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TWO STAGE TURBINE FOR ROCKETS

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ABSTRACT

The aerodynamic design and rig test evaluation of a small counter-rotating turbine system is described. The advanced turbine airfoils were designed and tested by Pratt & Whitney. The technology represented by this turbine is being developed for a turbopump to be used in an advanced upper stage rocket engine. The advanced engine will use a hydrogen expander cycle and achieve high performance through efficient combustion of hydrogen / oxygen propellants, high combustion pressure and high area ratio exhaust nozzle expansion. Engine performance goals require that the turbopump drive turbines achieve high efficiency at low gas flow rates. The low mass flow rates and high operating pressures result in very small airfoil heights and diameters. The high efficiency and small size requirements present a challenging turbine design problem. The shrouded axial turbine blades are 50% reaction with a maximum thickness to chord ratio near 1. At 6 degrees from the tangential direction, the nozzle and blade exit flow angles are well below the traditional design minimum limits. The blade turning angle of 160 degrees also exceeds the maximum limits used in traditional turbine designs.

INTRODUCTION

Studies at NASA have identified the need for a new propulsion system that can be utilized for a variety of missions. The goal of NASA's Advanced Chemical Engine (ACE) program is to develop key technologies required for the propulsion system of space vehicles such as upper stages, orbit transfer vehicles and landers. The new system will be an oxygen / hydrogen expander cycle engine that will rely on efficient components in order to achieve high performance. The range of missions demand that the engine should be capable of a high degree of throttling and operate over a wide range of propellant mixture ratios. In order to develop an engine with these qualities, several component technologies must first be demonstrated. The Advanced Expander Test Bed (AETB) described in references 1 and 2 has been designed by Pratt & Whitney in order to develop and demonstrate advanced components in an expander engine environment. Key technologies to be validated include the performance levels of the advanced turbopumps and system interaction effects at off-design operating conditions. A key part of the turbopump overall performance is the aerodynamic performance of the small, but high energy density two stage counter-rotating turbine. The aerodynamic performance of the counter-rotating turbine concept within the hydrogen turbopump has been demonstrated early in the AETB program. Pratt & Whitney has designed and tested a two stage turbine in a full scale rig at equivalent engine operating conditions using air as the test fluid (references 3 and 4).

TURBINE DESIGN

The turbines are required to have high efficiency in order to meet the performance goals of the AETB and future liquid space propulsion engines. The AETB hydrogen turbopump cross-section in Figure 1 shows the dual spool configuration. The two stage counter-rotating turbines use warm gaseous hydrogen as the working fluid to drive the primary and the secondary liquid hydrogen pumps.

The aerodynamic design process for the turbines was initiated with flow path parametric optimization studies using a meanline analysis and is described in reference 3. The design configuration that resulted from the optimization studies are two full admission 50% reaction turbines. The full admission turbine flow path allowed the use of efficient high reaction rotor blading. The selection of a full admission turbine configuration required a primary turbine blade turning angle of 160.6°, well above the traditional limit of 140°. Streamline analyses using a 3-D multi-stage Euler flow solver were used to analyze the complete turbine system. After numerous iterations, satisfactory airfoil contours were obtained that resulted in acceptable static pressure distribution along the airfoil surfaces, while minimizing the axial flow reversal due to the low axial thru-flow component of velocity. The resulting turbine airfoil shapes and the flow path are shown in Figure 2. The nozzle inlet angle is set at 22° to take advantage of the swirl produced by the tangential inlet volute. In this way, the reduced turning required through the nozzle vane results in reduced aerodynamic losses. Similarly, the flow exiting the second stage rotor has a high degree of swirl for reduced turning losses in the exit volute. The predicted velocity triangles during engine operation (hydrogen driven) are shown in Figure 3. While this two stage turbine is the result of numerous engine cycle design iterations, it is not the final turbine configuration that will be used in the AETB, but is very similar in overall dimensions and performance.

