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Influence of the Air Engine on Global Warming Issues - 21st Century Fuel Technology

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1. Introduction

Global warming or climate change is undoubtedly one of the most important challenges for our future generation, and quite possibly any generation in history. The worldwide scientific community is unanimous in its agreement that global warming is happening, that is our fault, and that the opportunity to stop it is slipping away. If we let it get out of our control, the consequences - which are already evident in most of our lifetimes - will be catastrophic. For example some of the consequences that can be reasonably expected are rising sea levels, frequent and severe natural disasters, large-scale food and water shortages, plagues, massive species extinctions, unprecedented numbers of refugees, intensified ethnic and political tensions, and a global economic depression the likes of which no one has ever seen.

1.1 Current situation

The situation is still within our grip, but we must act now, we must act strongly, and we must act together. Individuals, companies, and governments across the globe must each do what they can to reverse climate change. We will never get a second chance.

1.2 What can we do?

There are plenty of things that one can reduce the alarming carbon footprint shown in **Fig.1**. The key word is *reduce*. Anyone can greatly lessen the impact on climate change by using the planet's resources more responsibly. There are many things which can be reduced, and many ways that can reduce them, but three of the major ones are: reduce the amount of animal products being consumed (e.g., meat, dairy, eggs, leather, etc.), reduce the amount of fuel being used in cars, air travels, etc., and reduce the amount of electricity being used for domestic as well as industrial purposes utilizing some alternatives. There are plenty of good resources as detailed below encourages to-do the research.

Since the use of transport has become a part of life in the current civilization of developed and developing countries, the population of transport vehicles are increasing 2 to 3 times in every 5-7 years. Approximately 80% transport population in the developing countries such as; India, China, Taiwan, Romania, Bulgaria etc., are two wheelers, that is also adding about 77.8% of total emission in the atmosphere. Hence the transport sector alone, is responsible to

the faster consumption of hydrocarbon fuel and releases heavy tail pipe emissions, thereby adding billion tonnes of excessive carbon dioxide, carbon monoxide and unburnt hydrocarbon etc. (see **Table-1**), in the atmospheric air every day. This is causing a serious threat to the global warming. Also the fuel reserves are depleting very fast.

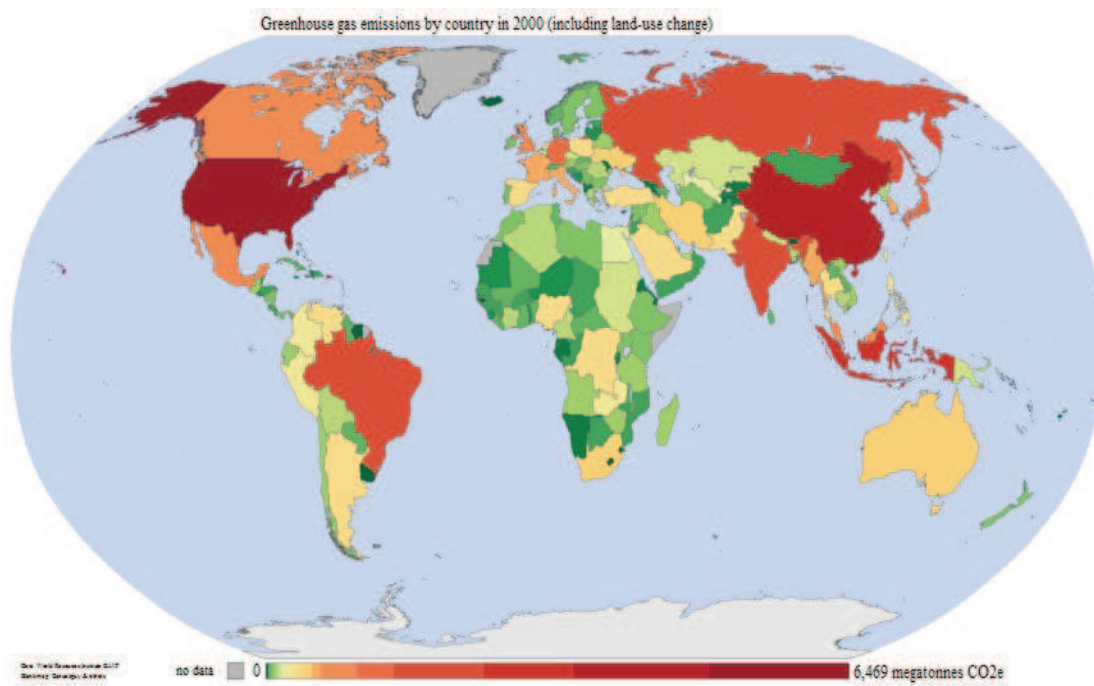


Fig. 1. Contrywise Green House Emission (Carbon Foot Print)

