Design of Single Stage Axial Turbine with Constant Nozzle Angle Blading for Small Turbojet

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Abstract. In this paper, an aerodynamic design of a single stage gas generator axial turbine for small turbojet engine is explained. As per design requirement, the turbine should be able to deliver power output of 155 kW at 0.8139 kg/s gas mass flow, inlet total temperature of 1200 K and inlet total pressure of 335330 Pa. The design phase consist of several steps, i.e.: determination of velocity triangles in 2D plane, 2D blading design and 3D flow analysis at design point using Computational Fluid Dynamics method. In the determination of velocity triangles, two conditions are applied: zero inlet swirl (i.e. the gas flow enter the turbine at axial direction) and constant nozzle angle design (i.e. the inlet and outlet angle of the nozzle blade are constant from root to tip). The 2D approach in cascade plane is used to specify airfoil type at root, mean and tip of the blade based on inlet and outlet flow conditions. The 3D approach is done by simulating the turbine in full configuration to evaluate the overall performance of the turbine. The observed parameters including axial gap, stagger angle, and tip clearance affect its output power. Based on analysis results, axial gap and stagger angle are positively correlated with output power up to a certain point at which the power decreases. Tip clearance, however, gives inversely correlation with output power.

1. Introduction
Small turbojet engine used for Unmanned Aerial Vehicle (UAV) has being developed in our laboratory. This turbojet engine consist of three main components, namely compressor, combustor and turbine. In the design of turbojet engine, a turbine is considered as a component which can stand high temperature loads of heated air from combustion chamber. The kinetic energy of the turbine in rotation is used to drive the compressor so that the engine attains idle condition and to produce thrust output. For small turbojet engine, the use of a single axial turbine is to give simplicity and to provide lower cost in development and manufacture. In addition, using the simple turbine, the engine is easy in maintenance. In this study of design axial turbine, there are several previous research that become a basis and reference, for example D.G Ainley and G.C.R. Matheison mentions in Ref. [1] that the information obtained from the cascade method (which gives two-dimensional of blade section) is not enough because the three- dimensional effect are so powerful. Donald E. Holeski and Samuel M. Futral predict turbine efficiency decreased linearly with increasing rotor tip clearance [2]. James Allen, Ref [3], predict that axial clearance (axial gap) can affect turbine efficiency and torque produced by the turbine. In this work,
the design of the axial turbine of small turbojet is carried out by considering constant nozzle. Two methods namely parametric cycle analysis (analytical) and computation fluid dynamics (numerical) approaches are used to obtain the axial turbine design which fulfills the turbine design requirement and objectives. With this study of design a simple axial turbine, be expected can contribute to turbomachinery field in develop a high performance turbine with low cost in manufacture and maintenance.

2. Design Point and Method
The designed turbine must fulfills its design points. The design points is summarized in Table 1. The steps that used to obtain design point (that have been appointed before), firstly use analytical method and then result of the analytical method is used as input value of numerical method to obtain the form of the turbine. The designed turbine and then simulated with CFD to assess its performance. For the analytical method in this paper use parametric cycle analysis, parametric cycle analysis is one of method to approximate thermodynamic properties through gas turbine engine primary components such as compressor, combustion chamber, and turbine, based on Brayton cycle. The result from analytical calculation with parametric cycle and then used to be input value to calculate the velocity triangle with numerical calculation. After obtaining the velocity triangle data, and then use the data to generate the airfoil profile and furthermore build the 3D model of the designed turbine. As previously discuss, that the last step is simulate the designed turbine with CFD to assess the designed turbine performance.

| Table 1. Design Requirement and Objective of Turbine |
|-----------------------------------------------|
| RPM turbine                                   | 80000 rev/min          |
| Mass Flow Inlet Turbine                       | 0.8139 Kg/s            |
| Temperature Inlet Turbine                     | 1200 deg K             |
| Total Pressure Inlet Turbine                  | 335.33 KPa             |
| Total Pressure Outlet Compressor              | 372.589 KPa            |
| Coefficient Pressure Ratio                    | 3.677                  |
| Compressor Efficiency                         | 67.1 %                 |
| Turbine Efficiency                            | 70 %                   |
| Mechanical Efficiency                         | 99 %                   |
| Fuel Flow                                     | 0.01723 Kg/s           |

