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Research Article

The Application of Counter-Rotating Turbine in Rocket Turbopump

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Counter rotating turbine offers advantages on weight, volume, efficiency, and maneuverability relative to the conventional turbine because of its special architecture. Nowadays, it has been a worldwide research emphasis and has been used widely in the aeronautic field, while its application in the astronautic field is seldom investigated. Researches of counter rotating turbine for rocket turbopump are reviewed in this paper. A primary analysis of a vaneless counter rotating-turbine configuration with rotors of different diameters and rotational speeds is presented. This unconventional configuration meets the requirements of turbopump and may benefit the performance and reliability of rocket engines.

1. INTRODUCTION

Turbopump is one of the main modules of liquid rocket engine and represents a large part of rocket engine overall cost. So improving the efficiency of turbopump and reducing its weight are effective ways to improve the performance of rocket engine [1]. Furthermore, to simplify the mechanical architecture of turbopump may improve the reliability of rocket engine.

Because of difference in densities of propellants, oxidizer pump and fuel pump of rocket engine require different rotational speed to avoid the caviation erosion. Generally, oxidizer's rotational speed is higher because the density of the oxidizer is higher than that of the fuel. What's more, for low density fuel, improving rotational speed can reduce the fuel-pump diameter and volume remarkably.

At early age, some LH2/LOX engines with a single turbine drive the LH2 pump, and by gearbox the LOX pump directly. But gearbox brings excess weight and reduces credibility of engine in the cryogenic environment of LH2. Two turbines in series driving pumps, separately, is another solution, however, this configuration will bring excess losses and make the engine more complex and less credible.

The counter rotating turbine is an axial turbine with a first stator followed by a first rotor, an optional second stator, and a second rotor, which rotates in opposite direction of the first stage. In 1958, Wintucky [2] presented the basic analysis of counter rotating turbine with restricted hypothesis like the same mean diameters for each rotor, the same rotational speed, and constant axial velocity. In 1980s, the scientific researchers made wide researches on counter-rotating turbine by stimulation of IHPTET (the integrated high-performance turbine-engine technology program), and now several countries have developed counter-rotating turbines for aircrafts.

Because of its unconventional architecture, counter-rotating turbine offers advantages on weight, volume, efficiency, and maneuverability relative to traditional multistage turbines. It must be emphasized that configuration of counter-rotating rotors can reduce the torque on the aircraft remarkably, so the maneuverability of aircraft driven by counter-rotating turbine engine is much higher.

These advantages are also helpful for rocket engines. The counter-rotating turbine with two rotors, which have different rotational speeds and powers to drive the fuel pump and oxidizer pump, respectively, is proposed (see Figure 1). This configuration can avoid the disadvantages of gearbox and two turbines configuration is mentioned in the above paragraphs.

2. REVIEW OF COUNTER-ROTATING TURBINE FOR TURBOPUMP

In 1984, Narou [3] of ISAS presented the idea of application of counter-rotating turbopump on upper-stage LOX/LH2 rocket engine.

In a research of NASA ACE project (advanced chemical engine), Huber and Veres [4–6] design a counter-rotating turbine for the upper-stage rocket engine. They take full-scaled experiments upon the turbine, and the experimental data accord well with the theoretical prediction. An unconventional blade with a 160° turning angle is introduced into this counter-rotating turbine. Earlier investigation on this blade in the National Launch System project [7, 8] indicates that it can improve turbine efficiency and decrease blade number remarkably.

In 1993, researchers of NAL [9–13] designed a counter-rotating turbine experiment facility and took a series of theoretical analysis, numerical simulations, and experiments on the counter-rotating turbine. Their research included a secondary flow loss of ultra-high-load turbine, feasibility of counter-rotating turbine and rotor-rotor interaction. NAL counter-rotating turbine also adopts UHLTC [10] (ultra-highly loaded turbine cascade) with 160° turning angle. Experimental data show the flow structures, and the loss mechanisms in UHLTC were basically the same as those seen in the conventional cascades, except for stronger-passage and leakage vortices. A large internal loss generates in cascade passage, and a large downstream mixing loss is found. Yamamoto figures out that those losses come from the strong passage vortices and the associated laminar flow separation due to the extremely large turning angle. Preliminary comparison between the experimental results and Hah's numerical predictions shows a good agreement [13].