TURBINE TEST RIG

In order to verify the performance of the turbine in the engine, a turbine test rig using room temperature air at reduced pressure as the working fluid was designed and built. The design point aerodynamic performance requirements for both the primary and the secondary turbine stages in the engine and in the turbine rig are shown in Table I. With the exception of Reynolds number, all of the key operating parameters can be simulated in the rig. The variation in efficiency between the engine and the rig is based on a predicted Reynolds number correction using turbulent boundary layer correlations. The predicted velocity triangles during testing in air at the referred conditions of Table I are shown in Figure 4. Rig instrumentation includes total pressure and temperature rakes, flow angle seeking cobra probes, wall static pressure taps and shaft torquemeters. The instrumentation has circumferentially traversable rings for measuring pressure and temperature contours in the inlet and exit flow fields.

Table I

Engine and Rig Operating Parameters

Parameter	Engine	Rig
Working Fluid	Hydrogen gas	Air
P inlet (psia)	3500.	100.
T inlet (°R)	985.	575.
Flow Rate (lbm/sec)	3.49	0.50
Primary Turbine		
RPM	100,000.	20,000.
Press. Ratio (T-T)	1.48	1.48
Predicted η (T-T)	79.0	76.8
Um / Co	0.45	0.45
Horsepower (HP)	1365.9	8.0
Work Δh (BTU/lbm)	276.7	11.3
γ	1.39	1.40
Reynolds No. (avg.)	3.75xE6	3.95xE5
Secondary Turbine		
RPM	100,000.	20,000.
Press. Ratio (T-T)	1.35	1.35
Predicted η (T-T)	86.1	84.3
Um / Co	0.515	0.515
Horsepower (HP)	1050.0	6.2
Work Δh (BTU/lbm)	212.7	8.8

PERFORMANCE TESTING

The test program was performed at Pratt & Whitney using warm air at 100 psia turbine inlet pressure. Test point conditions of inlet pressure and pressure ratio were controlled by the rig inlet and exit valves. The primary turbine stage was evaluated first over a wide a range of Reynolds numbers as possible, being limited by maximum allowable rig inlet pressure. The primary turbine efficiency at the design pressure ratio as a function of mean velocity ratio is shown in Figure 5 and is in excellent agreement with the expected level. In the next series of tests, the primary and secondary turbine stages were tested together with and without the vane in the secondary turbine stage. The best performing configuration was the two stage turbine with a vaneless secondary stage. The measured overall two stage counter-rotating turbine efficiency (vaneless secondary stage) is shown in Figure 6 for operation over a range of velocity ratios at design point pressure ratio.

CONCLUSIONS

The aerodynamic design and rig testing of the two stage counter-rotating turbine for an advanced upper stage rocket engine turbopump has been completed. The turbine configuration is unconventional in that it utilizes a full admission design in an application region that traditionally has used a partial admission turbine. The two stage full admission turbine having high blade turning and low exit angles has performed satisfactorily in an extensive series of rig tests. Measured efficiency levels of the primary and the vaneless secondary turbines are in close agreement with the predictions.