S.No.	Name of Major Countries	Population In Millions	Total CO ₂ Yearly Release (In Million Tonnes)	Remarks
1.	China	1334.8	6,126.7	
2.	USA	311.3	5,983.0	
3.	Russia	138.9	1,572.4	
4.	India	1183.3	1,526.5	
5.	Japan	126.6	1,316.6	
6.	Germany	82.1	878.5	
7.	Canada	33.8	561.0	
8.	Iran	77.5	519.3	
9.	Italy	57.9	486.4	
10.	South Korea	48.7	475.8	
11.	Mexico	113.5	440.0	
12.	South Africa	49.2	415.3	
13.	France	64.6	409.6	
14.	Australia	21.6	392.0	
15.	Saudi Arabia	26.0	385.6	

(Source: www.Breathingearth.net Feb'2011)

Table 1. List of 15-Countries Contributing Highest CO₂

In 1956, the Marion King Hubbert a noted geophysicist predicted that US Fuel reserves may peak by 1975 and fuel crisis will be noticed by 1995. He illustrated the projection with a bell shaped *Hubert Curve* based on the availability and consumptions of the fossil fuel. Large fields are discovered first, small ones later. After exploration and initial growth in output, production plateaus and eventually declines to zero (Hubbert, 1995). Thereafter in 2003, Aleklett and Campbell expressed their views that most of the countries will pass through peak oil days by 2010-12 and fuel consumption will reach to 80% by 2020-30 with the current rate of consumption (Alekett & Campbell, 2003).

In India, vehicular pollution is estimated to have increased eight times over the last two decades. This source alone is estimated to contribute about 70 per cent to the total air pollution. With 243.3 million tons of carbon released from the consumption and combustion of fossil fuels in 1999, India is ranked fifth in the world behind the U.S., China, Russia and Japan. India's contribution to world carbon emissions is expected to increase in the coming years due to the rapid pace of urbanization, shift from non-commercial to commercial fuels, increased vehicular usage and continued use of older and more inefficient coal-fired and fuel power-plants. Thus, peak oil year may be the turning point for mankind which in turn lead to the end of 100 year of easy growth, if self-sufficiency and sustainability of energy is not maintained on priority. It may end up a better world as per proceedings of conference held in Architectural Institute, 2004, Concept and Technology- First International Workshop on Sustainable Habitat Systems, at Japan. Presently major thrust is being given to explore wind energy, hydro-power, tidal and nuclear power generation etc. Efforts are also given to energy storage system for the clean energy by conversion system and its better utilization to run prime-movers for light vehicles.

This paper describes about the energy conversion and energy storage system. One of the dominant option is storage of compressed air from easily available atmospheric air which may be compressed by electricity or by alternative energy sources like wind, solar energy etc. or disaster energy sources and stored in the air receiver or storage tanks of suitable size. Such energy could be reutilized as clean energy source for running prime-movers of domestic appliances and light vehicles as a nearly zero pollution fuel sources. The design of air turbine / engine and its different parametric and performance aspect are also elaborated in this article. To maintain sustainability in 21st Century and check the global warming issues to the extent of 50-60%, the storage energy systems and its utilization to run the lighter vehicles or motorbikes by novel and efficient air engine / turbine could be one of the dominant technology. This may also leads to environmentally and ecologically better future.

2. Types of energy storage system

The Power Conversion System (PCS) is a vital part of all energy storage systems. It interfaces the energy storage, the energy storage device and the load (the end-user). PCS cost is significant and it can be greater than 25% of the overall energy storage system. PCS cost range from Rs. 4,700/kW for UPS markets to Rs.56, 000/kW for Standalone markets have been seen. Some of the major PCS markets include:

- Motor drives
- Power supplies
- UPS (uninterruptible power supply)
- Electric vehicles
- Inverters/Converters for solar-hybrid systems

- Micro-turbines
- Fuel cells
- Wind turbines

However, power conversion system technology has been evolving slowly due to the limited distributed energy resource (DER) market. As a result, Energy Storage System cost has been high with low profit margins and the manufacturing volume has been low impacting reliability and quality of the Power Conversion System designs. What is needed is a significant reduction in overall cost with improved reliability, development of state-of-the-art Power Conversion System with multiple uses, which increases production volumes for DER applications, improve controls and adaptability, and improve manufacturing.

2.1 Battery energy storage system

Sandia National Laboratory has a broad technical base of battery expertise focusing on integrated storage systems. These storage systems operate in varying environments and electrical conditions. In these storage systems there are many different types of battery technologies. With the different designs are having advantages under specific operational conditions. It is important to understand the capabilities and limitations of each storage technology.

- Lead-Acid Battery- short cycle life
- Li-Ion -Lithium Ion Battery-High energy and 100% efficiency
- NaS -Sodium Sulfur Battery- can run at high temperature of 300 deg centigrade.
- PSB - Polysulfide Bromide Flow Battery- 75% efficiency
- VRB -Vanadium Redox Flow Battery- 85% efficiency.

2.2 Super capacitor energy storage

Electrochemical capacitors (EC) store electrical energy in the two series capacitors of the electric double layer (EDL), which is formed between each of the electrodes and the electrolyte ions. The distance over which the charge separation occurs is just a few angstroms. The capacitance and energy density of these devices is thousands of times larger than electrolytic capacitors. The electrodes are often made with porous carbon material. The electrolyte is either aqueous or organic. The aqueous capacitors have a lower energy density due to a lower cell voltage but are less expensive and work in a wider temperature range. The asymmetrical capacitors that use metal for one of the electrodes have a significantly larger energy density than the symmetric ones and have lower leakage current.

