Design and Experimental Analysis of Fuel Booster Pump

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Abstract

This paper deals with the design and experimental analysis of fuel booster pump of Rocket Engine. In this paper the fuel booster pump is analyzed for the effect of gas entry along with the fluid. The fuel booster pump is a centrifugal pump. Two main components of fuel booster pump are the inducer and the casing. The inducer is a rotating component and the casing is a stationary component. In fuel booster pump the fluid enters axially through the inducer and exits radially. The pump casing guides the liquid to the inducer & converts the high velocity kinetic energy of the flow into pressure energy. The design and experimental analysis of fuel booster pump is carried out to study the effect of gas entry in the performance of the pump during the course of flight. To simulate this problem of gas entry, during pump testing known amount of nitrogen gas is injected in the pump feed circuit along with the fluid The effect of gas entry causes reduction in efficiency, head and increase in NPSH requirement. This can be analyzed in ANSYS-CFX and it can be validated by carrying out number of experiments.

Keywords: *Fuel Booster Pump, Volute casing, ANSYS-CFX, Efficiency, Head, NPSH.*

1. Introduction

Pumps are used in a wide range of industrial and residential applications. They are varying in size, type and material of construction. There have been significant research and development in the field of pumping systems. They are used to transfer liquid from low pressure to high pressure. Centrifugal pumps are widely used for chemical plants, oil refineries, steam power plants, water supply system and hydraulic power services.

A Centrifugal pump delivers useful energy to the fluid on pumping largely because of the velocity changes that occurs as the fluid flows through the impeller and the associated fluid passage ways of the pump. It converts mechanical energy to hydraulic energy of the fluid. The input power for the pump is the mechanical energy such as electrical motor or small engine. The output energy is hydraulic energy of the fluid being pumped.

The fuel booster pump transfers mechanical energy from external source to the liquid flowing through it and losses occur in the process of energy conversion. Euler Equation is used to find out the energy transferred. The type of losses in pumps can be internal losses and external or mechanical losses. The internal losses are hydraulic losses or blade losses by friction. The external losses or mechanical losses are the sliding surface losses due to bearing friction or seal friction

2. Design and experimental analysis

2.1 Design:

The design of pump depends on number of variables. The inducer head slip is to be predicted in the design

Specific speed is defined as the speed expressed in rpm of an imaginary pump (proto model) geometrically similar to actual pump that would deliver 1 liter per second water against a head of 1 metre

$$\text{Specific Speed, } N_s = \frac{3.65\, N\sqrt{Q}}{H^{3/4}} \quad (1)$$

Where Q and H are flow rate and head respectively

Capacity is the amount of water pumped per unit time and is known as volume flow rate

$$\text{Capacity, } Q = AV \quad (2)$$

Where A and V are area of pipe and flow velocity respectively

$$\text{Fluid Power, } P_o = \rho g Q H \quad (3)$$

Where ρ is density of fluid, g is acceleration due to gravity, Q is flow rate and H is head

$$\text{Shaft power, } P_i = 2\pi NT/60 \quad (4)$$

Where N and T are speed and torque respectively

$$\text{Pump efficiency, } \eta = \frac{\rho g Q H}{2\pi NT/60} \quad (5)$$

Dynamic load on bearing:

The equivalent dynamic load on bearing is

$$P_e = 0.56\ K_r F_r + K_t F_a \quad (6)$$

Where K_r is rotation factor, F_r radial load, K_t thrust factor and F_a axial thrust

Impeller Design:

Outlet Diameter of impeller is

$$D_1 = U_1 x\ 60/\pi N \quad (7)$$

Where U_1 and N are velocity and speed respectively

Inlet Diameter of impeller is

$$D = 2/3 \text{ to } 1/3 \text{ of } D_1 \quad (8)$$

In most cases

$$D = 0.5\ D_1 \quad (9)$$

Least Diameter of Impeller is

$$D_l = \frac{2x60x\sqrt{2gH_m}}{\sqrt{3}\pi N} \quad (10)$$

Design of suction and delivery pipes:

Dia of suction pipe is

$$d_s = \sqrt{\frac{4Q}{\pi \times V_s}} \quad (11)$$

Suction velocity V_s varies from 1.5 to 3 m/sec

Dia of delivery pipe is

$$d_d = \sqrt{\frac{4Q}{\pi \times V_d}} \quad (12)$$

Delivery velocity V_d varies from 3 to 5 m/sec

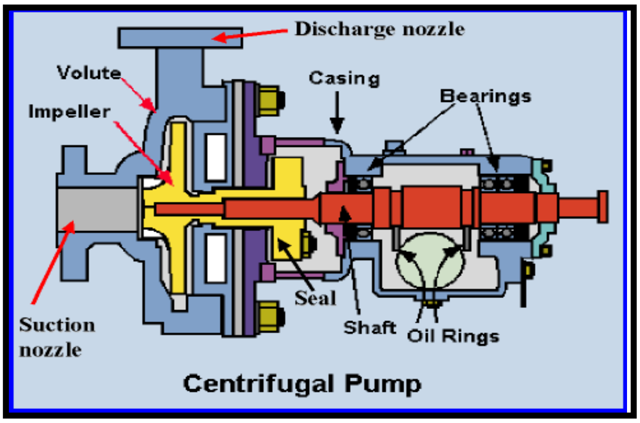

Fig.1 Sectional view of centrifugal pump

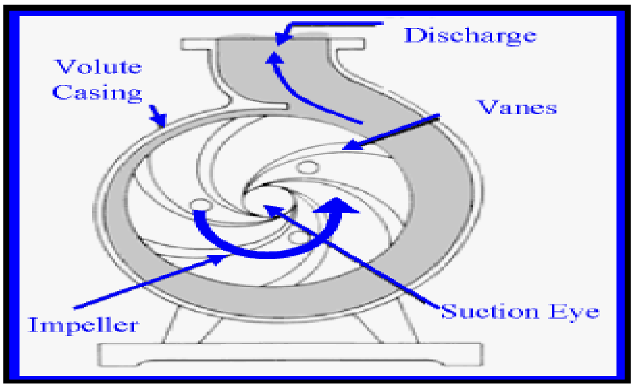

Fig. 2 Drawing of pump casing and impeller

Net Positive Suction Head (NPSH):

The Net Positive Suction Head (NPSH) is defined as the absolute pressure head corresponding to the temperature of the liquid pumped plus velocity head minus vapour pressure head at that point

$$\text{NPSH} = \frac{P_1}{\rho g} + \frac{V_1^{\,2}}{2g} - \frac{P_v}{\rho g} \quad (13)$$

Where P_1 is inlet pressure, ρ density of fluid, g acceleration due to gravity, V_1 flow velocity and P_v vapour pressure of fluid

Available NPSH (NPSHA):

NPSH available is the available energy (Head) at the inlet flange of the pump. It is possible to control available NPSH by altering the physical arrangement of installation, changes in piping, level of liquid supply etc for satisfactory operation

Required NPSH (NPSHR):

This is the function of pump design and varies from one make to another and with the capacity and speed of the pump. It is the head required to overcome pumps internal head losses, for instance, turbulence and friction losses created in the suction passage of the pump and losses incurred by the liquid passing the inlet edge of the impeller vanes.

Available NPSH should always be more than the required NPSH for satisfactory pump operation.