ACKNOWLEDGEMENTS

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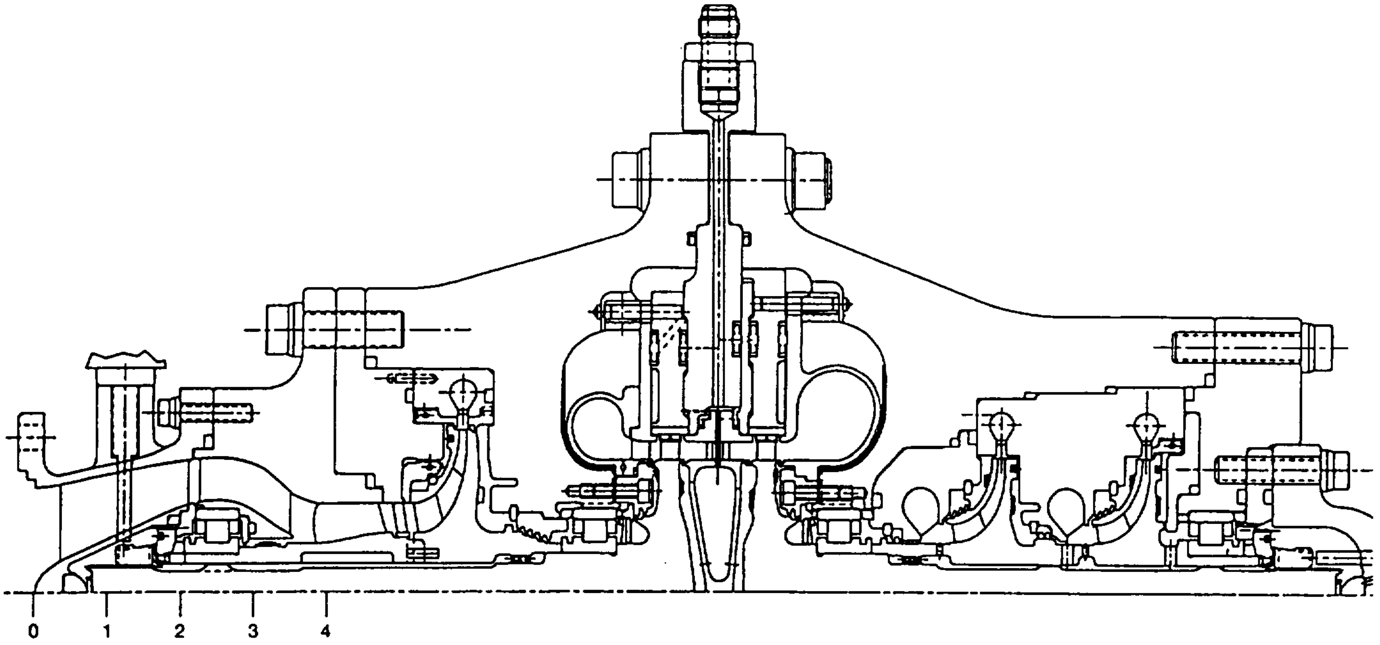

Figure 1 Liquid Hydrogen Turbopump Utilizing Two Stage Counter-Rotating Turbines.

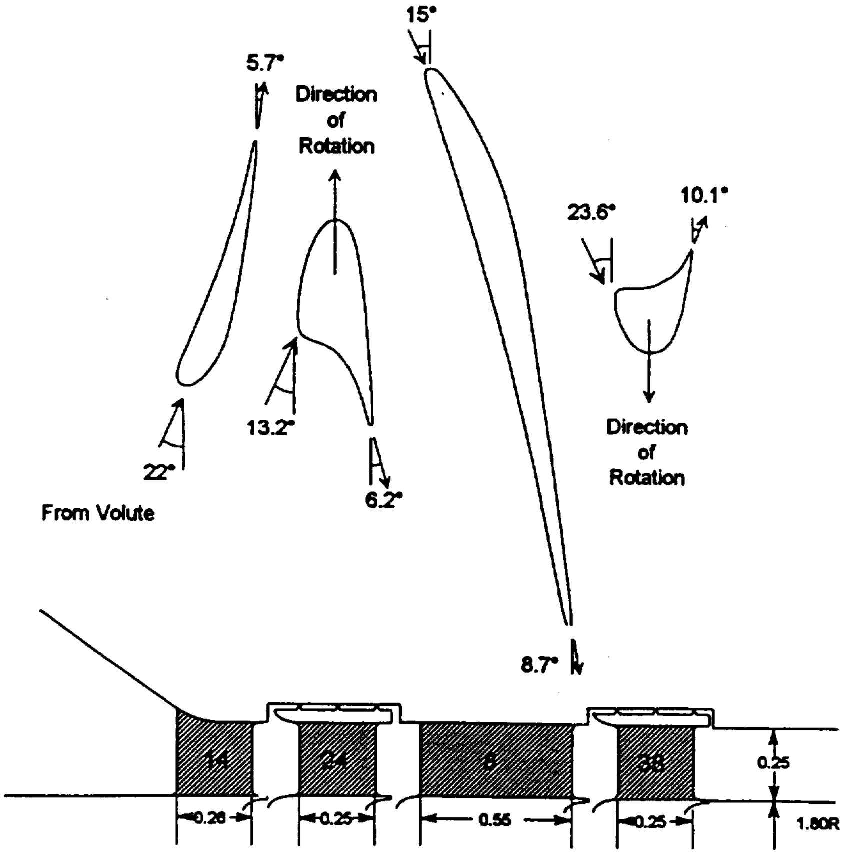

Figure 2 Pump Drive Turbine Airfoil Shapes and Flow Path Elevation.

