Optimization of Power Output of a Vaned Type Novel Air Turbine With Respect to Different Injection Angles

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ABSTRACT: This paper deals with the optimization of power output of a vaned type novel air turbine with respect to different injection angles. Mathematical model is done to quantify the effect of varying injection angle, expansion due to isobaric, adiabatic expansion and steady flow work of high pressure air. It is also concluded that total power output becomes large and optimum at injection angles 60° to 75° and decreases after 75°.

Keywords: Zero Pollution, Compressed Air, Air Turbine, Vane Angle, Injection Angle

1. INTRODUCTION

Global consumption pattern of hydrocarbon fuel and its effects on the environment have necessitated search for environment friendly alternative. US geologist Marion King Hubbert in 1956 predicted that most of the country may reach to peak oil day within 20 years and thereafter depletion of hydrocarbon fuel may cause serious threat within 40 years, which may also release huge amount of pollutant in the environment [**1**]. Aleklett and Campbell indicated that with the current rate of consumption, 80% of globally available resources of fossil fuel would be exhausted by 2020 [**2**]. This necessitates the use of non- conventional options, such as bio-diesel, wind power, biomass etc. and some other options like conversion of energy such as battery, hydrogen cell, photovoltaic cells and compressed air etc. to generate shaft work for running the engines of light vehicles [**3-9**].

The important work in the area of compressed air engine has been done by French technologist Guy Negre [**10**] and also by an inventor of quasi turbine G. Saint Hilaire [**11**]. The highly compressed air can be stored in the energy storage systems up to 20 bar pressure within 15–20 minutes, and reused for running compressed air engines. In view of the attractive features like nearly zero pollution and air compression using non-conventional resources, the compressed air engine appears to be comparable technology in place of the other in vehicle markets.

Here the parametric analysis of a small capacity air turbine having vane type rotor has been carried out and presented for investigating the effect of injection angle variation. Results obtained using the mathematical modeling are presented and analyzed here.

2. VANE TYPE NOVEL AIR TURBINE

In this study a multi-vane type air turbine is proposed as shown in Figures 1a and 1b. The proposed air turbine is considered to work on the reverse working principle of vane type compressor. In this arrangement total shaft work is cumulative effect of isobaric admission of compressed air jet on vanes and the adiabatic expansion of high pressure air. In earlier study conducted by authors a prototype of air turbine was developed and its functionality was ensured [**12**]. A cylinder for the storage of compressed air with a capacity of storing air for the requirement of 30 minutes running at initial stage and maximum pressure of 20 bar is used as a source of compressed air. The compressed air storage cylinder is designed to produce constant pressure for the minimum variation of torque at low volumes of compressed air and attached with filter, regulator and lubricator. The clean air then admits into air turbine through inlet nozzle. Vanes of novel air turbine are placed under spring loading to maintain their regular contact with the casing wall to minimize leakage which is proposed as improvement over the currently available vane turbine. A study on high efficiency energy conversion system for liquid nitrogen [**13**], design and verification of airfoil and its tests, influence of tip speed ratios for small wind turbine and parabolic heat transfer and structural analysis were also carried out for conceptualizing the energy conversion system and design of the air turbine [**14-17**]. Studies have shown feasibility of vane type novel air turbine [**18-21**]. The present objective is to investigate the performance of an air turbine with the variation of injection angle, i.e. angle at which air should be admitted into the turbine between first two consecutive vanes. The air turbine considered has capability to yield output of 5.25 to 6.50 HP at 4-6 bar air pressure for speed of 2000–2500 rpm, which is suitable for a motorbike.

