Unshrouded Impeller Technology Development Status

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ABSTRACT

To increase payload and decrease the cost of future Reusable Launch Vehicles (RLVs), engineers at NASA/MSFC and Boeing, Rocketdyne are developing unshrouded impeller technology for application to rocket turbopumps. An unshrouded two-stage high-pressure fuel pump is being developed to meet the performance objectives of a three-stage shrouded pump. The new pump will have reduced manufacturing costs and pump weight. The lower pump weight will allow for increased payload.

INTRODUCTION

In most large liquid-propellant rocket engines, the propellants are fed into the combustion chamber(s) at high pressure by turbopumps and are ignited there. The combustion products are then accelerated to high velocities to produce thrust. The turbopumps spin rapidly to achieve the high pressure necessary to inject the propellants into the combustion chamber(s). For a given turbopump, the pressure, otherwise known as the "head", generated will increase with an increase in the rotation rate. Typical rocket turbopumps have shrouds, heavy metal casings covering the blade passages, to help shape the flow, maintain performance, and balance the pump. However, shrouds add weight and manufacturing complexity to impellers. Also, as pumps spin faster, the mass of the shroud increases the stress, limiting the maximum pump operating speed. An unshrouded impeller can spin faster due to less stress, thus generating more head.

The Marshall Space Flight Center (MSFC) has been developing unshrouded technology to improve liquid rocket engine turbopump performance. The turbopump is typically between 25% and 30% of the gross engine weight and the housing assembly makes up about 80% of the total turbopump weight. Housing size is driven by the size of the rotor assembly. Use of unshrouded impellers allows for higher tip speeds, which increases stage loading resulting in reduction of rotor and housing size and weight. This project has shown that a Space Shuttle Main Engine (SSME) two-stage High Pressure Fuel Turbopump (HPFTP) Alternate Turbopump (AT) and a candidate RLV baseline two-stage HPFTP would reduce turbopump weight between 45% and 50% as compared to the three-stage designs. Table 1 illustrates the potential benefits of the increased stage loading possible with unshrouded impellers.

Table 1 - Turbopump weight savings potential.

	Shrouded (3-stage)	Unshrouded (2-stage)	Weight Savings
SSME HPFTP/AT	990 lbs.	490 lbs.	50%
RLV HPFTP	1870 lbs.	1010 lbs.	45%

OBJECTIVE

The overall objective of this effort is to develop an unshrouded impeller turbopump design that will achieve the performance of a three-stage pump with only two-stages[1]. To accomplish this, three major elements have been worked. The first was a design trade study conducted to find the optimal impeller design for a candidate RLV engine design point. This study included an extensive computational fluid dynamics (CFD) analysis of three candidate designs to determine which had the best performance. The second element was a test program initiated to experimentally determine tip clearance sensitivity of unshrouded impellers. Included in this element was a CFD study to anchor the computational prediction tools with the experimental data. The last element was the complete mechanical layout of a RLV turbopump using the new impeller design.

APPROACH

Design Parametric Study: Johannes Lauer, et. al.[2] describe an experimental study of 14 unshrouded impellers of different designs. Though not conclusive, the results did indicate that blade number and exit angle had the largest impact on tip clearance sensitivity. Low sensitivity of performance to tip clearance is needed to allow for incorporation of unshrouded impellers into rocket engine turbopumps. Based on literature review[3] and tip clearance modeling assumptions, nine primary design parameters were determined to be of interest. Three of these parameters: head coefficient, axial length (shroud contour) and impeller exit width (b_2) were fixed due to engine balance constraints or the need to minimize changes to the tester. With those parameters fixed, four others: blade solidity, blade wrap, diffusion factor, and exit blade angle, would change with blade number. This left blade number and cant angle as the remaining parameters to study. Cant angle has mostly second order effects on performance and was therefore eliminated from the study. Three impeller designs were evaluated for performance sensitivity: a 5+5 (five main blades and five splitter blades), a 6+6, and an 8+8 bladed impeller. Each impeller met the performance goals of the candidate RLV engine balance. Williams, et. al.[4] includes a detailed account of this study.