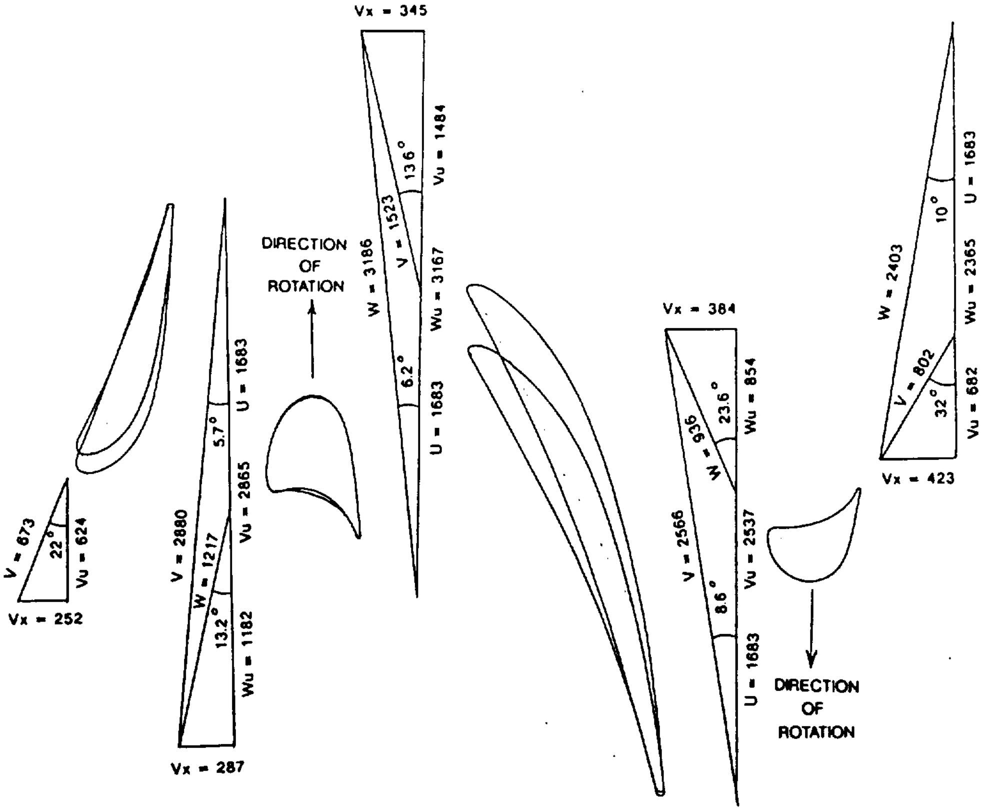

Figure 3 Engine Design Point Gaseous Hydrogen Driven Turbine Meanline Velocities.