Pratt and Whitney have developed a twin rotor turbopump (TRT) [14] for NASA ablative engine. The TRT is a liquid LOX/Kerosene turbopump that incorporates a back-to-back counter-rotating turbine. Although the counter-rotating turbine for a turbopump is theoretically good, there is no flight-proven counter-rotating turbine for fluid rocket engine despite of the above scientific projects.

3. VANELESS CONFIGURATION OF COUNTER ROTATING TURBINE

In order to obtain higher-engine performance, vaneless configuration of counter-rotating turbine is proposed. In the following, paragraphs, this kind of turbine will be called 1 + 1/2 counter-rotating turbine. The "1" means a full high-pressure stage (HP) with stator and rotor, while the "1/2" means the vaneless low-pressure stage (LP). This vaneless configuration offers significant potential advantages.

(i) The weight and volume of the engine is reduced remarkably because of the abolition of LP stator row.

(ii) Losses associated with LP stator blade are avoided.

(iii) The reliability of the engine is improved because the turbine structure is simplified.

Although the vaneless configuration may benefit turbine efficiency and engine reliability, it will bring difficulties to organize the flow in low-pressure rotor passage. So actually, it's not easy to get theoretic high efficiency.

In 1993, Huber and Veres [4] conducted contrastive experiments on 1 + 1/2 and 1 + 1 counter-rotating turbines. As the experiments results show, the removal of the LP stator is predicted to cause a significant increase in gas-incidence angle entering the LP rotor. This off-design incidence is predicted to decrease overall turbine efficiency approximately 3% at the design point. Performance estimates based on their test results indicate that an LP rotor designed for 1 + 1/2 turbine would achieve an increase in efficiency of 2% relative to a 1 + 1 counter-rotating turbine at the aero design point, and up to 7% higher efficiency at reduced-speed operation.

Yamamoto [12] also took experiments on vaneless counter-rotating turbine to investigate the cascade internal flow and loss mechanisms under the rotating condition. He found that low-energy fluids tend to migrate to the tip endwall in the rotating case while to the hub endwall in the stationary case.

Pempie and Ruet [15] compared three solutions for LOX/LH2 turbopump: 1 + 1 counter-rotating turbine, 1 + 1/2 counter-rotating turbine, and two turbines in series. As the results show, the configuration of 1 + 1 counter-rotating turbine is considered the best choice because of its good integration of arrangement and efficiency.

Pempie and Ruet also compared conventional turbine and counter-rotating turbine in another application to LOX/Methane main rocket engine. According to the comparison results, the counter-rotating turbine they design is smaller than the conventional single turbine, and reduces mass-flow rate remarkably. As a result of optimization, the rocket engine employing counter-rotating turbine obtains the specific impulse of 1.7 second increases.

Theoretical analysis presented by Ji Lucheng [16] indicates that the work ratio (the ratio of HP rotor work to LP rotor work) is propitious to obtain high efficiency. Generally, high-work ratio is unsuitable for the aircraft engine. However, it meets the requirements of the rocket turbopump by the square because the pumps of rocket engines demand different input powers (see Figure 2).

4. COUNTER-ROTATING TURBINE WITH ROTORS OF DIFFERENT DIAMETERS

Previous analysis has indicated that the counter-rotating turbine with rotors, which have different rotational speeds, can avoid the disadvantages of the gearbox and two turbines configurations.

In 2003, Pempie and Ruet [15] presented their solution of the counter-rotating turbine for the rocket turbopump. They introduced a counter-rotating turbine with rotors of different rotational speeds and mean diameters, which is quiet different to the existing one, and present a basic one-dimensional design theory for this turbine basing on the traditional turbine design method.

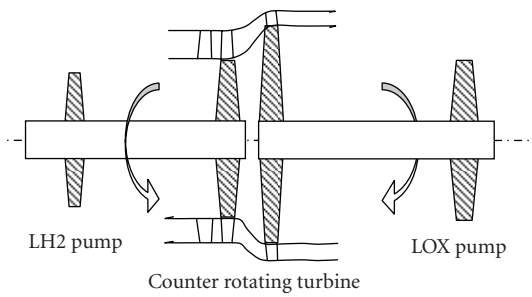

Figure 1: Counter-rotating turbopump.