CFD analysis of the three impellers was conducted at flow rates between 80% and 120% of the design flow rate. Impeller tip clearances of 0%, 6%, 10%, and 20% of the b_2 width were examined with the inlet and b_2 tip clearances varied separately. Global performance parameters and local flow uniformity were assessed to determine the best candidate geometry for the two-stage RLV HPFTP design.

Figures 1 and 2 show impeller developed head and efficiency comparisons for the three designs at three different tip clearances at the impeller design point. As expected, global performance parameters (head and efficiency) were greater for the 5+5 design due to more work performed on the fluid with greater blade turning and less viscous loss with shorter blade length. Locally, however, the aggressive blade turning of the 5+5 design produced undesirable flow non-uniformity. Figure 3 shows the 5+5 design had substantially greater back flow at the blade leading edge.

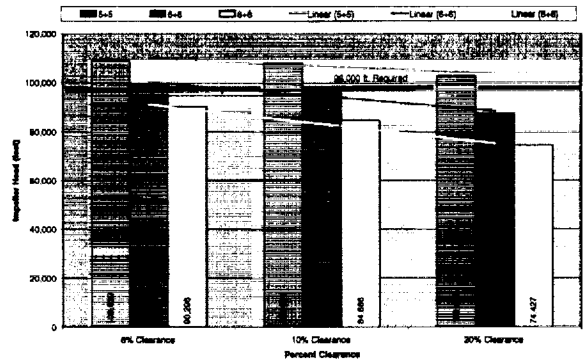

Figure 1 - Impeller developed head.

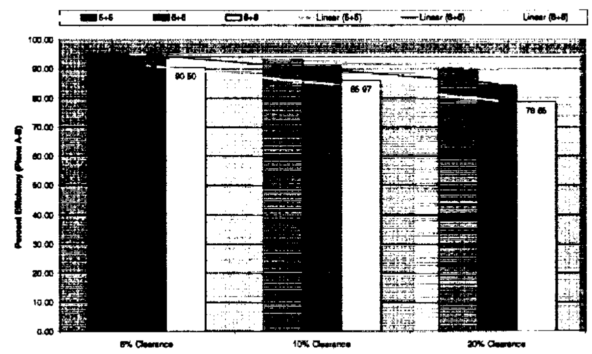

Figure 2 - Impeller efficiency.

The 6+6 design was selected for the RLV HPFTP two-stage unshrouded impeller configuration based on overall performance and flow uniformity. The 6+6 design at 6% clearance also reached the 98,000-ft. developed head requirement per pump stage. The objective of this study was accomplished with the 6+6 impeller design.

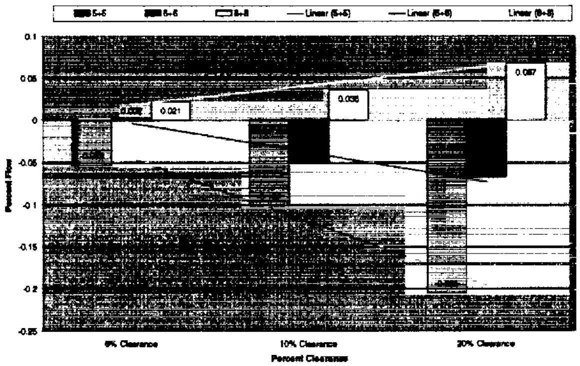

Figure 3 – Back flow at the blade leading edge.

Vehicle system trades were performed to determine the overall potential increase in payload to orbit. The 6+6 unshrouded impeller design at 6% clearance had similar performance to a shrouded design and at this clearance and the increase in payload per engine was found to be 860 pounds. With larger operational clearances, however, the turbopump efficiency began to decrease. Rocket engine specific impulse (Isp) also began to decrease resulting in a smaller potential increase in payload. Figure 4 illustrates the increase in payload per engine for three designs and three tip clearances.