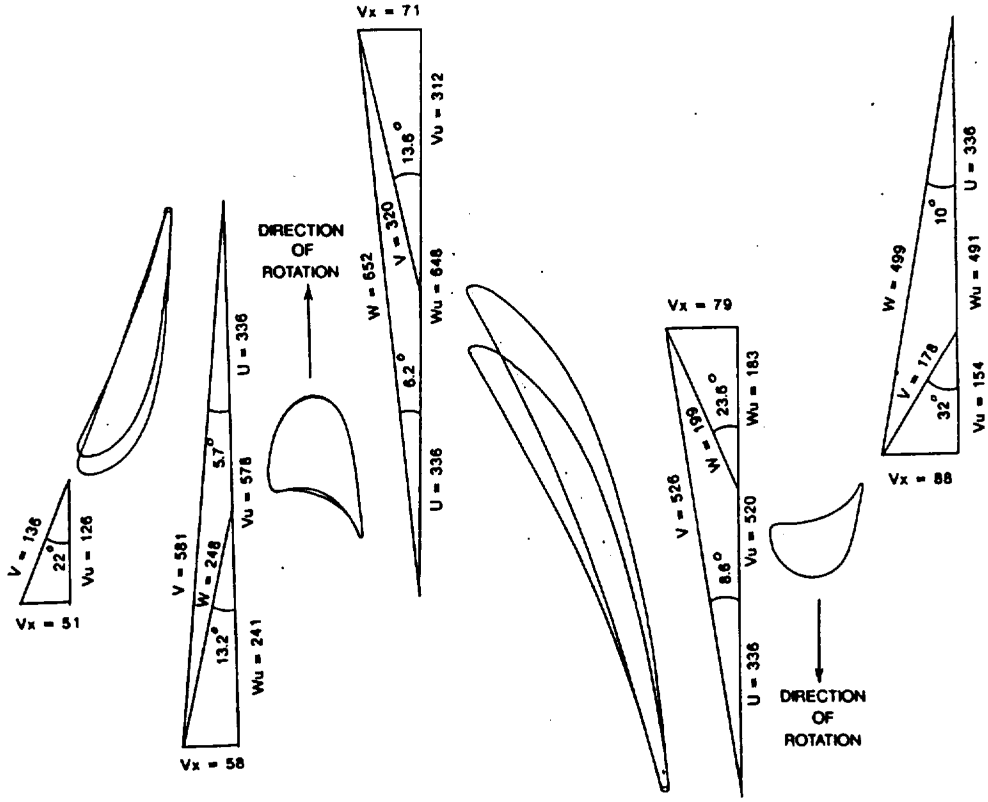

Figure 4 Meanline Velocity Triangles, Air Driven at Referred Conditions

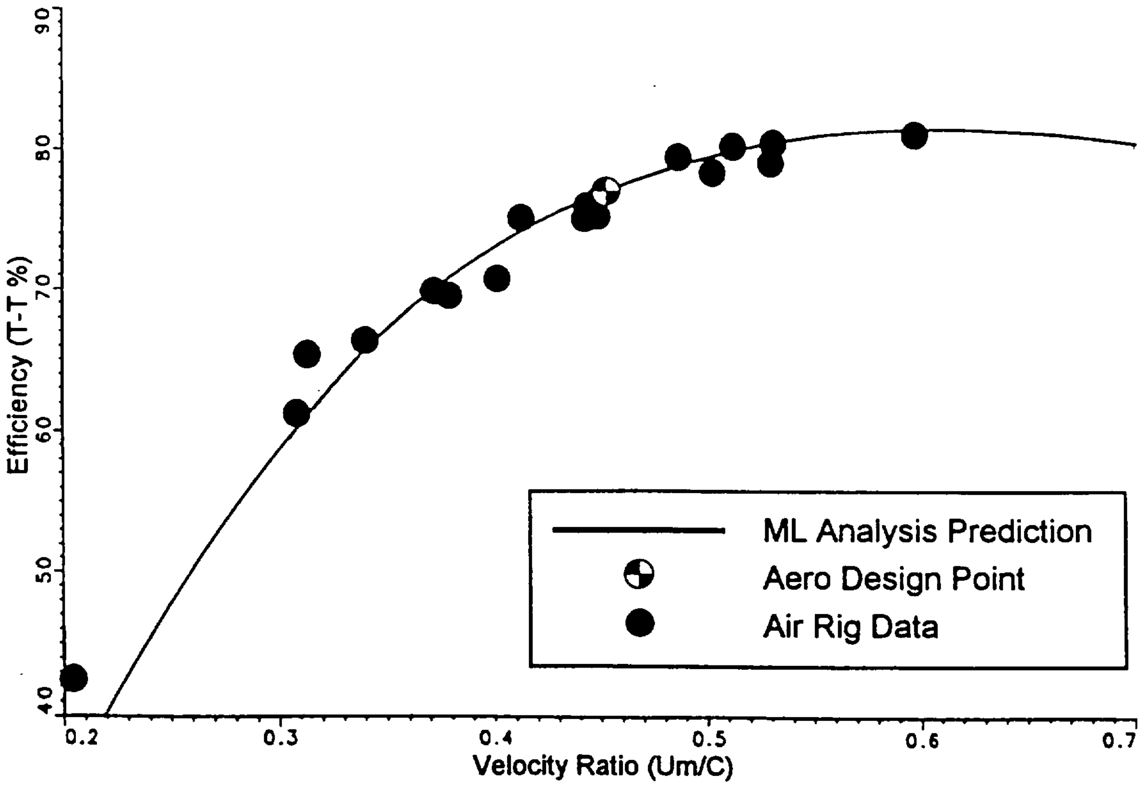