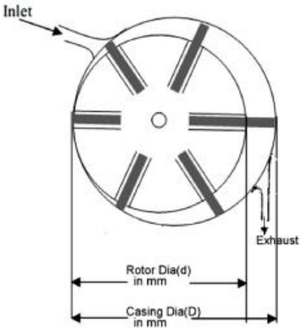

Figure 1a: Air Turbine

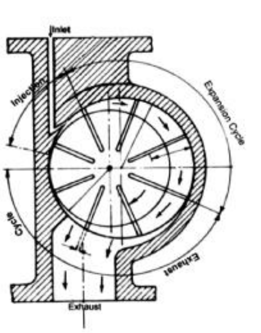

Figure 1b: Air Turbine- Model

3. MATHEMATICAL MODELING

The high pressure jet of air at ambient temperature drives the rotor in novel air turbine due to both isobaric admission and adiabatic expansion. Such high pressure air when enters through the inlet passage, pushes the vane for producing rotational movement through this vane and thereafter air so collected between two consecutive vanes of the rotor is gradually expanded up to exit passage. This isobaric admission and adiabatic expansion of high pressure air both contribute in producing the shaft work from air turbine. Compressed air leaving the air turbine after expansion is sent out from the exit passage. It is assumed that the scavenging of the rotor is perfect and the work involved in recompression of the residual air is absent as seen from Figure 1b.

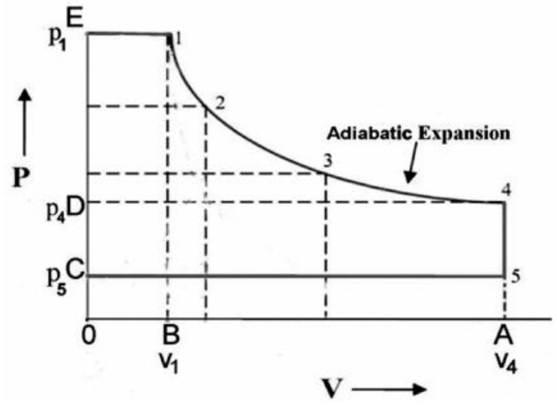

Figure 2: **Thermodynamic Processes (Isobaric, adiabatic and Isochoric Expansion)**

The model is already presented in previous publications of authors [**22-25**], but for maintaining continuity and benefits to readers, important equations are again reproduced here.

From Figure 2, it is seen that work output is due to isobaric admission (E to 1), and adiabatic expansion (1 to 4) and reference 2, 3 in the figure shows the intermediate position of vanes. Thus, total work output due to thermodynamic process may be written as:

Total work output = [Thermodynamic expansion work (*w₁*)] + [Exit steady flow work (*w₂*)]

$$\text{or} \qquad w = [(w_1) + (w_2)] \tag{1}$$

Now thermodynamic expansion work (w_1), can be written as:

$$w_1 = p_1.v_1 + \left(\frac{p_1.v_1 - p_4.v_4}{\gamma - 1} \right) - p_4.v_4$$

Considering adiabatic process between state 1 and 4 it can be given as,

$$w_1 = \left(\frac{\gamma}{\gamma - 1} \right).p_1.v_1.\left\{ 1 - \left(\frac{p_4}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \right\} \tag{2}$$

The process of exit flow (4-5) takes place after the expansion process (E- 4) as shown in Fig. 2 and air is released to the atmosphere. In this process; till no over expansion takes place pressure p_4 can't fall below atmospheric pressure p_5. Thus at constant volume when pressure p_4 drops to exit pressure p_5, no physical work is seen. Since turbine is functioning as positive displacement machine and hence under steady fluid flow at the exit of the turbine, the potential work is absorbed by the rotor and flow work (w_2), can be written as:

$$w_2 = \int_4^5 v.dp = v_4(p_4 - p_5) \tag{3}$$

Applying equations (2), (3) into equation (1), considering air turbine has *n* number of vanes, then shaft output [**26**] can be written as:

$$w_n = n.\left(\frac{\gamma}{\gamma - 1} \right).p_1.v_1\left\{ 1 - \left(\frac{p_4}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \right\} + n.(p_4 - p_5).v_4 \tag{4}$$

where w_n is work output (in Nm), for complete *one cycle.*

Therefore, the total power output or work done per unit time (W), for speed of rotation N rpm, will be:

$$W_{total} = n.(N/60).\left(\frac{\gamma}{\gamma - 1} \right).p_1.v_1.\left\{ 1 - \left(\frac{p_4}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \right\} + n.(N/60).(p_4 - p_5).v_4 \tag{5}$$

Figure 1a shows that if vanes are at angular spacing of θ degree, then total number of vanes will be n = (360/θ). The variation in volume during expansion from inlet to exit (i.e. *v₁* to *v₄*) can be derived by the variable extended length of vane as shown in Figure 3 at every point of movement between two consecutive vanes.