2.3 Fly wheel energy storage

Most modern flywheel energy storage systems consist of a massive rotating cylinder (comprised of a rim attached to a shaft) supported on a stator by magnetically levitated bearings that eliminate bearing wear and increase system life. To maintain efficiency, the flywheel system is operated in a low vacuum environment to reduce drag. The flywheel is connected to a motor/generator mounted onto the stator that interact with the utility grid. Some of the key features of flywheels are little maintenance, long life (20 years or 10s of thousands of deep cycles) and environmentally inert material. Flywheels can bridge the gap between short term ride-through and long term storage with excellent cyclic and load following characteristics. The choice of using solid steel versus composite rims is based on the system cost, weight, size, and performance trades of using dense steel (200 to 375 m/s

tip speed) vs. a much lighter but stronger composite that can achieve much higher rim velocities (600 to 1000 m/s tip speed). Actual delivered energy depends on the speed range of the flywheel as it cannot deliver its rated power at very low speeds. For example, over 3:1 speed range, a flywheel will deliver ~90% of its stored energy to the electric load.

While high-power flywheels are developed and deployed for aerospace and UPS applications, there is an effort, pioneered by Beacon Power, to optimize low cost commercial flywheel designs for long duration operation (up to several hours). 2kW / 6kWh systems are in telecom service today. Megawatts for minutes or hours can be stored using a flywheel farm approach. Forty 25kW / 25 kWh wheels can store 1MW for 1 hour efficiently in a small footprint.

The stored energy can be approximated by:

$$E = (I\omega^2)/2 = (mr^2\omega^2)/2 = (mv^2)/2$$

where ω is the rotational velocity (rad/sec), I the moment of inertia for the thin rim cylinder, m is the cylinder mass and v is linear rim velocity.

2.4 Compressed air energy storage

The Technology of air engine is not new. The Sterling air engine was developed in 1790-1810, but due to its limitation no much work was carried out. In view of fire problems in Coalmines and other volatile places, where high flammable fuel like fossil fuel vehicles are not advisable, compressed air operated vehicles are normally being put in use. Now from last two decades major thrust is being given by the researchers for development of compressed air engine. Some technical developments, which may be considered to work on 21st Century Energy Storage system and can work on compressed air or hybrid system as an alternative to fossil fuel for running light vehicles, are listed below:-

2.4.1 Reciprocating compressed air engine

Guy Negre, a French Scientist, in 1998 developed compressed air- 4- cylinders engine run on air and gasoline, claims zero pollution cars and got 52- patents registered since 1998 to 2004. The car was demonstrated in Oct. 2004 publically (Negre, 2004).

2.4.2 Rotary hot air motor (Quasi-turbine)

Saint Hilaire G., an inventor developed zero pollution cars using Quasiturbine with a set of 14- engines parameters and disclosed on Sept 2005 using gasoline (Saint-Hilaire, 2005). In the basic single rotor Quasiturbine engine, an oval housing surrounds a four-sided articulated rotor, which turns and moves within the housing. The sides of the rotor seal against the sides of the housing, and the corners of rotor seal against the inner periphery, dividing it into four chambers.

3. Compressed air as alternative and zero emission source to fossil fuel

3.1 History of air engine

The compressed air as an energy and locomotion vector is precisely not a recent technology. In fact at the end of the 19th century the first approximations to what could one day become a compressed air driven vehicle already existed, through the arrival of the first pneumatic locomotives. Yet even two centuries before that Dennis Papin apparently came up with the idea of using compressed air (Royal Society London, 1687).

The first recorded compressed-air vehicle in France was built by the Frenchmen Andraud and Tessie of Motay in 1838. A car ran on a test track at Chaillot on the 9th July 1840, and worked well, but the idea was not pursued further. In 1872 the Mekarski air engine was used for street transit, consisting of a single-stage engine. It represented an extremely important advance in terms of pneumatic engines, due to its forward thinking use of thermodynamics, ensuring that the air was heated, by passing it through tanks of boiling water. Numerous locomotives were manufactured and the first in Nantes in 1879. The H. K. Porter Company in Pittsburgh sold hundreds of these locomotives to coal-mining companies in the eastern U.S. With the hopeful days of air powered street transit over, the compressed air locomotive became a standard fixture in coal mines around the world because it created no heat or spark and was therefore invaluable in gassy mines where explosions were always a danger with electric or gas engines.

Also in 1896, Porter supplied ten compressed air motor cars for the Eckington System in Washington, D.C. There was a tank on the front of the engine and it was recharged at the station. Between 1890 and 1902 ten compressed air trams circulated in Bern, Switzerland. In 1892, Robert Hardie introduced a new method of heating that at the same time served to increase the range of the engine. However, the first urban transport locomotive was not introduced until 1898, by Hoadley and Knight, and they introduced a two stage engine. Later on, in 1912 the American's method was improved by Europeans, adding a further expansion stage to the engine (3 stages).