The following are the brief explanation of the steps from the method that used (analytical method and analytical method)

2.1 Analytical Method
2.1.1 Parametric Cycle analysis
The Figure 1 is summarized of the parametric cycle analysis, as previously explained that parametric cycle analysis is analytical method used to obtain the performance of the gas turbine (start from compressor, combustion chamber, and then turbine).
2.1.2 Choice of Blading Design
There are some kinds of blading design that commonly applied such as free vortex, constant nozzle angle, and constant mass flow [4]. Free vortex blading commonly have stage characteristic such as the stagnation enthalpy $h_0$ is constant over the annulus, the axial velocity is constant over the annulus, and the whirl velocity is inversely proportional to the radius. Constant nozzle angle blading is one of blading type with specific form of stator (NGV) blade is not twisted. Blading design that used in this study is constant nozzle angle type, this type is selected due to the simple geometry in stator (NGV) contour and with simple geometry contour will be affected in manufacturer cost.

2.1.3 Velocity Triangle
The determination of angles of the turbine blades (stator blade and rotor blade) uses velocity triangle method as shown in Figure 2 (left). The angles such as alpha-2, beta-2 and beta-3 are used to generate the profile of airfoil at each section along span. As a result the full configuration turbine blade are created. The typical zero inter stage swirl velocity triangle used in the design process of turbine blade is shown in Figure 2 (right).

As shown in the Figure 3, the velocity triangle of each section is changed from tip section to the hub section of the turbine blade. Changes on the flow angle is significantly can be seen at the tip section to the mean section of the blade (the flow angle is reversed). The flow angle for mean section to the hub section is increased from 22.4 degree to 41 degree. The following are the illustration of velocity triangle of the turbine at the tip, middle (mean), and hub section.
Figure 3. Illustration of velocity triangle of each section of designed turbine blade (tip (left), mean (middle), and hub (right) [4]

The following are the detail calculation to derive the specific flow angle at each blade section (tip, mean and hub section). From the velocity triangle, it can be derived the equation to determine flow angle (such as alpha-2, beta-2 and beta-3. The derivation of flow angle equations can be started by defining other parameters, namely flow coefficient, $\phi$ and work coefficient, $\psi$ as follows:

$$\phi = \frac{C_x}{U}$$  \hspace{1cm} (1)

$$\psi = \frac{\Delta h_0}{U^2}$$  \hspace{1cm} (2)

From equations 1 and 2, by performing some mathematical manipulation, the relation between velocity and flow angles of the blade can be obtained as follows:

$$\frac{U}{C_a} = tan\alpha_2 - tan\beta_2$$  \hspace{1cm} (3)

$$\frac{U}{C_a} = tan\beta_3 - tan\alpha_3$$  \hspace{1cm} (4)

And then the equations of the flow angles $\alpha_2$, $\beta_2$ and $\beta_3$ can be obtained as follows:

$$\alpha_2 = \varepsilon_s = arc\tan(\psi/\phi)$$ \hspace{1cm} (5)

$$\beta_2 = arc\tan\left(\frac{\psi-1}{\phi}\right)$$ \hspace{1cm} (6)

$$\beta_3 = arc\tan\left(\frac{1}{\phi}\right)$$ \hspace{1cm} (7)

The axial velocity variable, $Ca$ in Equations 3 and 4 can be derived by taken constant nozzle angle shown in the following equations:
\[ C_a \frac{dc_a}{dr} + C_w \frac{dc_w}{dr} + c_w^2 \frac{dr}{r} = \frac{dh_0}{dr} \]  

(8)

\[ \frac{c_{a_2}}{c_{w_2}} = \cot \alpha_2 = \text{constant} \]  

(9)

\[ C_{w_2} \cot^2 \alpha_2 \frac{dc_{w_2}}{dr} + C_{w_2} \frac{dc_{w_2}}{dr} + \frac{c_{w_2}^2}{r} \]  