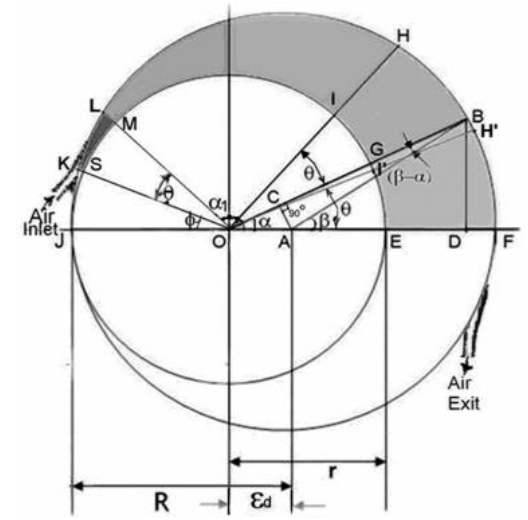

Figure 3: Variable Length BG and IH and Injection Angle Ø

Figure 3, shows that when two consecutive vanes at OK and OL move to position OH and OB, the extended vane lengths varies from SK to IH and LM to BG, thus the variable length BG at variable α_i is assumed as $X_{at'\text{var}iable'\alpha}$ can be written from the geometry:

$$BG = x_{at,\text{var}iable'\alpha'} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin\alpha\right\}\right]+(R-r).\cos\alpha - r \quad \textbf{(6)}$$

where 2R=D is diameter of casing and 2r=d is diameter of rotor, α is angle ∠BOF, β is angle ∠BAF and θ is angle ∠HOB or ∠H′OF or ∠KOL, between two consecutive vanes and ϕ is angle ∠KOJ at which injection pressure admits to the air turbine.

Variable volume of cuboid B-G-I-H-B can be written as:

$$v_{cuboids} = L.\left\{\frac{(X_{1i}+X_{2i})(2r+X_{1i})}{4}\right\}.\sin\theta \quad \textbf{(7)}$$

where BG= X_{1i} and IH= X_{2i} variable length of vanes when rotate into turbine as shown in Figure 3. The volume at inlet v_1 or $v_{\min}$ will fall between angle ∠LOF= $\alpha_{1\min} = (180-\theta-\phi)$ and angle ∠KOF = $\alpha_{2\min} = (\alpha_{1\min}+\theta) = (180-\phi)$ as seen in Figure 3, when air is admits into turbine at angle ϕ .

Applying above conditions into equations (6), then LM=X_{1min} and SK=X_{2min} can be written as:

$$X_{1\min} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin(180-\theta-\phi)\right\}\right]+ \left[(R-r).\cos(180-\theta-\phi)-r\right] \quad \textbf{(8)}$$

$$X_{2\min} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin(180-\phi)\right\}\right]+ \left[(R-r).\cos(180-\phi)-r\right] \quad \textbf{(9)}$$

Applying values of X_{1min} and X_{2min} to equation (7),

$$v_1 = v_{\min} = L.\left\{\frac{(X_{1\min}+X_{2\min})(2r+X_{1\min})}{4}\right\}.\sin\theta \quad \textbf{(10)}$$

The Volume at exit v_4 or $v_{\max}$ will fall between angle ∠BOF $\alpha_{1\max} = \alpha = 0$ and angle ∠HOF $\alpha_{2\max} = (\alpha_{1\max}+\theta) = \theta$

Applying above conditions into equations (6), then FE=X_{1max}=Corresponding to BG at α =0 degree and I′H′=X_{2max}=Corresponding IH at $(\alpha+\theta)=\theta$ degree can be written as:

$$X_{1\max} = (D-d) = 2(R-r) \quad \textbf{(11)}$$

$$X_{2\max} = R.cos\left[\sin^{-1}\left\{\left(\frac{R-r}{R}\right).\sin\theta\right\}\right]+\left\{(R-r).\cos\theta\right\}-r \quad \textbf{(12)}$$