In 1926, Lee Barton Williams of Pittsburg USA presented his invention: an automobile which he claimed run on air. The motor starts on gasoline, but after it has reached a speed of ten miles an hour the gasoline supply is shut off and the air starts to work. At the first test his invention attained a speed of 62 miles an hour.

In January 1932 what appears to be the first journalistic article ever written about a car driven by compressed air was published. In 1934, a 21-year-old researcher Johannes Wardenier announced the development of world's first fuel-less automobile. For weeks Dutch newspapers reported of an incredible invention that would change the world for ever.

After the Second World War the term "air engine" was never used again in textbooks in reference to compressed air or pneumatic locomotives and, whenever they mentioned it the article would go on to state that these engines are of little use or efficiency.

In 1970's, Willard Truitt presented his invention in McKees Rocks, USA. But because he did not have the financial means to develop his compressed air car further, he gave the rights of his invention to NASA and the US Army in 1982.

In 1979, Terry Miller decided that compressed air was the perfect medium for storing energy. He developed Air Car One, which he built for \$ 1,500. Terry's engines showed that it was feasible to manufacture a car that could run on compressed air. He patented his method in 1983 (US4370857).

In the 1980's Carl Leissler developed a motor that was able to function on air. The retired horticulturalist had been working from his garage in Hollywood for over 15 years. He says that to use his motor in a car you might have to use a small electric or gas energy source to help drive the air compressor. 'We might be able to get 2000 miles per gallon; air is a power in itself' Leissler comments.

Until 1987 the German company Arnold Jung Lokomotivenfabrik GmbH produced locomotives functioning on compressed air to be used in mines. In the 1980's they were still selling and renovating locomotives.

Currently the tram association in Bern Switzerland (BTG) is developing a locomotive according to the original plans.

At present (2008) various researchers and industries are developing compressed air engines/motors applicable to transportation, apart from the many industries that produce and commercialize compressed air motors for industrial purposes.

3.2 Advantages / disadvantages of air engine

There are advantages and disadvantages of air engines in comparison to the electric motors.

3.2.1 Advantages

- Air turbines do not need any electric power to run and hence, they can easily be used in volatile atmospheres also.
- Air turbines of the same size as that of electric motor can deliver more power as power density of the air engine is higher and thus, air engine the same size as that of electric motor can deliver more power.
- The air turbines can operate without any type of auxiliary speed reducers unlike electric motors.
- Overloads cause no harm to the air turbines whereas in the case of electric motor, it can easily trip the circuits, which have to be restored.
- Air engines can easily be controlled by simple flow control by means of valves whereas electric motor need electronic speed controls. By regulating the pressure, the torque produced by the air turbines can easily be varied.
- Air turbines do not need any magnetic starters like the electric motors.
- Air turbines generate very less heat as compared to the electric motors.

3.2.2 Disadvantages

- There are some drawbacks of air engines as the flow of air or the pressure is disturbed; the torque being produced by the air engines suffers in a great way.

3.3 Working principles of air engine / air turbine

3.3.1 Thermodynamic principle

The high pressure jet of air when injected into the rotor of vaned air turbine causes its rotation. Rotor movement is caused due to impact of air jet and the expansion of high pressure air admitted in turbine. Thus the high pressure air entering 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 till the rotation brings vanes in front of exit passage. This can be considered like isobaric admission and adiabatic expansion of high pressure air both contributing in producing the shaft work from air turbine. Compressed air leaving the air turbine after expansion is sent out from the exit passage.

The proposed air turbine is considered to work on the reverse working principle of vane type compressor and transforms the energy of the compressed air into shaft work. The multi-vane type air turbine has casing diameter 100 mm and rotor diameter 75 mm as shown in **Fig. 2**. 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 an earlier study conducted by authors a prototype of air turbine was developed (Singh & Singh, 2008c).

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 (Honton,2004) 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 (Faglsang, 2004; Gorla, 2004; Knowlen, 1998; Schreck, 2004; Selig, 2004). Studies have shown feasibility of vane type novel air turbine (Singh & Singh 2006; 2007; 2008 a, b; 2009 a-f).

