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Prediction of Losses in Small Scale Axial Air Turbine Based on CFD Modelling

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Abstract

Efficient small scale axial air turbines play a major role in determining the overall conversion efficiency in certain energy cycles using renewable energy sources. Loss predictions are vital for the development and optimization of such small scale turbines. Since all published loss prediction schemes were developed for large scale turbines, therefore there is a need for an effective approach to predict such losses for the small scale axial turbines. This work aims to develop a new approach to predict the losses in a small scale axial air turbine using both conventional loss models and computational fluid dynamics (CFD) simulations. Results showed that the Kacker & Okapuu model gave the closest values to the CFD simulation results thus it can be used to produce the initial turbine design that can be further optimised through CFD simulations.

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Keywords: Small Scale Axial turbine, CFD, Simulation, Total Loss.

Nomenclature:

Y	Total Loss Coefficient	Y_{Tl}	Trailing Loss coefficient	X_{Te}	Ainely Correction factor
Y_P	Profile Loss Coefficient	Y_k	Tip Clearance Loss	K_P	Mach number Factor
Y_s	Secondary Loss Coefficient	Y_{shock}	Loss due to shocks	ζ_N	Nozzle Loss Factor
C_L	Lift Coefficient	C_d	Drag Coefficient	ζ_R	Rotor Loss Factor

1. Introduction:

The availability of efficient small scale axial air turbines is vital for the development of renewable energy systems like the solar thermal air driven Brayton cycle [1-2] and small scale compressed air energy storage systems [3-4], were compressed air can be used to drive air turbines and generate power output.

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In general, published losses predictions correlations have been developed for large scale turbines, but as turbine sizes get smaller the effect of aerodynamic losses becomes more significant, therefore, the development of more accurate loss prediction techniques is required for small scale turbines where the efficiency is reduced due to loss development [2].

The estimation of losses using Ainely- Mthieson correlations is the most widely method used in turbine design [1]. This approach was improved by Dunham and Came (1971), also Craig and Cox (1971) proposed an improved correlations for losses prediction. Moustapha et al. (1990) provided a review about exist correlation for losses prediction and concluded that all the used correlation needs improvements to meet continues developments in blade airfoil shapes.

Benner et al. (2006) presented a new scheme for secondary losses prediction, in his study the losses were obtained based on a new empirical correlation which includes span wise penetration depth. This work aims to develop a new approach to predict the losses in a small scale axial air turbine using both the conventional loss models and computational fluid dynamics (CFD) simulations.

2. Loss Prediction Correlations:

2.1 Soderberg:

Soderberg (1949) provided a relation to predict total profile and secondary loss and neglecting tip clearance:

$$\zeta_{\mathrm{N}} = \left(\frac{10^5}{\mathrm{Re}}\right)^{1/4}\left[(1+\zeta^*)\left(0.993 + 0.075\frac{\mathrm{l}}{\mathrm{H}}\right) - 1\right] \tag{1}$$

$$\zeta_R = \left(\frac{10^5}{Re}\right)^{1/4}\left[(1+\zeta^*)\left(0.975 + 0.075\frac{l}{H}\right) - 1\right] \tag{2}$$

2.2 Ainely& Mathieson:

This model was provided by Ainely &Mathieson (1951). In this scheme, Ainely and Mathieson assumed that the effect of Mach number and flow outlet angles on pressure distribution is negligible.

$$\mathrm{Y} = (\mathrm{Y_P} + \mathrm{Y_S} + \mathrm{Y_{Tl}})\chi_{\mathrm{Te}} \tag{3}$$

$$Y_{P(i=0)} = \left\{Y_{P(\alpha'_{in}=0)} + \left(\frac{\alpha'_{in}}{\alpha_{out}}\right)^2\left[Y_{P(\alpha'_{in}=\alpha_{out})} - Y_{P(\alpha'_{in}=0)}\right]\right\}\left(\frac{t_{max}/l}{0.2}\right)^{\frac{\alpha'_{in}}{\alpha_{out}}} \tag{4}$$

$$Y_s = \lambda\left(\frac{C_L}{t/l}\right)^2\left(\frac{cos^2\alpha_{out}}{cos^3\alpha_m}\right) \tag{5}$$