Applying values of X_{1max} and $X_{2\,max}$ to equation (7),

$$v_4 = v_{\max} = L.\left\{\frac{(X_{1\max}+X_{2\max})(2r+X_{1\max})}{4}\right\}.\sin\theta \quad \textbf{(13)}$$

Applying values of v_1 and v_4 from equations (10) and (13) to equation (5), the total power output available W_{total} can be written as:

$$W_{total} = n.(N/60).\left(\frac{\gamma}{\gamma-1}\right).\left\{1-\left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} p_1.\left[L.\left\{\frac{(X_{1\min}+X_{2\min}).(2r+X_{1\min})}{4}\right\}.\sin\theta\right] +n.(N/60).(p_4-p_5). \left[L.\left\{\frac{(X_{1\max}+X_{2\max}).(2r+X_{1\max})}{4}\right\}.\sin\theta\right] \quad \textbf{(14)}$$

4. INVESTIGATIONS AND ANALYSIS

4.1 Considerations of Input Parameters

Detailed analysis of varying injection angles was carried out for flow work, percentage contribution of expansion and flow and total works at different vane angles and different speed of rotation 500-2500 rpm. The contribution of expansion work becomes considerably large when injection angle of air turbine is kept more than 30^o at constant vane angle 45^o (i.e. 8 vanes), injection pressure 6 bar and speed of rotation 2500 rpm.

In this study various input parameters are listed in Table 1 for investigation of different air injection angle and its optimization for larger shaft output.

Table 1

Symbols	*Parameters*
$R=(D/2)$	100 mm (outer)
$r=(d/2)$	80 mm (inner) corresponding
p_1	2 bar(=30 psi), 3 bar(=45 psi), 4 bar(=60 psi), 5 bar (=75 psi), 6 bar (=90 psi)
p_5	1.0132 bar (atmospheric pressure)
p_4	$(v_1/v_4)^{\gamma}.p_1 > p_5$ assuming adiabatic expansion
θ	45^{o} (i.e. rotor contains correspondingly 8 number vanes)
N	2500 rpm (as total power is directly proportion to rpm)
L	35 mm length of rotor
γ	1.4 for air
n	Number of vanes = (360 / θ)
ϕ	10^{o}, 15^{o}, 20^{o}, 25^{o}, 30^{o}, 45^{o}, 60^{o}, 75^{o}, 90^{o} angles at which compressed air enters through nozzle into rotor

4.2 Results and Discussion

Based on the various input parameters listed in Table-1 and mathematical model, the effects of injection angles, speed of rotation and injection pressure on the expansion work, exit flow work and total work output from air turbine are studied. Here the vane angle θ of the air turbine is considered to be constant at 45^{o} for whole study. The results obtained have been plotted in Figures 4 to 8.

Figure 4 shows the variation of expansion power at different air injection angles, air injection pressure 2 - 6 bar and speed of rotation 2500 rpm. It is evident that the shaft power due to expansion (W_{exp}) is low at 2 bar admission pressure at 10^{o} injection angle, it gradually increases with increase in injection angles from 15^{o} to 60^{o} and thereafter it further decreases with increase in injection angles from 60^{o} to 90^{o}. Also expansion power is seen to be large for higher injection pressure 3 - 6 bar which is attributed to the large power capacity. The expansion power is small at lower speed of rotation 500 rpm and 1500 rpm for all injection angle and injection pressure.

Figure 5 shows the percentage contribution of expansion power in total power output at different speeds of rotation. It is observed that percentage contribution of expansion power is largest at 2 bar when the injection angle is 10^{o}, thereafter from 15^{o} to 30^{o}, it gradually decreases and beyond 30^{o} (i.e. 45^{o} to 90^{o}) the contribution of expansion power decreases rapidly. It signifies that the expansion power contribution is found maximum for the injection angle of 10^{o} and thereafter decreases which may be attributed to the increased volume available between two consecutive vanes at this condition. At further higher injection pressures of 3 to 6 bar the percentage contribution of expansion power is found to follow the same trend.