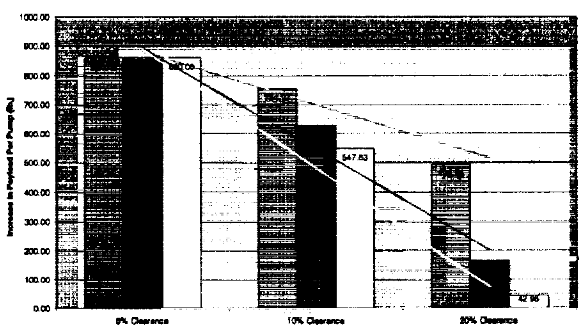

Figure 4 - Increase in payload

Tip Clearance Sensitivity Experiment and CFD Tool Validation Study: Performance of the SSME HPFTP/AT was experimentally verified at the MSFC pump test equipment (PTE) facility[5]. This is a water flow facility capable of testing impellers over a wide range of parameters. Table 2 summarizes the operating parameter ranges.

The modular test article design allows for test with a variety of inlet guide vanes (IGVs), impellers, and diffusers. For this particular test, there were 15 inlet guide vanes with an exit blade angle of 55°. The 6+6+12 impeller design, shown in figure 5, included six full-length blades, six medium-length splitter blades, and 12 short splitter blades. The vaned radial diffuser had 23 flow passages and exited into a generic collector volute. Five shims were manufactured to control the impeller blade tip clearance. The three clearances evaluated in this test are summarized in table 3.

Table 2 - PTE operating envelope.

Parameter	Range
Shaft Speed	360-3600 rpm
Facility Flow Rate	300-3000 gpm
Inlet Total Pressure	4-75 psia
Pump Pressure Rise	0-250 psid
Shaft Torque	0-500 ft-lbf
Drive Line Power	0-350 hp
Water Temperature	60-160 deg F

Figure 5 - Picture of Impeller

Table 3 - Baseline Impeller clearance summary.

Rig Build	Tip Clearance	Percent b_2
1	0.024 inches	5.33%
2	0.065 inches	14.4%
3	0.088 inches	19.6%

Impeller blade passage height – b_2 = 0.45 inches.

Impeller performance over a range of scaled operating conditions was evaluated at a constant shaft speed of 2700 rpm. Five test series were conducted at each tip clearance to document pump performance. Instrumentation included both steady state and dynamic measurement devices. Test article performance was calculated from measured values.

CFD calculations were conducted using this geometry to anchor the CFD analysis tools. Steady state calculations were conducted at three tip clearances for up to three different flow conditions. These conditions are summarized in table 4.

Table 4 – Baseline impeller CFD runs

Tip Clearance	Percent b_2	Percent of design flow rate
0.0271 inches	6.0%	100%, 120%
0.0491 inches	10.9%	80%, 100%, 120%
0.0912 inches	20.2%	80%, 100%, 120%

CFD analysis was performed on individual components of the tester. The flow through the IGVs was computed separately from the flow through the impeller; meaning that any flow characteristics seen in the test due to the coupling of the IGVs and the impeller were not captured in the calculations. In addition, the diffuser in the impeller calculations was modeled as a constant-area vaneless diffuser; whereas, the test rig incorporates a 23 vaned diffuser. Again, any impeller-diffuser flow coupling was not modeled.

Performance comparisons were made between the CFD runs and the test values. Figure 6 shows a head coefficient comparison and figure 7 shows an efficiency comparison. While the computed performance values did not exactly match the experimental values, CFD could do a reasonable job of predicting the change in performance with respect to tip clearance. Table 5 shows the comparison between the CFD and the experiment for predicting performance change between the 6% and 20% cases. In figures 6 and 7, the CFD results do not follow the trends seen in the experimental results at the 80% flow rate. This is thought to be caused by the experiment beginning to experience an IGV stall at that flow rate. An IGV stall is an impeller-IGV flow coupling induced phenomena that cannot be seen in the CFD results because the impeller flow was calculated separately from the IGV flow.