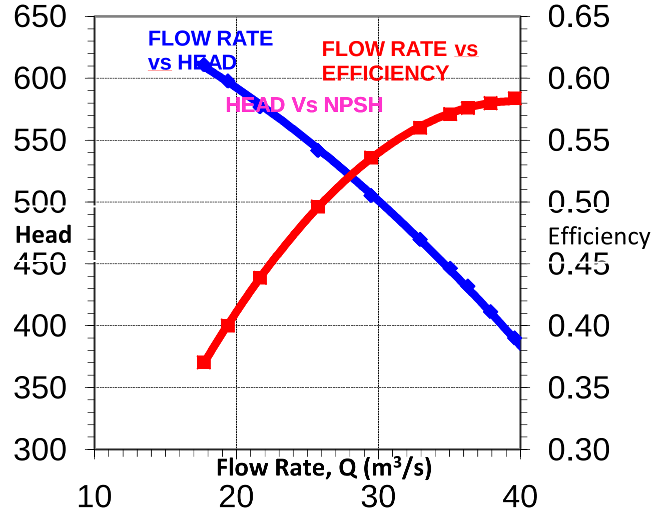

Fig 3.Theoritical NonCavitation Performance graph

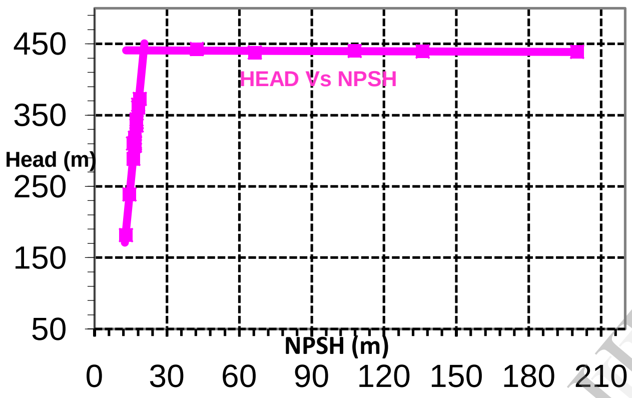

Fig 4.Theoritical Cavitation Performance graph

2.2 Experiments:

Non- Cavitation test:

Performance evaluation of the pump at simulated conditions with water as working fluid at nominal and off nominal conditions. Here the variation of head (H) with flow rates (Q) & variation of efficiency (η) with flow rates (Q) will be established.

Cavitation Test

Cavitation performance evaluation of the pump at nominal condition with water as working fluid. Here the critical Net Positive Suction Head (NPSH) of the pump will be established

Test Requirements:

Table 1
Non Cavitation test parameters

Parameters	Unit	Value
Rotational speed, N	rpm	10000±50
Inlet pressure,P1	bar(a)	1.07±0.06
Water flow rate, Q	l/s	11.6±0.2 ($Q_{nominal}$) 5.8 ±0.2 6.38±0.2 7.1 ±0.2 8.3 ±0.2 8.5 ±0.2 9.4 ±0.2 9.8 ±0.2 10.8±0.2 11.6±0.2 12.00±0.2 12.62±0.2 13.13±0.2 13.39±0.2 13.64±0.2 13.9 ±0.2

Table 2
Cavitation test parameters

Parameters	Unit	Value
Rotational speed, N	rpm	10000±50
Water flow rate, Q	l/s	11.6±0.15
Inlet pressure,P1	bar(a)	3.0 ±0.1 2.0 ±0.1 1.63±0.1 1.09±0.1 0.63±0.1 0.51±0.1 0.47±0.1 0.38±0.1 0.28±0.1 0.23 0.21 0.18

2.3 Test Setup:

The fuel booster pump was driven at the required test speed of 10,000±50 rpm using variable speed drive system. The drive system consists of variable speed DC Motor (50 kW, 3000 rpm) with Thyristor Control System, Gear box (1:5) and Torquemeter (20Nm, 15000rpm). All these equipments are connected using flexible couplings and aligned. The test article was aligned with the drive system and the misalignment value was 60 micron against the permissible misalignment of 100 micron

De Mineralized (DM) water is used as working fluid for Fuel Booster Pump testing. The water is filled in the Run Tank TWT 901 ($30m^3$,11bar).The cleanliness level of the DM water circuit was checked before the test by collecting water sample from the outlet of flexible hose to be connected to the test article. The cleanliness level obtained was better than class VI as per NAS 1638 standard. The Fuel Booster Pump was mounted on the mounting fixture. The inlet and outlet pipes, pressure transducer, vibration sensor were connected and carried out the pneumatic leak testing at 3 bar(a) pressure and ensured no leakage with snoop solution through the joints

2.4 Test Procedure:

Non Cavitation Test:

- Switch on electric motor
- Achieve 10,000 rpm speed
- Ensure nominal flow rate of 11.6 l/s by using a control valve and inlet pressure 1.07bar
- Vary the flow rate from 5.8 l/s to 13.9 l/s in steps
- Measure different parameters namely Speed, Torque, flow rate, inlet pressure & outlet pressure