(10)

\[ \frac{dc_{a_2}}{dr} = \frac{dc_{w_2}}{dr} \cot \alpha_2 \]  

(11)

\[ (1 + \cot^2 \alpha_2) \frac{dc_{w_2}}{dr} + \frac{c_{w_2}}{r} = 0 \]  

(12)

\[ \frac{dc_{w_2}}{dr} = -\sin^2 \alpha_2 \frac{dr}{r} \]  

(13)

\[ C_{w_2} r \sin^2 \alpha_2 = \text{constant} \]  

(14)

\[ C_{a_2} r = C_{a_2} m \left( \frac{r_m}{r} \right) \sin^2 \alpha_2 \]  

(15)

\[ C_{a_2} m = C_{a_3} m = C_{w_2} m \cot \alpha_2 \]  

(16)

2.1.4 Turbine Blade Cross Section

Based on the analytic calculation discussed at the previous section, the profile of the airfoil is obtained by using some numerical methods. The calculated angle from analytical method is imported as an input value and target value to obtain the desired flow angle whether flow inlet angle or flow outlet angle from each blade sections. Also, the variable such as airfoil maximum camber location, camber angle theta, stagger angle, pitch chord ratio, and airfoil profile thickness is arranged in such a way, that the input value (flow inlet angle) can provide desired output angle (correspond with analytical calculation). Furthermore it also can provide the proper shock free beta angle (wherever possible the beta angle and shock free beta angle gives the same value). The detailed airfoil profile geometry parameter of each section (NGV, hub rotor, mean rotor, and tip rotor) is summarized in Table 2.

| Table 2. Specification of NGV and rotor blade turbine design |
|---------------------------------------------------------------|
| **NGV Airfoil Profile**                                      |
| Airfoil Type       | C4 base profile                                      |
| **Profile Thickness Scale**       | 1                                               |
| Camber line type  | Parabolic                                          |
| x/l of maximum camber | 0.2                              |
| Camber angle theta | -90 degree                                 |
| Stagger angle lamda | 39.6 degree                                    |
| Pitch/chord ratio t/l | 1                                      |
| Fluid inlet angle beta 1 | 0 degree                                    |
| **Rotor Hub Airfoil Profile**   |
| Airfoil Type       | C4 base profile                                      |
| **Profile Thickness Scale**       | 1.2                                              |
| Camber line type  | Parabolic                                          |
| x/l of maximum camber | 0.3                              |
| Camber angle theta | 107.7 degree                                   |
| Stagger angle lamda | -8 degree                                    |
| Pitch/chord ratio t/l | 1                                      |
| Fluid inlet angle beta 1 | 41 degree                                    |
Table 2. Specification of NGV and rotor blade turbine design (cont.)

| Rotor Mean Airfoil Profile | C4 base profile |
|----------------------------|----------------|
| **Airfoil Type**           | C4 base profile |
| Profile Thickness Scale    | 1.2            |
| Camber line type           | Parabolic      |
| x/l of maximum camber      | 0.3            |
| Camber angle theta         | 100 degree     |
| Stagger angle lamda        | -22 degree     |
| Pitch/chord ratio t/l      | 1              |
| Fluid inlet angle beta 1   | 22.4 degree    |

| Rotor Tip Airfoil Profile  | C4 base profile |
|----------------------------|----------------|
| **Airfoil Type**           | C4 base profile |
| Profile Thickness Scale    | 1.2            |
| Camber line type           | Parabolic      |
| x/l of maximum camber      | 0.3            |
| Camber angle theta         | 82 degree      |
| Stagger angle lamda        | -38 degree     |
| Pitch/chord ratio t/l      | 1              |
| Fluid inlet angle beta 1   | -5 degree      |

Illustration of the stator (NGV) – rotor configuration both of with airfoil profiled NGV and flat plate profiled NGV is depicted in Figure 4. In the flat plate profiled NGV configuration, the flat plate is generated by following the main camber line of the airfoil that previously used, the flat plate thickness that used in the configuration is 2 mm (will be discussed at the following chapter).