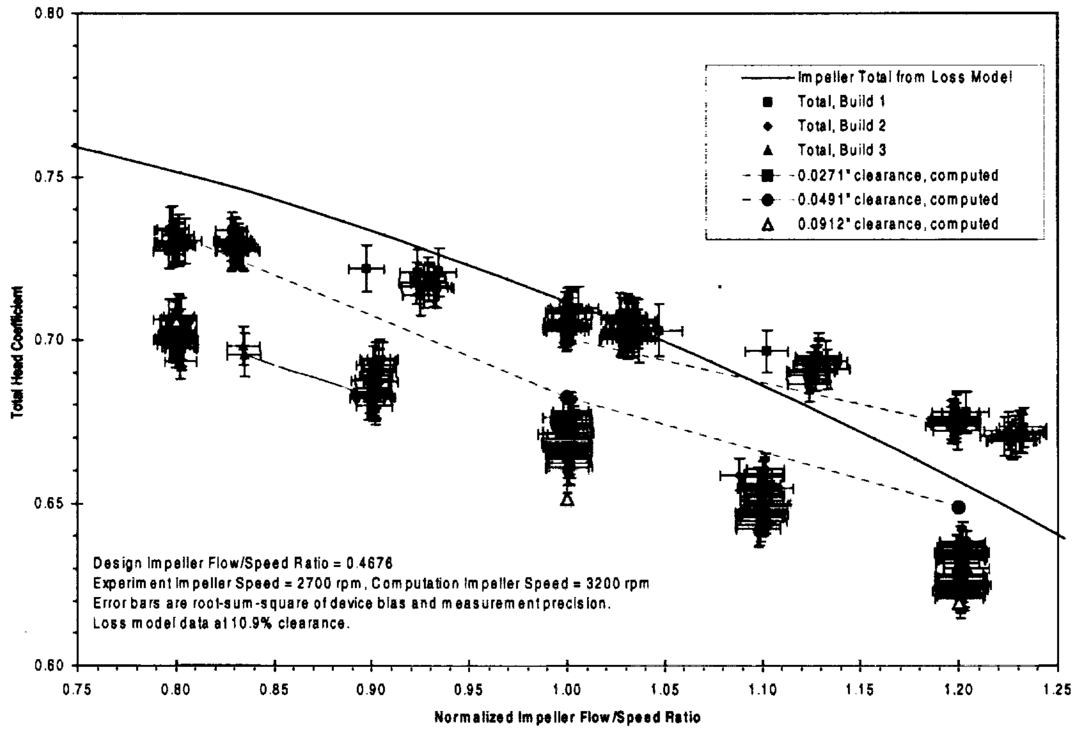

Figure 6 - Head Coefficient Comparison

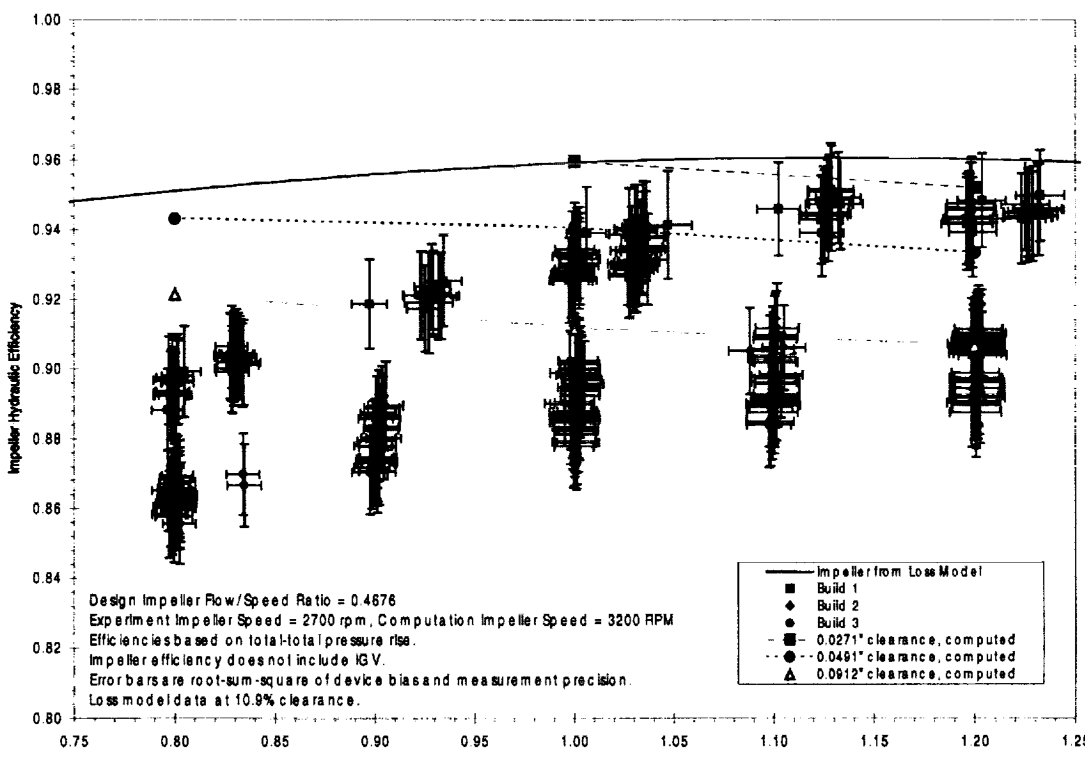

Figure 7 - Efficiency comparison

Table 5 – Performance change between 6% b_2 and 20% b_2

Percent of design flow rate	Change in Efficiency - Test	Change in Efficiency - CFD	Change in Head Coefficient - Test	Change in Head Coefficient - CFD
100%	3.48% to 5.55%	4.79%	0.0315 to 0.0489	0.0491
120%	4.05% to 5.76%	4.55%	0.0438 to 0.0564	0.0540

The CFD results showed that the flow through the unshrouded impeller is complex. Figure 8 shows streamlines for a typical run. The flow was seen to swirl over the blade tips and travel upstream in the tip clearance region.