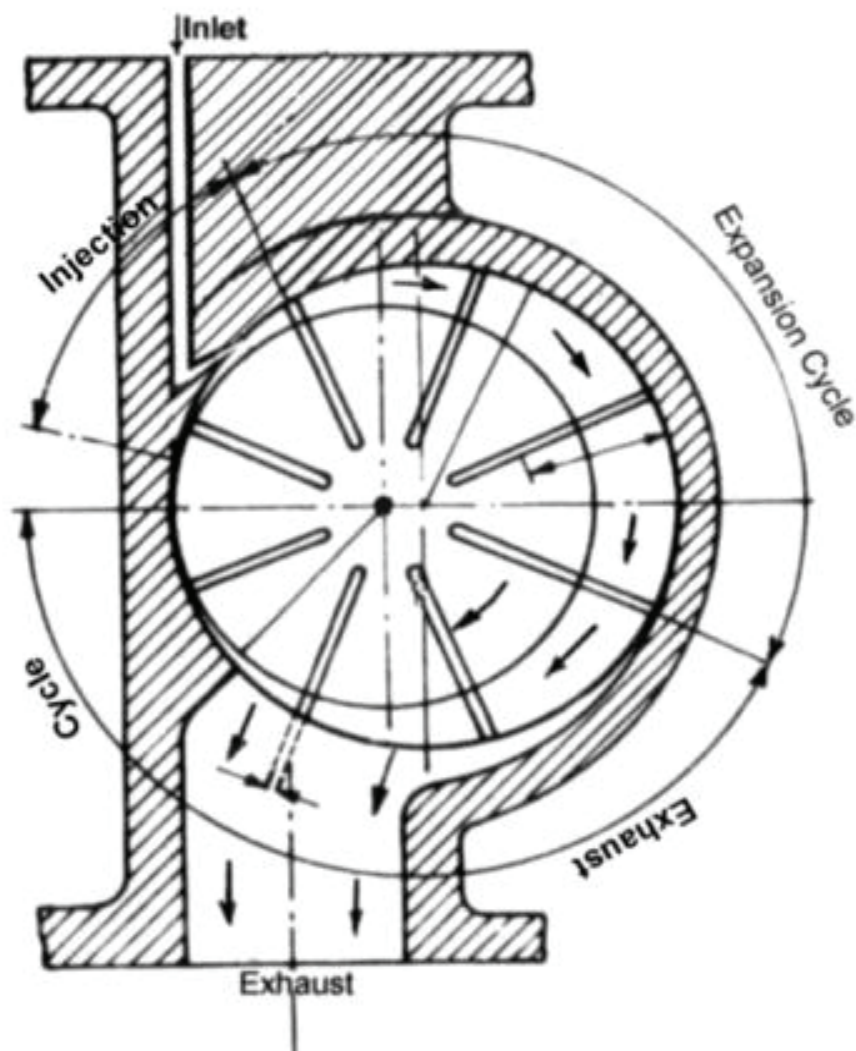


Fig. 2. Air Turbine- Model

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 here 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 motorcycle. It is assumed that the scavenging of the rotor is perfect and the work involved in recompression of the residual air is absent. The assumptions made for thermodynamic analysis are as under.

- Admission of air takes place isobarically.
- High pressure air admitted in turbine rotor expands adiabatically.
- There is no residual air in rotor after the expanded air is discharged from rotor. Thus no recompression of air takes place.
- Loss of work due to rubbing friction between vanes and casing walls is neglected.
- Leakage of air across the vane tip and rotor casing contact interface is negligible.
- Mechanical losses due to shaft friction are negligible.
- Trace of the lubricant added to the air being admitted is negligible compared to total mass flow of air.
- Loss due to throttling of air at admission and exit is negligible.
- Exit of expanded air occurs isochorically
- Flow across the turbine is of steady flow type.

3.3.2 Mathematical modeling

The mathematical model shown here is already presented in the author's publications (Singh & Singh, 2010a, b, c, d, e, f, g and h). But for the benefits of readers it is again reproduced here in brief. 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.

From **Fig. 3**, it is seen that work output is due to isobaric admission (E to 1), adiabatic expansion (1 to 4) and steady exit flow work (4 to 5). Thus, total work done due to thermodynamic process may be written as:

$$[\text{Area under (E145CE)}] = [\text{Area under (E1BOE)} + \text{Area under (14AB1)} - \text{Area under (4AOD4)} + \text{Steady Flow (45CD4)}]$$

$$\text{Total Work output} = [\text{Thermodynamic expansion work } (w_1)] + [\text{Exit steady flow work } (w_2)]$$

$$w = [(w_1) + (w_2)] \quad (1)$$

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

$$w_1 = p_1 \cdot v_1 + \left(\frac{p_1 \cdot v_1 - p_4 \cdot v_4}{\gamma - 1} \right) - p_4 \cdot v_4 \quad \text{or} \quad w_1 = \left(\frac{\gamma}{\gamma - 1} \right) (p_1 \cdot v_1 - p_4 \cdot v_4)$$

For adiabatic process, $p.v^\gamma = p_1.v_1^\gamma = p_4.v_4^\gamma = \text{constant}$

$$\text{or } v_4 = \left(\frac{p_1}{p_4}\right)^{\frac{1}{\gamma}}.v_1$$

Thus thermodynamic expansion work output would be:

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

The exhaust of expanded air to atmosphere (4-5) takes place after the expansion process (E-4) as shown in Fig.3. 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, 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:

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

Substituting equations (2), (3) into equation (1), the net work output will be:

$$w = (w_1 + w_2) = \left(\frac{\gamma}{\gamma-1}\right).p_1.v_1 \cdot \left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} + (p_4 - p_5).v_4 \quad (4)$$

When air turbine is having n number of vanes, then shaft output can be written as:

$$w_n = n \cdot \left(\frac{\gamma}{\gamma-1}\right).p_1.v_1 \cdot \left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} + n.(p_4 - p_5).v_4 \quad (5)$$

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

Therefore, the total power output (work done per unit time) (W_{total}), for speed of rotation N rpm will be mentioned as (Book; Singh O., 2009):

$$W_{total} = n.(N / 60) \cdot \left(\frac{\gamma}{\gamma-1}\right).p_1.v_1 \cdot \left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\} + n.(N / 60).(p_4 - p_5).v_4 \quad (6)$$

where

$$W_{exp} = n.(N / 60) \cdot \left(\frac{\gamma}{\gamma-1}\right).p_1.v_1 \cdot \left\{1 - \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right\}$$

and $W_{flow} = n.(N / 60).(p_4 - p_5)v_4$

Fig. 2. shows that if vanes are at angular spacing of θ degree, then total number of vanes will be $n = (360/\theta)$. The variation in volume during expansion from inlet to exit (i.e. v_1 to v_4) can be derived by the variable extended length of vane as shown in Figure 3 at every point of movement between two consecutive vanes.