2.3 **Dunham & Came:**

Dunham & Came (1970) made an improvement on Ainely & Mathieson approach by considering the influence of Reynolds number on losses.

$$Y = \left((Y_P + Y_S)\left(\frac{Re}{2\times10^5}\right)^{-0.2} + Y_{Tl}\right)\chi_{Te} \tag{6}$$

$$Y_P = [1 + 60(M_{out} - 1)^2]\chi_i Y_{P(i=0)} \tag{7}$$

$$Y_s = 0.0334(\frac{l}{H})[4(tan\alpha_{in} - tan\alpha_{out})^2]\left(\frac{cos^2\alpha_{out}}{cos\alpha_m}\right)\left(\frac{cos\alpha_{out}}{cos\alpha'_{in}}\right) \tag{8}$$

$$Y_{Tl} = B\frac{l}{h}\left(\frac{\tau}{l}\right)^{0.78} 4(tan\alpha_{in} - tan\alpha_{out})^2\left(\frac{cos^2\alpha_{out}}{cos\alpha_m}\right) \tag{9}$$

2.4 **Kacker & Okapuu:**

Kacker & Okapuu (1982) developed his coloration by adding the influence of shock losses into the loss calculation with a new breakdown model for profile and secondary loss are presented.

$$Y = \chi_{Re}Y_P + Y_s + Y_{TI} + Y_{Te} \tag{10}$$

The correction factor (χ_{Re}) can be calculated using following equation:

$$\mathrm{x_{Re}} = \begin{cases} \left(\frac{\mathrm{R_e}}{2\times10^5}\right)^{-0.4} & \mathrm{R_e} \leq 2\times10^5 \\ 1.0 & 2\times10^5 > \mathrm{R_e} < 10^6 \\ \left(\frac{\mathrm{R_e}}{10^6}\right)^{-0.2} & \mathrm{R_e} > 10^6 \end{cases} \tag{11}$$

$$Y_P = 0.914\left(\frac{2}{3}K_P\chi_i Y_{P(i=0)} + Y_{shock}\right) \tag{12}$$

$$Y_{shock} = 0.75\left(M_{in,H} - 0.4\right)^{1.75}\left(\frac{r_H}{r_T}\right)\left(\frac{P_{in}}{P_{out}}\right)\frac{1-\left(1+\frac{\gamma-1}{2}M_{in}^2\right)^{\frac{\gamma}{\gamma-1}}}{1-\left(1+\frac{\gamma-1}{2}M_{out}^2\right)^{\frac{\gamma}{\gamma-1}}} \tag{13}$$

$$Y_s = 0.04\left(\frac{l}{H}\right)\chi_{AR}[4(tan\alpha_{in} - tan\alpha_{out})^2]\left(\frac{cos^2\alpha_{out}}{cos\alpha_m}\right)\left(\frac{cos\alpha_{out}}{cos\alpha'_{in}}\right)\left[1 - \left(\frac{l_x}{H}\right)^2(1 - K_P)\right] \tag{14}$$

$$Y_{Te} = \frac{\left[1+\frac{\gamma-1}{2}M_{out}^2\left(\frac{1}{1-\Delta E_{Te}}-1\right)\right]^{-\gamma/\gamma-1} - 1}{1-\left(1+\frac{\gamma-1}{2}M_{out}^2\right)^{-\gamma/\gamma-1}} \tag{15}$$

3 CFD Modeling:

In this work, the air flow inside a small axial turbine design, CFD simulation is a powerful tool to obtain a detailed turbine design. In present work, the small scale axial turbine is simulated using ANSYS CFX 15which is based on finite volume technique to solve governing equations iteratively for each control volume. For high accuracy simulation, Shear Stress Transport (SST) k-ω model is chosen.