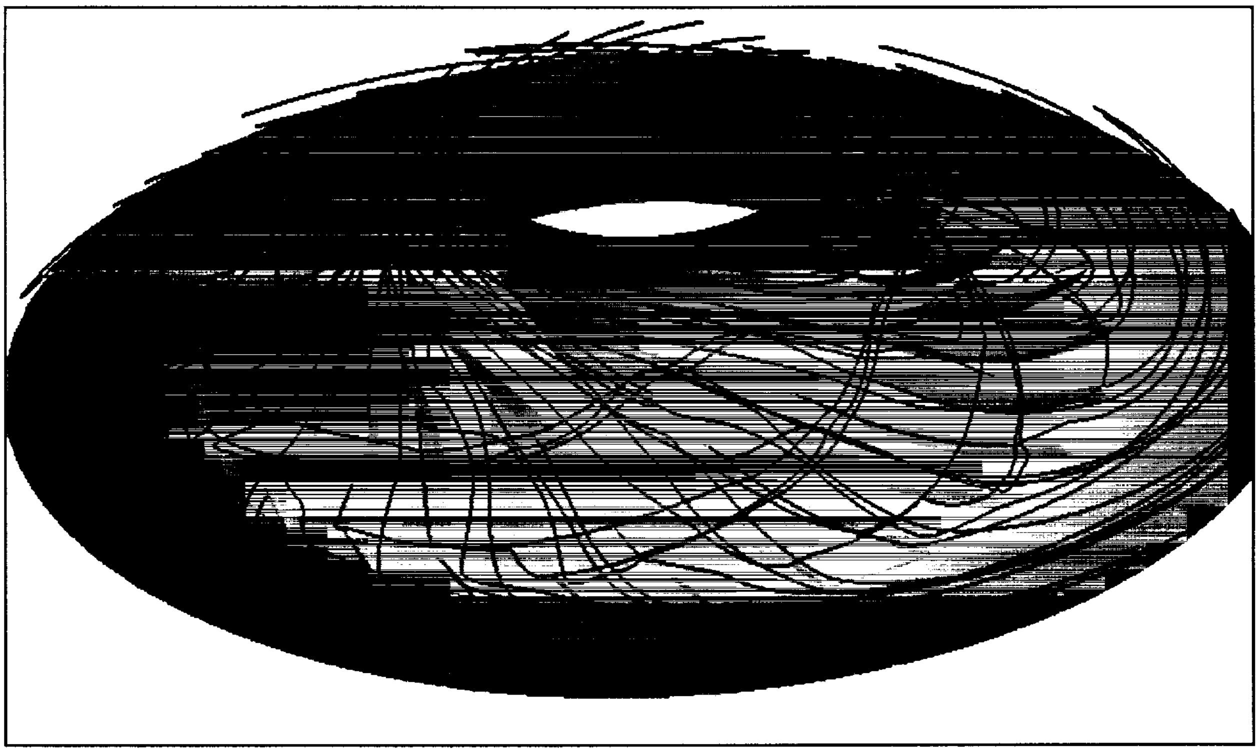

Figure 8 - Streamlines and pressure profile of baseline impeller

Turbopump Mechanical Layout: The final element of this effort was to create a viable turbopump mechanical layout including a two-stage unshrouded impeller for the RLV design point. A preliminary two-stage turbopump mechanical layout was completed based on the candidate RLV engine balance[6]. An inducer was sized to meet the engine suction performance requirements. Assuming long life goals, hydrostatic bearings were baselined. A clutching bearing was integrated into the layout to allow for transient start and shutdown loads. Wear rings and an inter-stage seal were defined to balance axial thrust and provide rotordynamic stability. The turbine envelope definition was based on an advanced turbine under development in a parallel NASA/MSFC project. Axial length, based on design rules, provided spacing between turbine and pump to accommodate turbine temperatures defined in the governing balance. The preliminary mechanical layout for the two-stage RLV HPFTP incorporating unshrouded impellers is illustrated in figure 9.

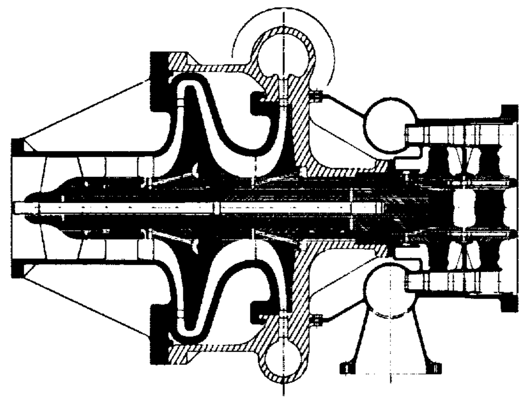

Figure 9 - RLV HPFTP unshrouded concept.

An SSME style rotor stack up was used on the turbopump rotor to ensure adequate preload during assembly, chill, and operation and to maximize rotor stiffness for rotordynamics. The rotor stack up and balance piston was designed to allow for turbopump operational tip-clearance between 6% and 12% of the impeller discharge blade height. The preliminary design also included assessment of axial thrust, rotordynamics, weight, and impeller stress to ensure a viable concept to advance to an operational turbopump.

CURRENT STATUS

The design parametric study, the first phase of the tip clearance sensitivity experiment and CFD tool validation study, and the turbopump mechanical layout have been completed. The tip clearance sensitivity study will include testing using the 6+6 impeller design for the two-stage RLV turbopump. Currently, the test rig is in the process of being installed in the facility. All phases of this activity, including documentation, should be concluded by March, 2001.

MSFC is working with Ames Research Center and Glenn Research Center in the development of codes that can run time-accurate, fully-coupled CFD simulations of the impeller assembly from the IGVs through the impeller and diffuser. Initial versions of these codes are being applied to the flow field in the test rig.

ACKNOWLEDGEMENT

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