From Fig. 4, it is seen that when two consecutive vanes at OK and OL moves 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 $X_{at\ variable\ \alpha}$ can be written from the geometry:

$$BG = X_{at\ variable\ \alpha} = (1/2).D.\cos\left[\sin^{-1}\left\{\left(\frac{D-d}{D}\right).\sin\alpha\right\}\right] + (1/2).(D-d).\cos\alpha - d/2 \quad (7)$$

where D is diameter of casing and d is diameter of rotor, α is angle $\angle BOF$, β is angle $\angle BAF$ and θ is angle $\angle HOB$ or $\angle KOL$, between two consecutive vanes and ϕ is angle $\angle KOJ$ at which injection pressure enters the air turbine.

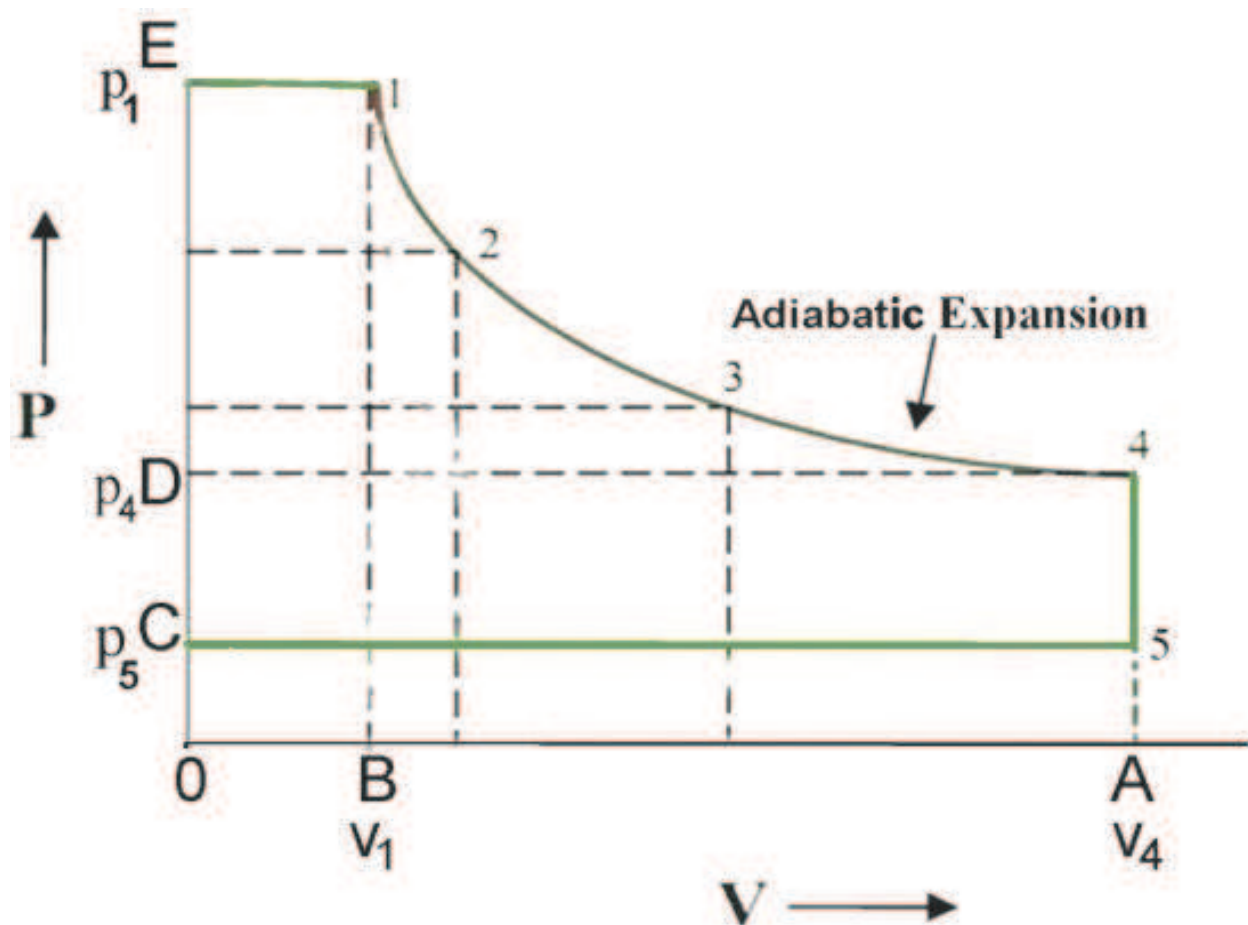


Fig. 3. Thermodynamic Processes (Isobaric, adiabatic and Isochoric Expansion)

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

$$v_{cuboids} = L \cdot \left\{ \frac{(X_{1i} + X_{2i})(d + X_{1i})}{4} \right\} \cdot \sin \theta \quad (8)$$

Where $BG = X_{1i}$ and $IH = X_{2i}$ are variable projected lengths of vanes when rotor rotates in the turbine as shown in Fig. 4.