Two rotors are used to drive the pumps, respectively, so rotational speeds and works of the rotors are determined by requirements of pumps:

$$N_A = N_O, \qquad N_B = N_F,$$
$$\frac{\Delta h_A{}^*}{\Delta h_B{}^*} = \frac{P_F}{P_O} = \frac{U_A(V_{U1} - V_{U2})}{U_B(V_{U3} - V_{U4})}. \tag{1}$$

The velocity triangle-calculation process of the counter-rotating turbine is similar to the traditional multistage turbine except for the difference of rotors mean diameters. According to the conservation laws of mass and momentum moment, parameters on LP outlet section and HP inlet section must satisfy

$$\rho_2 D_A H_A V_{2M} = \rho_3 D_B H_B V_{3M}$$
$$D_A V_{2U} = D_B V_{3U}. \tag{2}$$

The following equation expresses the efficiency of turbine:

$$\eta = \frac{U_A(V_{U1} - V_{U2}) + U_B(V_{U3} - V_{U4})}{\Delta h}. \tag{3}$$

The degrees of freedom are the following:

(i) the mean diameters of rotors: D_A, D_B;
(ii) the mean blade speed: U_A, U_B;
(iii) the degree of reaction Ω and the pressure distribution through the turbine blade.

5. PRIMARY EFFICIENCY ANALYSIS OF THE COUNTER-ROTATING TURBINE

In 2001, Lucheng [16] presented a primary efficiency analysis of 1 + 1/2 counter-rotating turbine basing on conventional multistage turbine-analysis theory. Although his analysis does not take the difference of rotor diameters into account, the existing analysis method can be also suitable for this new-style counter-rotating turbine after giving some modification on velocity-diagram calculation according to Pempie's one-dimensional design theory.

In order to simplify the architecture of the rocket engine, the simplest 1 + 1/2 configuration is adopted, which consists of HP stator, HP rotor for fuel pump, and LP rotor for oxidizer pump. Turbine inlet and outlet flow directions are assumed to be axial. Velocity triangles of the turbine are illustrated by Figure 3.

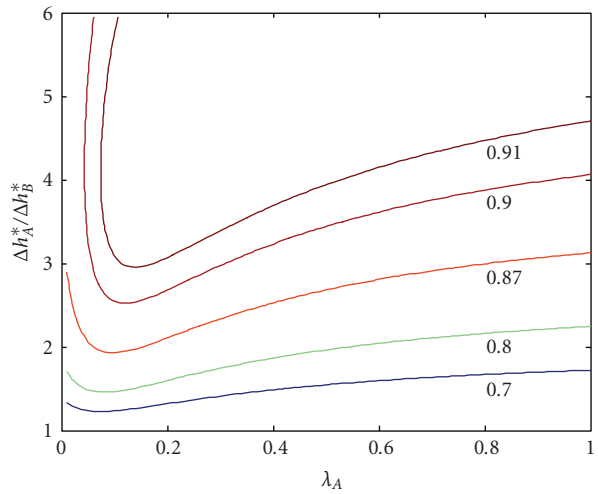

Figure 2: Influence of work ratio on HP efficiency.

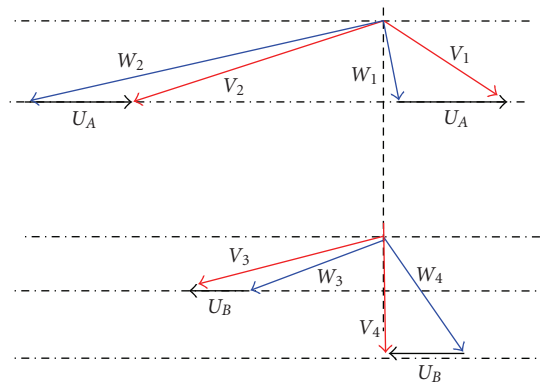

Figure 3: Velocity triangle diagram.