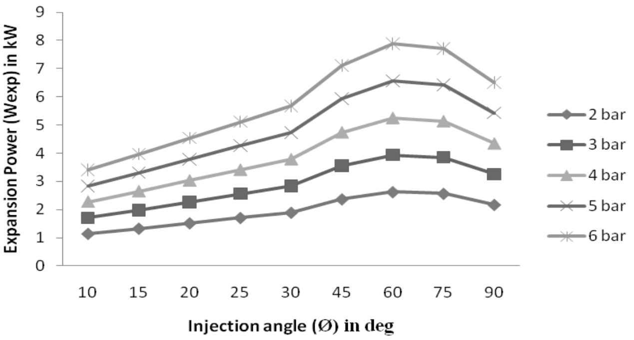

Figure 4: Variation of expansion power at different injection angles and different air injection pressure 2-6 bar and 2500 rpm

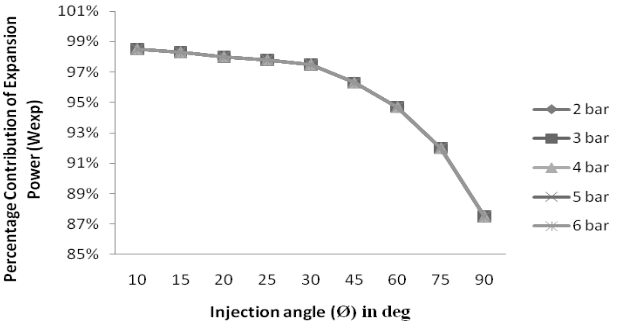

Figure 5: Percentage contribution of expansion power vs. injection angle at different air injection pressure 2-6 bar and 2500 rpm

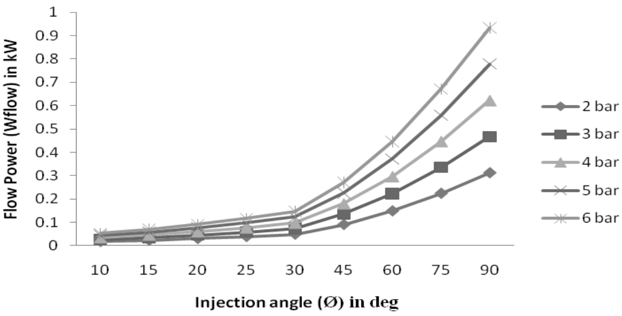

Figure 6: Variation of flow power at different injection angles and at different air injection pressure 2-6 bar and 2500 rpm

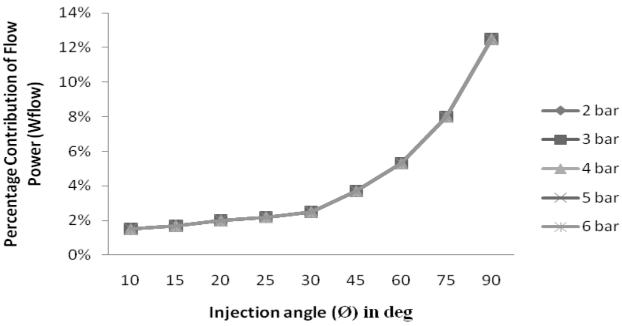

Figure 7: Percentage contribution of flow power vs. injection angle at different air injection pressure 2-6 bar and 2500 rpm

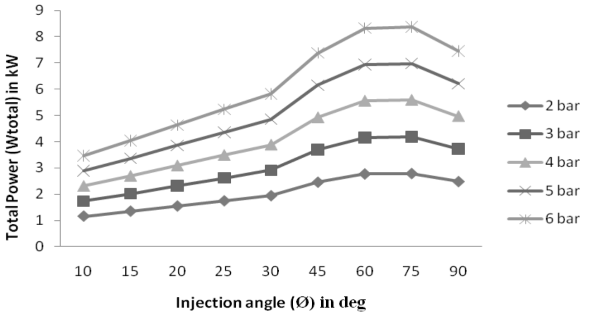

Figure 8: Variation of total turbine power output at different injection angle and at different air injection pressure 2-6 bar and 2500 rpm

Figure 6 shows the variation of shaft power due to exit flow action with respect to injection angles 10° - 60°, for different injection pressures 2 - 6 bar and speed of rotation 2500 rpm. It is apparent from graphical patterns that the exit flow power is low at 2 bar admission pressure at 10° injection angle, it gradually increases with increase in injection angles from 15° to 30° and thereafter it rapidly increases at injection angles from 45° to 90°. Also exit flow power is seen to be large for higher injection pressure 3 - 6 bar which is attributed to the large power capacity and follow same trend for all the injection angles 10° - 90° as stated above in the case of injection pressure 2 bar.