Cavitation Test

- Switch on electric motor
- Achieve 10,000 rpm speed
- Maintain nominal flow rate 11.6 l/s
- Vary inlet pressure from 3.0 bar to 0.18 bar
- Measure different parameters namely Speed, Torque, flow rate, inlet pressure & outlet pressure

3. Experimental data analysis

3.1 Test data

Table 3
Non Cavitation Test Data

Inlet Pressure (bar)	Outlet Pressure (bar)	Flow rate (l/s)	Speed (rpm)	Torque (Nm)	Power (kW)
1.07	5.66	11.6	10000	9	9.2

Table 4
Cavitation Test Data

Speed (rpm)	Torque (Nm)	Flow rate (l/s)	Outlet Pressure (bar)	Inlet Pressure (bar)
10000	9	11.6	5.66	0.18

3.2 Performance Analysis:

The performance of pump was calculated as follows:
1. Determination of non-cavitation performance
2. Determination of cavitation performance

In non-cavitational performance test, head raise (H) & efficiency (η) are estimated and in cavitation performance test, critical NPSH is estimated

Estimation of Head Rise (H):

1. Dynamic head rise (H_{dyna}) = $\frac{v2^2-v1^2}{2g}$ (14)

2. Total Head rise (H_{tot})= $\frac{p2-p1}{\rho g} + \frac{v2^2-v1^2}{2g}$ (15)

3. Seal head rise (H_{seal}) = $\frac{ps-p1}{\rho g}$ (16)

Estimation of Efficiency (η):

4. Efficiency (η)= $\frac{\rho gQH}{2\pi NT/60}$ (17)

Estimation of NPSH:

5. NPSH = $\frac{P_1}{\rho g} + \frac{V_1{}^2}{2g} - \frac{P_v}{\rho g}$ (18)

3.3 Experiment Results:

The experiment was conducted satisfactorily as per test requirement. The parameters arrived from experiment results for the rated flow rate and speed are as follows

Table 5
Experiment Results

Sl. No	Parameter	Test result
1	Head (m)	433.59
2	Efficiency (%)	57.14
3	$NPSH_{cr}$, (m)	17.7

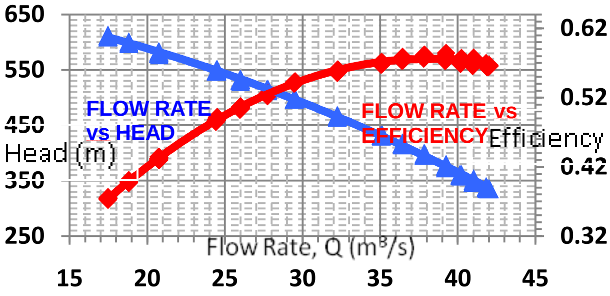

Fig.5 Actual Efficiency, Head relative to flow rate

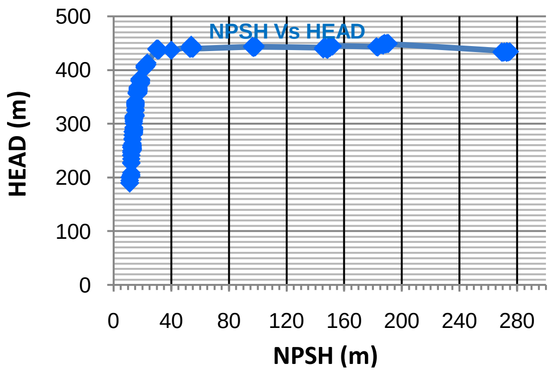

Fig.6 Actual Head relative to NPSH

4. Analysis of pump

One of the main objectives is to analyze the pump using ANSYS-CFX software. It consists of 3D modeling of inducer, inlet pipe & outlet pipe and volute casing and fluid flow analysis. The verification of analysis value as well as experimental results will be carried out after extensive experiments

5. Conclusion and future work

This paper deals with the design and experimental analysis of fuel booster pump rotating at high speed of 10,000 rpm. The reference test results are analyzed and reference data was obtained for fuel booster pump. Following the reference test, complete modeling and analysis of fuel booster pump as well as number of experiments in the pump by injecting nitrogen gas in the suction side fluid to study the effect of gas entry are planned.

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