The work-speed coefficient λ is introduced to correlate turbine efficiency. It's defined as the ratio of the square of the blade velocity to the specific work of the stage as follows:

$$\lambda_A = U_A^2/\Delta h_A{}^* = U_A/\Delta V_A$$
$$\lambda_B = U_B^2/\Delta h_B{}^* = U_B/\Delta V_B. \tag{4}$$

Referring to the velocity triangle diagram, the changes of circumferential absolute velocities can be derived as follows:

$$\begin{aligned} V_{1U} &= W_{1U} + U_A \\ V_{2U} &= W_{2U} + U_A \\ V_{3U} &= W_{3U} + U_B \\ V_{4U} &= W_{4U} + U_B = 0 \end{aligned} \quad \Longrightarrow \quad \begin{aligned} \Delta V_A &= W_{1U} - W_{2U} \\ \Delta V_B &= W_{3U} - W_{4U} = V_{3U}. \end{aligned} \tag{5}$$

In this analysis, it's assumed that row loss is in direct proportion to average kinetic energy at row inlet, so the efficiency of the high-pressure stage can be written as

$$\eta_A = \frac{\Delta h_A{}^*}{\Delta h_A{}^* + k_S\omega(V_0{}^2 + V_1{}^2) + k_R\omega(W_1{}^2 + W_2{}^2)}, \quad (6)$$

where ω represents the ratio of a blade-surface area to an equivalent weight flow per unit-annular area, and as an assumption, the relation between rotor-loss coefficient k_R and stator-loss coefficient k_S is obtained as $k_R = 2k_S$. According to some experiential relation expressions in [17], the expression of η_A can be modified to

$$\eta_A = \frac{\lambda_A}{\lambda_A + 0.01172\cdot\tan|\alpha_1|\cdot\Pi} \quad (7)$$

$$\Pi = (1+\Psi)^2(6\,\mathrm{ctg}^2\alpha_1 + 1) + 2(1+\Psi-\lambda_A)^2 + 2(\Psi-\lambda_A)^2,$$
$$\Psi = U_B/U_A\cdot\lambda_A/\lambda_B.$$

Expression of η_B can be obtained by applying the method used in deriving η_A as follows:

$$\eta_B = \frac{\lambda_B}{\lambda_B + T\tan|\alpha_3|\left\{4\,\mathrm{ctg}^2\alpha_3 + 2\left[(1-\lambda_B)^2 + \lambda_B^2\right]\right\}}. \quad (8)$$

The efficiency of turbine can be expressed as

$$\eta = \frac{1/\lambda_A + (U_B/U_A)^2(1/\lambda_B)}{1/\lambda_A\eta_A + (U_B/U_A)^2(1/\lambda_B\eta_B)}. \quad (9)$$

In order to obtain these analytical expressions, some experiential relation expressions are introduced, and reheat effect and the secondary flow loss due to the change of rotors diameter are ignored. So the results of this primary analysis are instructional to the selection of design parameters but not so exact.

6. EFFICIENCY OPTIMIZATION

According to the above-mentioned analysis, turbine efficiency is expressed as terms of blade-velocity ratio U_B/U_A, work-speed coefficient λ_A, λ_B, and flow angle α_1 and α_3. So the performance of turbine can be optimized by adjusting these parameters, and the optimization processes are illustrated with contour charts of efficiency in Figures 4–6. These charts are plotted on the condition of $\alpha_1 = 60^\circ$, $\alpha_3 = 60^\circ$, $U_B/U_A = -0.3$, and more charts corresponding to various conditions are not shown here for limitation on extent. According to the comparison of Figures 4–6, turbine efficiency η is mainly decided by the high-pressure stage.

The influence of α_1 on HP efficiency is illustrated by Figure 7 plotted on the condition of $\lambda_A = 0.6$, $U_B/U_A = -0.3$. When α_1 satisfies the following equation, η_A can achieve maximum:

$$\alpha_1 = \mathrm{arctg}\sqrt{\frac{6\Psi^2}{\Psi^2 + 2(1+\Psi-\lambda_B)^2 + 2(\Psi-\lambda_B)^2}}. \quad (10)$$