Figure 5 Primary Turbine Stage Efficiency. (Ref. 3)

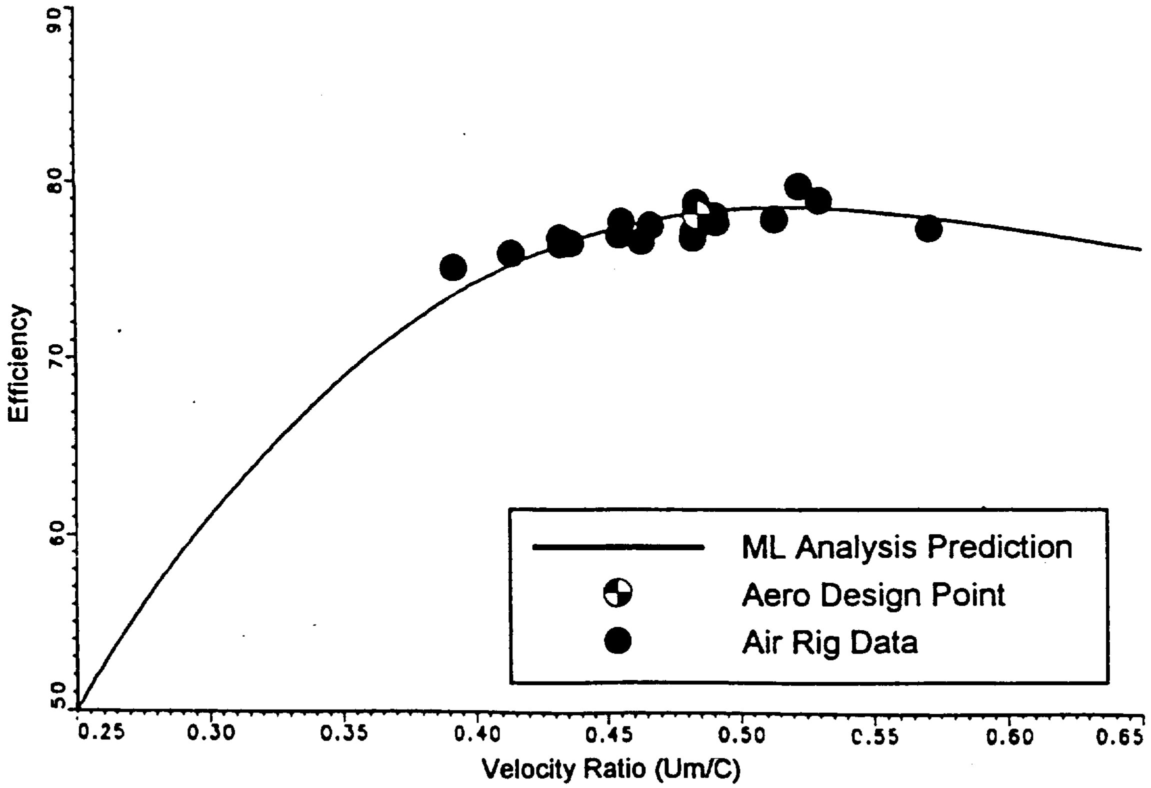

Figure 6 Overall Two Stage (Primary & Vaneless Secondary) Turbine Efficiency. (Ref. 3)