Continuity Equation: $$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{16}$$

Momentum Equation: $$\frac{\partial}{\partial x_i}\left(\rho u_i u_j\right) = \frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_j}{\partial x_i}\right) - \frac{\partial P}{\partial x_i} \tag{17}$$

Energy Equation: $$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{K}{C_p}\frac{\partial u_j}{\partial x_i}\right) \quad (18)$$

In order to validate the CFD analysis, the simulation was carried out for the large scale axial turbine geometry and the experimental data published by Ning Wei (2000) using the same geometrical parameters and boundary conditions. Figure 1 show the predicted (CFD) efficiency compared to the experimental one with +/- 10% deviations. Also, grid sensitivity analysis was carried out based on turbine total efficiency as shown in figure 2. It is clear from this figure that with number of grid cells higher than 650000, the turbine total efficiency remains constant indicating that the solution is not affected by the number of grid cells.

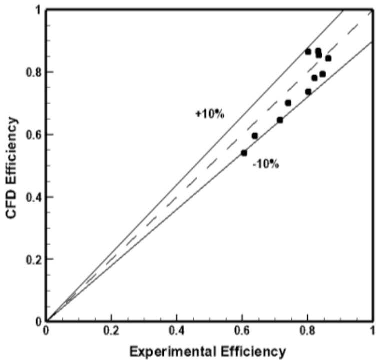

Fig.1: CFD Model Validation based on Ning Wei (2000) data

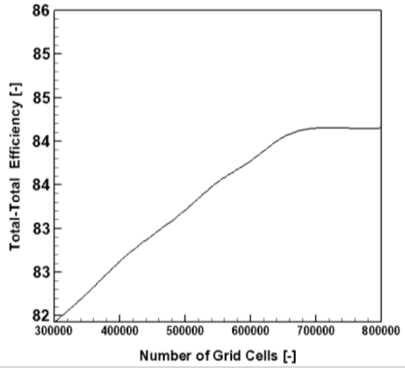

Fig.2: Grid Sensitivity Analysis Based on Total-Total Efficiency

Small Scale Axial air Turbine Losses Prediction:

This section presents a comparison between losses prediction using published colorations and losses obtained using ANSYS CFX simulations for the operating conditions and axial turbine geometry presented in table 1. Figures 3 shows the velocity vectors for 5kW axial air turbine, and figure 4 shows its mean line stream wise pressure distribution.

Table (1): Turbine Design Parameters:

Power output (kW)	5	Total inlet temperature (K)	360
Mass flow rate (kg/sec)	0.3225	Inlet relative flow angle	59.04
Shaft speed (rpm)	14000	Exit absolute flow angle	65.12
Total inlet Pressure (kpa)	200	Hub-tip ratio	0.75
Mean radius (mm)	35mm	Rotor span (mm)	10mm

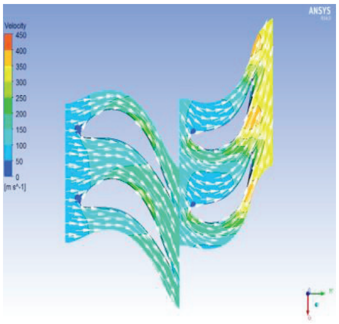

Fig.3: Velocity vectors for 5kW Axial Air Turbine

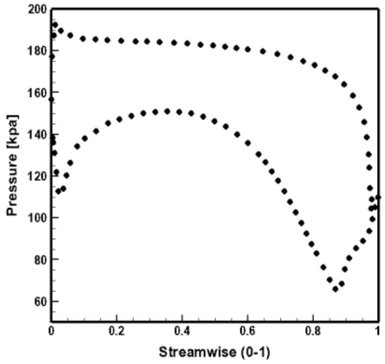

Fig.4: Rotor Blade Loading for 5kW Axial Air Turbine

Figures 5 and 6 present the predicted rotor total losses versus rational speed and pressure ratio using Came & Dunham, Kacker & Okapuu, and Ainely colorations versus CFD predictions. It is clear from these figures that Kacker & Okapuu predicted losses are the closest to CFD results, while results by Ainely & Mathieson approach are the lowest loss values. Therefore, the CFD and Kacker & Okapuu approach were used to carry out a parametric analysis to study the effects of trailing edge thickness and leading edge radius on turbine rotor total losses at various RPM ranging from 1000 to 18000 RPM, as shown in Figures 7 and 8. These results show that small scale turbine is experienced high loss and choosing acceptable loss prediction scheme is needed for preliminary design stage.