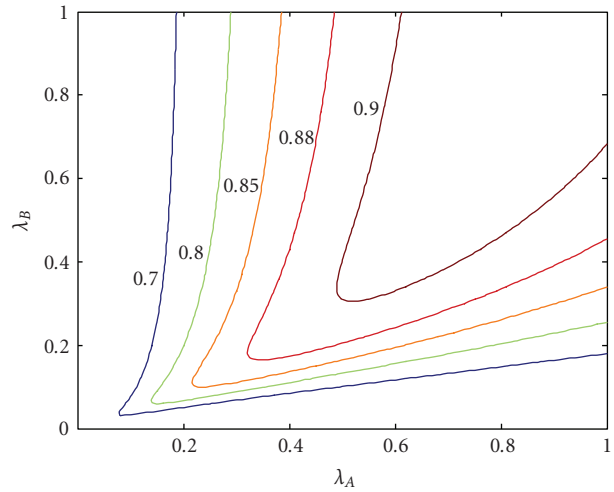

Figure 4: Contour of HP stage efficiency.

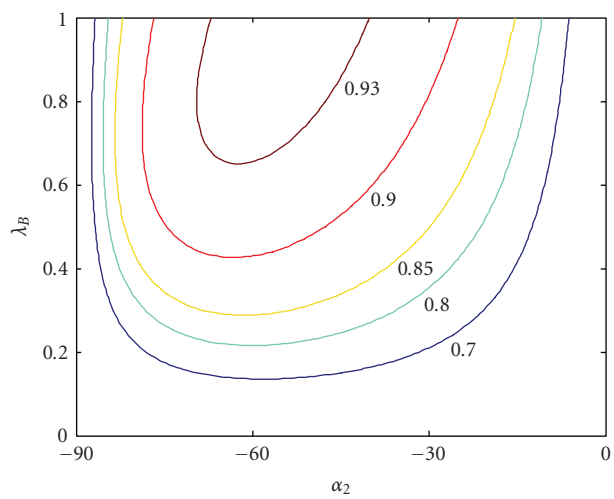

Figure 5: Contour of LP stage efficiency.

When α_3 satisfies the following equation, η_B can achieve maximum:

$$\alpha_3 = \mathrm{arctg}\frac{\lambda_B}{\lambda_B + 0.09376\sqrt{\lambda_B{}^2 - \lambda_B + 0.5}}. \quad (11)$$

7. INFLUENCE OF ROTORS DIAMETER CHANGE

For a certain design project, pump rotational speed ratio N_O/N_F and pump work ratio P_F/P_O are given by requirements of pumps, so blade velocity ratio U_B/U_A can be expressed as

$$\frac{U_B}{U_A} = \frac{N_B}{N_A}\frac{D_B}{D_A} = \frac{N_O}{N_F}\frac{D_B}{D_A}. \quad (12)$$

Combine definition expressions of λ_A and λ_B to yield

$$\lambda_B = \left(\frac{\Delta h_A{}^*}{\Delta h_B{}^*}\right)\left(\frac{U_B}{U_A}\right)^2\lambda_A = \left(\frac{P_F}{P_O}\right)\left(\frac{N_O}{N_F}\frac{D_B}{D_A}\right)^2\lambda_A. \quad (13)$$

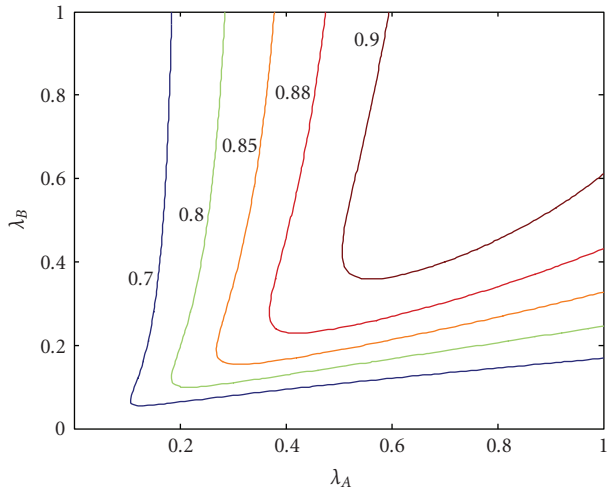

Figure 6: Contour of turbine efficiency.

