed that, at lower mass flow rate than that at the design value ($\phi/\phi_d = 0.84$), flow separation occurs at the tip (region "A" of figure 7 (b)) of the inducer due to which vortices are formed. Thus, with the decrease in mass flow rate, chances of increase in backflow vortices lead to stalling of the pump due to choking [17]. This flow reversal can be revealed by velocity vectors shown in figure 7 (a) and figure 7 (b).



Figure 7. Velocity vector plot (a) for $\phi / \phi_d = 1$, (b) for $\phi / \phi_d = 0.84$

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As observed from the figure 8 (a) to (g), when the mass flow rate is decreased from its design value, the region of vortex flow at the inlet advances towards the discharge side.



Figure 8. (a) to (g) Vorticity contours for different throttling conditions in which mass flow varies from $\phi / \phi_d = 1.13$ to $\phi / \phi_d = 0.80$. It shows that the backflow vortice regime increases as the mass flow rate decreases. This may lead to choking of blade passage. Tip vortex cavitation is predominant at low mass flow rate.

4.2.2. *Effect of operating speed variation.* The design speed of the inducer has more influence on turbopump design than any other performance parameter. If the speed is too low, the weight of the turbopump unit will be too high, and efficiency and specific impulse will be too low. On the other hand, if the speed is too high, the turbopump may not meet the reliability and life requirements [16].

Figure 9 (a) to (i) shows that from 4500 RPM to 5197 RPM the low pressure region has advances in 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, the pump inducer should work in the range of 5197 RPM to 7221 RPM.



(e) 6000 RPM (f) 6500 RPM (g) 7016 RPM (h) 7221 RPM (i) 7500 RPM **Figure 9. (a) to (i)** Iso-surface corresponding to vapour pressure for the varying speed value ranges from 4500 RPM to 7500 RPM.

4.2.3. *Effect of Inlet pressure variation*. Cavitation in turbomachines appears when the pressure drops below the vapor pressure. Isosurfaces for the area subjected to pressure equal to, or less than the vapour pressure has been shown in figure 10 (a) to (j).

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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. When the cavitation region becomes large enough to provide complete saturation of liquid in the blade passage, the head coefficient begins to reduce, and breakdown conditions are achieved. This event is responsible for the erosive damage of the inducer, and for the loss of performance.



Figure 10. (a) to (j). Isovolume contours for the absolute static pressure value equal to or less than the vapor pressure for different inlet total pressure values varying from 0.62 M Pa to 0.1 M Pa. It shows that fraction of Iso volume increases with the decrease in p_{0,1} / p_{0,1,d}. And flow is completely blocked when the pressure drops below the vapor pressure.

5. Conclusion

This paper elucidates the CFD analysis of the axial inducer of a LOX booster turbopump for a staged combustion cycle based rocket engine to investigate its performance under design and off-design condition. Through the performance characteristics curves, it has been found out that the pump inducer is 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 the 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 $\phi / \phi_d = 0.94$ in the speed range 5197 RPM to 7221RPM for the designed inlet pressure value. Flow instabilities such as tip vortex cavitation, backflow vortices and stall occurs at off design condition. The need for design modification may arise if the inducer is to be operated at wider operating range. The trend of the performance curves and some of the observations of the flow phenomenon match with those reported in literature [13, 15]. Validation and quantitative verification of the data need to be performed through experimental investigation. The data generated are useful for design iteration.

Nomenclature

 $p_{0,2}$ = Stationary frame total absolute pressure at the inducer exit [M
Pa] V_i = velocity at the inlet of axial flow inducer [m/s] $p_{s,1}$ = Absolute static pressure at the inducer inlet [M Pa]
 $p_{s,2}$ =Absolute static pressure at the inducer exit [M Pa]Required Net Positive Suction Head $[m] = NPSH_r = \frac{P_{0,1} \cdot P_v}{\rho \times g} + V_1^2/2g$ Total head $[m] = H = \frac{P_{0,2} \cdot P_{0,1}}{\rho \times g}$ Available Net Positive Suction Head $[m] = NPSH_a = \frac{P_{0,1} \cdot P_v}{\rho \times g}$ Q=Volumetric flow rate $[m^3/s]$ Available Net Positive Suction Head $[m] = NPSH_a = \frac{P_{0,1} \cdot P_v}{\rho \times g}$ Q=massflowrate / ρ Thoma Cavitaton Factor $= \sigma = \frac{NPSH_a}{H}$

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Specific speed = $N_s = \frac{N \sqrt{Q}}{H^{\frac{3}{4}}}$ Suction Specific speed = $N_{ss} = \frac{N \sqrt{Q}}{NPSH_a^{\frac{3}{4}}}$

 $r_{ref} = \text{Reference radius at the inducer tip}$ $r_{ref} = 0.12325 [m]$ D = Inducer inlet blade tip diameter [m] $D = 2 × r_{ref} [m] = 0.2465 [m]$ $D_h = Inlet hub diameter = 0.086 [m]$ $<math>\nu = D_{h/} D$ $N_{ss}' = \frac{N_{ss}}{\sqrt{(1 - \nu^2)}}$

 $\begin{array}{l} U_{tip}{=}\ Mean\ tip\ velocity\ at\ reference\ radius\ [m/s]\\ U_{tip}{=}\ r\ _{ref}{\times}\ \omega\ [m/s]\\ \end{array} \\ O$

Flow Coefficient =
$$\phi = \frac{Q}{A U_{tip}}$$

Where A= Area at the inlet

Cavitation Number = $\sigma_{cav} = \frac{\mathbf{p}_{0.1} \cdot \mathbf{p}_v}{\frac{1}{2} \rho \times U_{up}^2}$ Total Head Rise Coefficient = $\psi_p = \frac{\mathbf{p}_{0.2} \cdot \mathbf{p}_{0.1}}{\frac{1}{2} \rho \times U_{up}^2}$ Static Head Rise Coefficient = $\psi_x = \frac{\mathbf{p}_{s,2} \cdot \mathbf{p}_{s,1}}{\frac{1}{2} \rho \times U_{up}^2}$ Hydraulic Power = $\mathbf{p}_H = \frac{\rho \times \mathbf{g} \times \mathbf{Q} \times \mathbf{H}}{1000}$ [kW] $\mathbf{r} = \text{Torque}$ Input Power = $\mathbf{p}_t = \tau \times \omega [kW]$ P $_{te} \tau_x \omega / 1000$ [kW] Hydraulic Efficiency = $\eta_H = \frac{P_H}{P_t}$ **Subscripts** d : Design point 1 : Inducer inlet 2 : Inducer outlet o : Total

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s : Static

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