Figure 7 shows the percentage contribution of exit flow power to the total power output from air turbine. It is seen that percentage contribution due to exit flow power at admission air pressure of 2 bar and injection angle 10° is found to be considerably low to the order of 1.5% and it gradually increases with increase in injection angle from 15° to 30° and it further increases rapidly beyond 30° - 90°. But for injection pressures 3 - 6 bar and injection angles from 10° to 90°, exit power contribution follows the same trend.

Variation of total power output from air turbine with respect to injection angles 10° -60° is shown in Figure 8, for different air injection pressures 2 - 6 bar and at speeds of rotation 2500 rpm. Total work output is seen to increase with small pace at increasing injection angles from 10° to 30° at 2 bar admission pressure, it gradually increases with increase in injection angles from 15° to 60° and thereafter it suddenly decreases with increase in injection angles from 60° to 90°. Also total power output is seen to be large for higher injection pressure 3 - 6 bar and follow the same trend as shown in graphical patterns, which attributes to the large power capacity.

It is thus, observed that in the multi-vane turbine, total shaft power is combined effect of the component of expansion and exit flow power. The contribution of exit flow power is varying approximately from 1.5% to 12.5% at admission pressure 2 - 6 bar and at varying injection angles 10° to 90°. Thus the exit flow power cannot be ignored as such it helps for smooth running of vane turbine. It is also observed that the multi-vane turbine develops maximum shaft power output when injection angle is kept 60° or 75° for all injection pressures 2-6 bar.

5. CONCLUSIONS

Based on the input parameters considered and results obtained, the following conclusions are drawn in reference to the power output of a small multi-vane novel air turbine:

- The positioning of air injection angles into multi-vane air turbine has significant effect to optimize the power output.
- Total shaft power output developed from multi-vane air turbine is combination of the expansion power and exit flow power which gets affected significantly when variations in injection angles are applied.
- More vanes in air turbine develop more friction and thus reduce output.
- Vane turbine having fewer vanes give larger volumes between 2 - consecutives vanes and gives rise to more space for expansion and ultimately increases the power output.

Thus from above study, it is noticed that the shaft output will become large and optimum when injection angle is kept at 60^0 or 75^0, vane angle at 45^0 (i.e. rotor is of 8 vanes), injection pressure at 6 bar and speed of rotation at 2500 rpm.

NOMENCLATURE

d : diameter of rotor (2r) in meter

D : diameter of outer (2R) cylinder in meter

L : length of rotor having vanes in meter

n : no. of vanes = (360/θ)

N : no. of revolution per minute

p : pressure in bar

p_1, v_1 : pressure and volume respectively at which air strike the Turbine,

p_4, v_4 : pressure and volume respectively at which maximum expansion of air takes place.

p_5 : pressure at which turbine releases the air to atmosphere.

v : volume in cum

w : theoretical work output in (J) Joules

W : theoretical power output (W) Watts

X_{1i} : variable extended lengths of vane at point 1

X_{2i} : variable extended lengths of vane at point 2

Subscripts

$_{1, 2...4, 5}$: subscripts – indicates the positions of vanes in casing

e, exp : expansion

min : minimum

max : maximum

Greek symbols

α : angle BOF

α_1 : angle LOF (=180-ϕ)

α_2 : angle KOF (=180-θ-ϕ)

β : angle BAF

γ : 1.4 for air

θ : angle between two vanes (BOH)

ϕ :angle at which compressed air enters into rotor through nozzle

ξ_d : eccentricity *(R-r)*

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