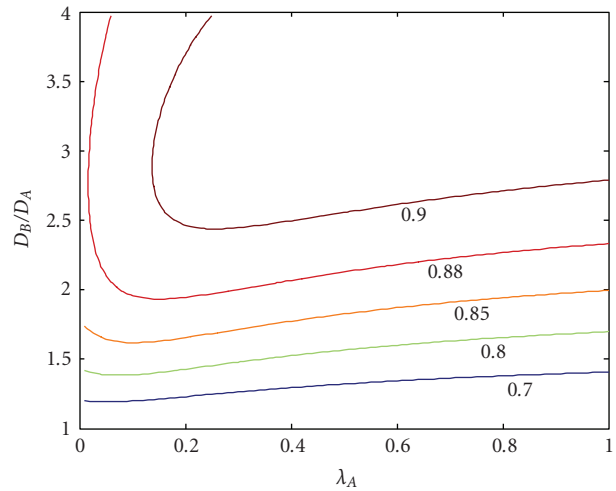

Figure 8: Contour of HP stage efficiency.

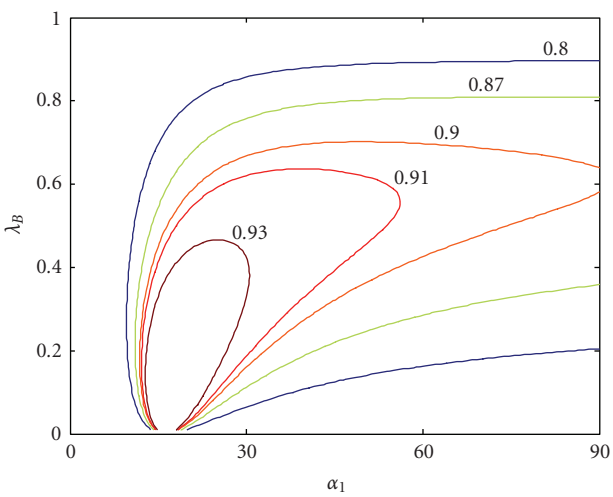

Figure 7: Contour of HP stage efficiency.

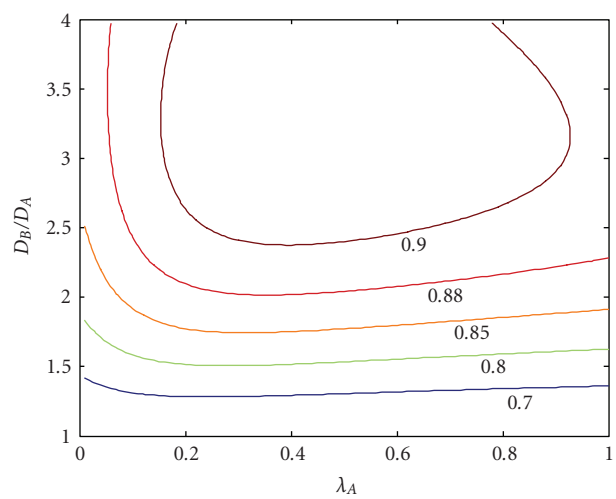

Figure 9: Contour of turbine efficiency.

Then the turbine efficiency can be expressed as terms of rotors diameter ratio D_B/D_A, λ_A, α_1, and α_3. Referring to the requirements in Table 1 and condition of $\alpha_1 = 50^\circ$, $\alpha_3 = 60^\circ$, contour charts of efficiency are plotted as Figures 8 and 9.

As these figures show, high-rotor-diameter ratio D_B/D_A may benefit the performance of turbine, but actually, excessive D_B/D_A may make the duct geometry between two rotors unconventional and bring some excess losses.

The primary fluid mechanical problem of this type of duct is caused by the tendency of the boundary layer to separate from walls if the channel curvature is too high. The result of too high curvature is always large losses. On the other hand, if the curvature is too low, the fluid is exposed to an excessive length of duct and friction losses.