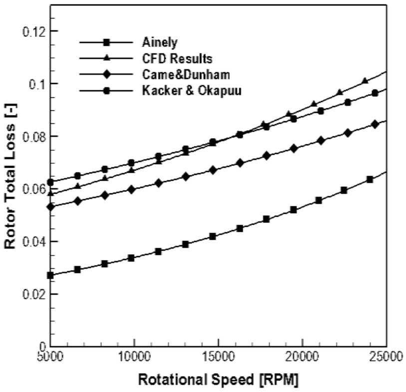

Fig.5: Total loss for different RPM

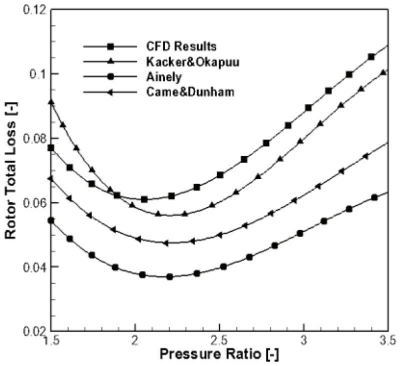

Fig.6: Total loss for different pressure ratio

As shown in Figure 7 the total loss increases with trailing edge thickness due to flow separation. Also, the leading edge radius has a significant impact on loss generation as shown in Figure 8 where the rotor loss decrease till radius of 0.45 then the loss increases for all RPMs. Also it is clear from Figures 7 and 8 that the CFD predictions were close to Kacker & Okapuu for all the study carried out.

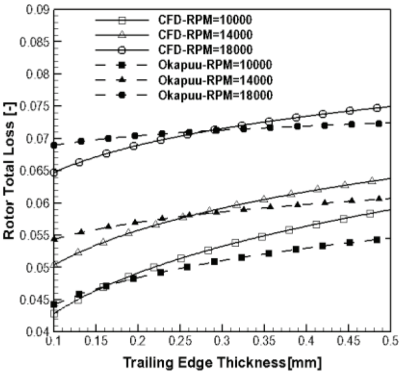

Fig.7: Rotor Loss Vs Trailing Edge Thickness

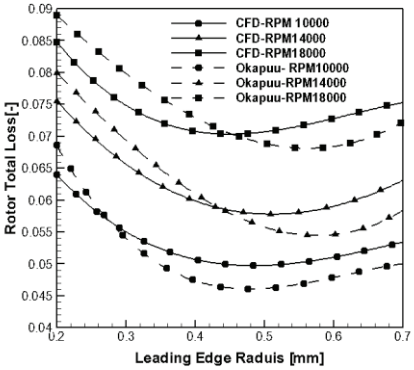

Fig.8: Rotor Loss Vs Leading Edge Radius

Conclusion:

Loss predictions are vital for the development of efficient and cost effective small scale air driven axial turbines. All published loss prediction schemes are developed for large scale turbines. Therefore there is a need for an effective approach to predict such losses for the small scale axial turbines. This work compared the predicted losses based on published literature colorations with those from CFD simulations. Results showed that the Kacker & Okapuu model gave the closest values to the CFD simulation results. Therefore, this work recommends using Kacker & Okapuu approach to predict the losses and to generate the initial blade profile for small scale turbine. Then, the CFD analysis can be used to further improve the initial design by investigating the effects of various parameters that cannot be investigated using correlations like number of blades, leading edge geometry, axial distance between the stator and the rotor and blade turning angle to achieve an optimised design with minimum losses.

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