![Illustration of stator and rotor configuration](image)

**Figure 4.** Turbine airfoil arrangement (stator (left) and rotor (right))
2.2 CFD Simulation

2.2.1 3D Model of Designed Turbine
The generation of three dimensional blade model as full configuration of the turbine is used for numerical simulation and turbine performance computation. The single blade model and full NGV – rotor model are shown in Figure 5.

![Figure 5](image)

*Figure 5. Three-dimensional blade model (left) and full three dimensional designed turbine (right)*

2.2.2 Numerical Model
The equation that used in the simulation is Reynolds Averaged Navier-Stokes with K-epsilon turbulence model. The number of mesh that applied on the computational domain geometry is around 5 million to 6 million mesh. The type of the simulation is quasi-steady simulation. This simulation type uses relative move of the flow in the domain to simulate the rotational movement of the rotor blade. The rotor is remain at rest but the flow in the rotor domain move with certain rpm that inputted. This conditions is known by applying frozen rotor interface.

2.2.3 Boundary Condition
The computational simulation starts with the generation of computational domain in which the thermodynamic properties such as velocity, pressure and temperature are computed. The domain is defined with some boundaries such as inlet, shroud, hub, and interfaces as shown in Figure 6. The boundary conditions that applied in the pre-setting of the simulation steps are inlet (in this boundary conditions use mass flow to be input value and total temperature), wall (use default setting of the wall boundary conditions), and outlet (in this boundary use static pressure as input value). The place of the boundary conditions that applied at the computational domain is depicted in Figure 6. In the simulation, two type of the convergence criteria i.e., error convergence criteria and residual result convergence criteria, were used to check the convergence. The final step of the simulation is running numerical process to get convergence solution.

![Figure 6](image)

*Figure 6. Computational domain (left) and meshing (right) that used in this design study*
3 Convergence of the Simulation
The criteria of convergence used in the simulation is residual growth of mass and momentum as well as the curves of normal force of blade as shown in Figure 7. The residual is one of the most fundamental measures of an iterative solutions convergence, as it directly quantifies the error in the solution of the system equation. In a CFD analysis, the residual measures the local imbalance of a conserved variable in each control volume. In an iterative numerical solution, the residual will never be exactly zero. For CFD, RMS residual levels of 1E-4 are considered to be loosely converged, level 1E-5 are considered to be well converged, and the last level of 1E-6 are considered to be tightly converged. For complicated problems, however, it is not always possible to achieve residual levels as low as 1E-6 or even 1E-05. As shown in the Figure 7 (residual error curve) that the curve is already achieve convergence level of 1E-4. In a steady state analysis, the solution field should not change iteration to iteration for an analysis to be deemed converged. Monitoring integrated quantities such as force, drag, or average temperature can help judge if the simulation have been converged or not. In the Figure 7 (quantities of interest curve) is shown that the curve is already converged since iteration 40.

Figure 7. Error curve (left) and quantities of interest curve (right) from running process

4 Result (On Design Performance)
4.1 Case 1: Turbine with Airfoil-Profiled NGV
Figure 8 below shows the detailed dimension of the turbine for simulation. Figure 9 shows the effect of axial gap and clearance on turbine output power resulted from simulations. From Figure 9, it can be seen that the maximum power for various clearance is resulted for the axial gap of 20 % of stator (NGV) chord. The turbine power increases about 20% by changing the tip clearance from 10% to 2.5% of the blade span. The configuration of the axial turbine designed with methodologies as explained before, specifically with 4 mm axial gap (20 % stator chord) and airfoil-profiled stator blade is presented in Figure 8 as follows. The detailed sizes of the designed axial turbine is also presented in Figure 8.
Figure 8. Designed Turbine (left) detailed of turbine size specification (right)

Figure 9. Effect of axial gap and turbine rotor clearance due to turbine power

The effect of tip clearance is examined further for 4 mm axial gap turbine case. Table 3 shows the performance of the axial turbine with the axial gap of 4 mm for the tip clearances of 0.5 mm (left) and 1.0 mm (right), respectively. As can be seen from Table 3, the output power increases by reducing clearance.