Duct pressure loss, defined as the following expression, is introduced to evaluate the losses in duct:

$$\mathrm{Loss}_D = \frac{p_2{}^* - p_3{}^*}{p_2{}^*}. \tag{14}$$

Duct total pressure loss is a function of the duct geometry and the inlet dynamic pressure head [18] as follows:

$$\mathrm{Loss}_D = L(p_2{}^* - p_2), \tag{15}$$

where duct geometry is accounted by a loss coefficient L. Value of L for a given geometry must initially be determined from experience and by using commercially available correlations. The variation of L with inlet swirl angle is illustrated by Figure 10. So once duct geometry has been set, then total pressure loss only varies with inlet dynamic head and swirl angle.

Considering the complicated influence of duct geometry on turbine efficiency, to select a moderate diameter ratio is very important for optimization of turbine performance. In order to reduce duct losses, the duct geometry between two rotors has to be designed carefully, and as shown in [18], total pressure loss of well-treated swan-neck duct is no more

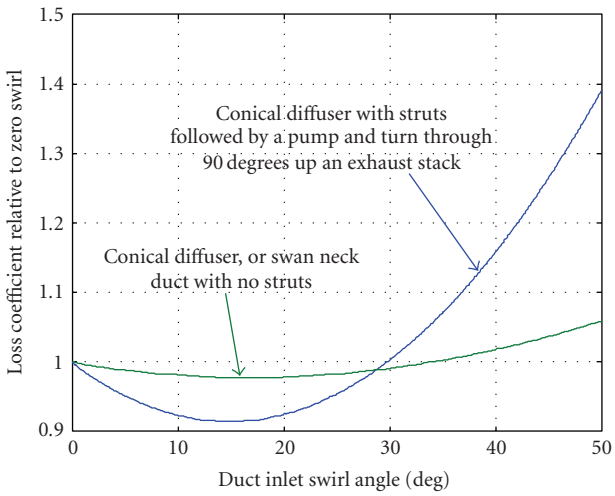

Figure 10: Effect of inlet swirl on loss coefficient (P. P. Walsh, P. Fletcher, *Gas Turbine Performance*).

Table 1: Requirements of LH2/LOX pumps.

	LH2 Pump	LOX Pump
Work	2500 kW	390 kW
Rotational speed	91000 rpm	18800 rpm

than 2.5%. However, if D_B/D_A is too high, boundary layer separation may occur and secondary flow loss will be high. At this time, the 1 + 1 counter-rotating turbine will be more suitable because the LP stage stator can benefit the flow field organization.

Finally, it must be emphasized that this evaluation of duct losses is just approximate and only for primary analysis.

8. CONCLUSION

Counter-rotating turbine can improve performance and reliability of rocket engine because of its special architecture and high performance. The counter-rotating turbine with two rotors of the different diameters and rotational speeds can optimize performance and configuration of rocket engine. Review of research on counter-rotating turbine for rocket turbopump is presented in this paper.

Primary analysis basing on conventional turbine-design theory for this unconventional 1 + 1/2 counter-rotating turbine has been proposed. The influence of optimization parameters on turbine efficiency is illustrated by contour charts and analytical expressions. For a certain project, free design parameters are D_B/D_A, λ_A, α_1, and α_3, and as the results show, the overall turbine efficiency is determined mainly by the high-pressure stage. Finally, influence of rotors diameter changes, and duct geometry between two rotors on the turbine efficiency is discussed. To reduce losses in the duct, moderate diameter ratio and well-treated duct geometry are necessary. LP stator is also helpful to avoid the secondary flow in the duct, if necessary.

NOMENCLATURE

A: Area
D: Mean diameter of rotors
G: Mass flow
h: Enthalpy
H: Blade height
k: Loss coefficient
N: Rotational speed
U: Rotor blade velocity
V: Absolute velocity
W: Relative velocity
P: Power (or work)
p: Pressure
Q: Average dynamic pressure
α: Angle with absolute velocity
β: Angle with relative velocity
λ: Work-speed coefficient
η: Efficiency

SUBSCRIPT AND SUPERSCRIPT

A: High-pressure stage
B: How-pressure stage
D: Duct (between two rotors)
F: Fuel pump
O: Oxidizer pump
S: Stator
R: Rotor
U: Circumferential (velocity triangle)
M: Axial (velocity triangle)
$*$: Stagnation
0: Inlet of high-pressure stator
1/2: Inlet/outlet of high-pressure rotor
3/4: Inlet/outlet of low-pressure rotor

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