Table 3. Performance of two type designed turbine, turbine with 4 mm axial gap-0.5 mm rotor clearance (left) and turbine with 4 mm axial gap-1 mm rotor clearance (right)

|                | 0.5 mm rotor clearance | 1 mm rotor clearance |
|----------------|------------------------|----------------------|
| Total Pressure Inlet | 373.2 KPa              | 356.2 KPa            |
| Total Pressure Outlet | 156.1 KPa              | 158.4 KPa            |
| Total Temperature Inlet | 1200 deg K            | 1200 deg K           |
4.2 Case 2: Turbine with Flat Plate Profile that applied at the Stator (NGV) Section
Considering manufacture cost and simplicity, the airfoil-profiled stator blade might possibly be substituted by a curved flat plate profile which follow the camber line of the airfoil as shown in Figure 10. The curved plate axial turbine is then simulated with the axial gap of 4 mm for two different clearances, 0.5 mm and 1 mm. The thickness of the plate is set to 2 mm.

![Figure 10. Stator profile using airfoil profile (left) and using flat plate (right)](image)

The performances of the designed turbine with curved plate stator blade are presented in Table 4. Based on the simulation result between two kind of turbine models (turbine with NGV blade is airfoil profiled and turbine model with flat plat profiled), the output power of turbine model with flat plate profiled NGV is decreasing around 3% from the previous NGV model. Although the flat plate NGV model give lower output power but the reduction is not significant, with simple NGV geometry turbine with flat plate NGV is still worth to be developed.

| Total Pressure Inlet       | 3.812e+05 Pa | Total Pressure Inlet       | 3.817e+05 Pa |
|----------------------------|--------------|----------------------------|--------------|
| Total Pressure Outlet      | 1.586e+05 Pa | Total Pressure Outlet      | 1.588e+05 Pa |
| Total Temperature Inlet    | 1.200e+03 K  | Total Temperature Inlet    | 1.200e+03 K  |
| Total Temperature Outlet   | 1.028e+03 K  | Total Temperature Outlet   | 1.031e+03 K  |
| Mass Flow                  | 0.8319 kg/s  | Mass Flow                  | 0.8139 kg/s  |
| Power                      | 156831 watt   | Power                      | 152082 watt   |

4.3 The Effect of Stagger Angle and Flat Plate Thickness to Turbine’s Output Power
4.3.1 The Effect of Turbine Stagger Angle to Turbine Output Power
The influence of stagger angle on turbine output power is depicted in Figure 11. The simulation results show the turbine output power are lower than 155 KW for the turbine models with clearance 1.5% and 2%. The turbine power output can be increased by setting up stagger angle of the blades to the right position. As shown from the simulation, the higher angle of stagger gives more power to the turbine.
However, the increase in stagger angle that produces higher power output required higher inlet pressure and decreases turbine efficiency also as shown in Figure 11.

![Figure 11. Effect of Stagger angle due to turbine efficiency (left) and turbine power (right)](image)

4.3.2 Flat Plate Thickness Effect
The change of turbine power output due to the thickness of the flat plate is shown in Figure 12. In this study, the flat plate thickness is varied as 1 mm, 2 mm and 3 mm. From simulation results, the maximum turbine power output is obtained for the flat plate thickness of 2 mm. The layout of the turbine power output for various thickness is also depicted in Figure 12.

![Figure 12. Three models of designed turbine (left) and effect of flat plate due to turbine power (right)](image)

5. Conclusion
In the design of axial turbine there are several things that affect output power of the turbine such as stagger angle, axial gap, clearance, and the profile of the airfoil (both the stator and rotor profile). Based on the simulation results there is a certain distance of axial gap that provide optimal power, and the output power of the designed turbine is tend to decrease with increasing clearance (distance between rotor blade and shroud wall). The design model that closest with design point (the design point are: turbine that can produce 155 KW in power wihit 0.8139 kg/s mass flow at 80000 RPM) is the turbine model with 20% axial gap, 1 mm clearance between tip rotor blade and shroud wall and still use airfoil
profile at the NGV section. The flat plate NGV model also can achieve the design point with change the clearance from 1 mm to 0.5 mm or may be can also change the stagger angle of the NGV’s blade.

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