The lengths (IG, HB and LK, SM.), are considered linear whereas all are chords of circles. This approximation is done in mathematical model which has very least impact on the overall values.

The volume at inlet v_1 or v_{min} will fall between angle $\angle LOF = \alpha_{1min} = (180 - \theta - \phi)$ and angle $\angle KOF = \alpha_{2min} = (\alpha_{1min} + \theta) = (180 - \phi)$ as seen in Fig. 3, when air is admits into turbine at angle ϕ .

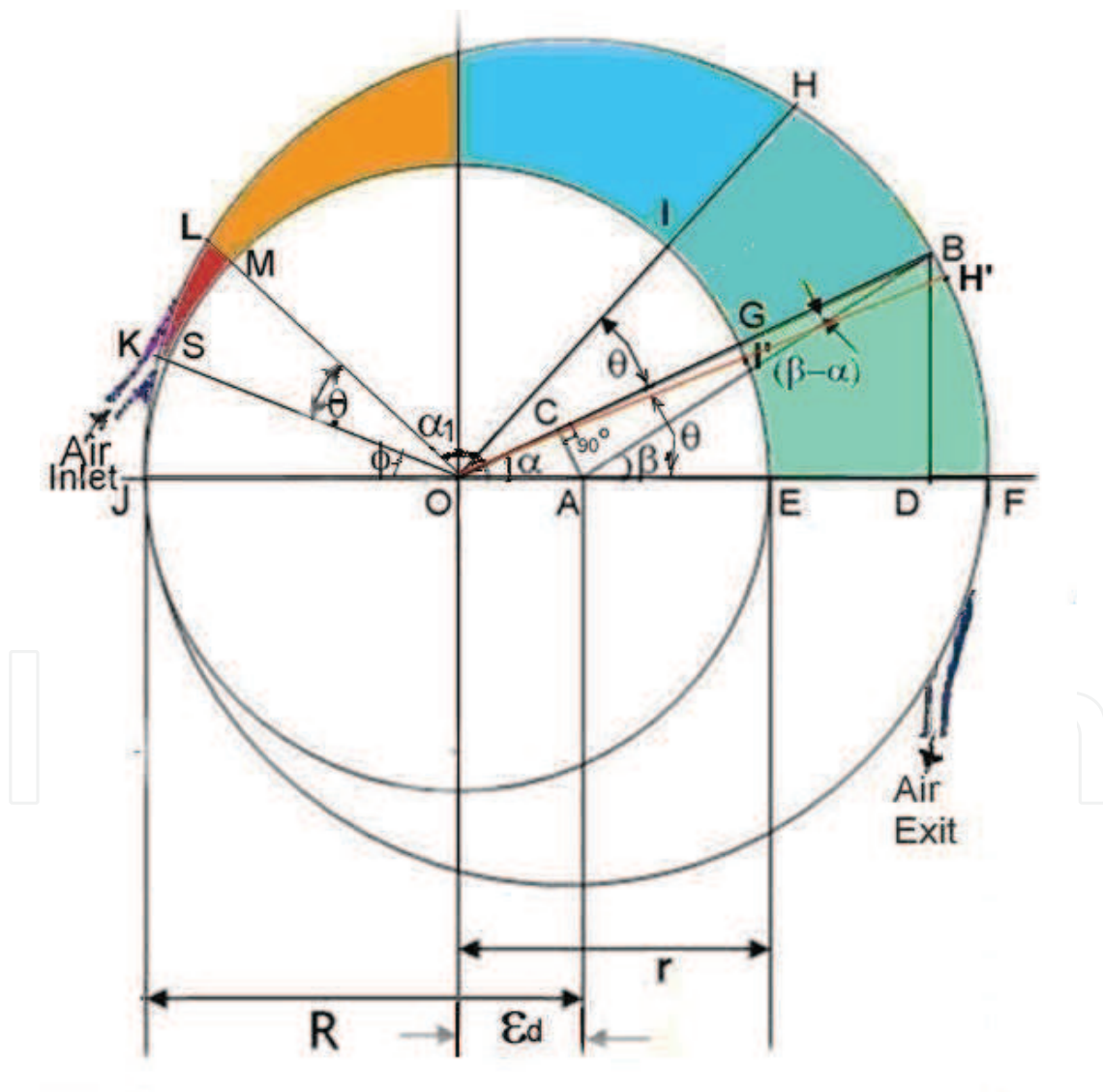


Fig. 4. Variable length BG and IH and injection angle ϕ

Applying above conditions into equations (7), then $LM=X_{1min}$ and $SK=X_{2min}$ can be written as:

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

$$X_{2min} = R.\cos \left[\sin^{-1} \left\{ \left(\frac{R-r}{R} \right) . \sin(180 - \phi) \right\} \right] + [(R-r).\cos(180 - \phi) - r] \quad (10)$$

Applying values of X_{1min} and X_{2min} to equation (8),

$$v_1 = v_{min} = L. \left\{ \frac{(X_{1min} + X_{2min})(2r + X_{1min})}{4} \right\} . \sin \theta \quad (11)$$

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

Applying above conditions into equations (7), then $FE=X_{1max}$ =Corresponding to BG at $\alpha = 0$ degree and $I'H'=X_{2max}$ =Corresponding IH at $(\alpha + \theta) = \theta$ degree can be written as:

$$X_{1max} = (D - d) = 2(R - r) \quad (12)$$

$$X_{2max} = R.\cos \left[\sin^{-1} \left\{ \left(\frac{R-r}{R} \right) . \sin \theta \right\} \right] + \{(R-r).\cos \theta\} - r \quad (13)$$

Applying values of X_{1max} and X_{2max} to equation (8),

$$v_4 = v_{max} = L. \left\{ \frac{(X_{1max} + X_{2max})(2r + X_{1max})}{4} \right\} . \sin \theta \quad (14)$$

Substituting values of v_1 and v_4 from equations (11) and (14) to equation (6), the total power output available W_{total} can be written as:

$$W_{total} = n.(N / 60). \left(\frac{\gamma}{\gamma - 1} \right) . \left[1 - \left(\frac{p_4}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} \right] p_1 . \left[L. \left\{ \frac{(X_{1min} + X_{2min}).(2r + X_{1min})}{4} \right\} . \sin \theta \right] + n.(N / 60).(p_4 - p_5) . \left[L. \left\{ \frac{(X_{1max} + X_{2max}).(2r + X_{1max})}{4} \right\} . \sin \theta \right] \quad (15)$$

4. Input parameters and assumptions

In this study the vane angle (θ) of air turbine is considered 30°, 45°, 51.4°, 60°, 72° and 90° (i.e. 12, 8, 7, 6, 5 and 4 vanes respectively) and injection angle (ϕ) is kept 30°, 45° and 60°. The outer diameter of Casing is considered 200 mm, 150 mm and 100 mm and correspondingly Rotor diameter is chosen 150 mm, 100 mm and 75 mm correspondingly.

Other various input parameters are listed in **Table 2, 3, 4** for investigation of optimum shaft power output at different vane angles, and injection angles.

4.1 To Optimize the power by selecting various options of vane angles (θ)

4.1.1 Input parameters for investigation of effect of vane angle

Symbols	Parameters
$D=2R$	150 mm (outer)
$d=2r$	100 mm (inner) corresponding
p_1	2bar (=30psi), 3bar (=45 psi), 4bar (=60 psi), 5bar (=75 psi), 6bar (=90 psi)
p_4	$= (v_1 / v_4)^\gamma . p_1 > p_5$ assuming adiabatic expansion
p_5	1 atm = 1.0132 bar
θ	30°, 36°, 45°, 51.4°, 60°, 72°, 90° angles between 2- consecutive vanes (i.e. rotor contains correspondingly 12, 10, 8, 7, 6, 5, 4 vanes)
N	2500 rpm
L	35 mm length of rotor
γ	1.4 for air
n	Number of vanes (360 / θ)
\emptyset	Injection angles at which compressed air enters through nozzle into rotor <i>Case-1: 30°, Case-2: 45° and Case-3: 60°</i>

Table 2. Input Parameters for Investigation of Vane angles

4.1.2 Results and discussion

From **Fig. 5** to **Fig. 7**, it is noted that there is an optimum power output value for each set of injection pressure for different vane angles. Thus the optimum total power output is obtained as:

Case-1. For injection angle 30°

Total work power from **Fig. 5**, is seen to increase with increasing vane angles from 36° to 60° or with the decrease in number of vanes from 12 to 6 on rotor and thereafter it declines from vane angles (θ) = 72° to 90°. With increase in injection pressure the work output increases gradually as shown in graphical patterns. Thus the optimal total shaft output is found at vane angle (θ) = 60° (i.e. 6- vanes).

Case-2. For Injection angle 45°

Similarly, total power output from **Fig. 6**, is seen to increase with increasing vane angle up to 36° to 51.4° or with the decrease in number of vanes from 12 to 7 on rotor and thereafter it declines from vane angles (θ) = 60° to 90°. With increase in injection pressure the work output increases gradually as shown in graphical patterns. Thus the optimal total shaft output is found at vane angle (θ) = 45° and 51.4° (i.e. 8-7 vanes).

Case-3. For Injection angle 60°

Here also the total power output from Fig. 7, is seen to increase with increasing vane angle up to 36° or with the decrease in number of vanes from 12 to 10 on rotor and thereafter it declines for vane angles (θ) = 45° to 90°. With increase in injection pressure the work output increases gradually as shown in graphical patterns. Thus the optimal total shaft output is found at vane angle (θ) = 36° (i.e. 10 vanes).

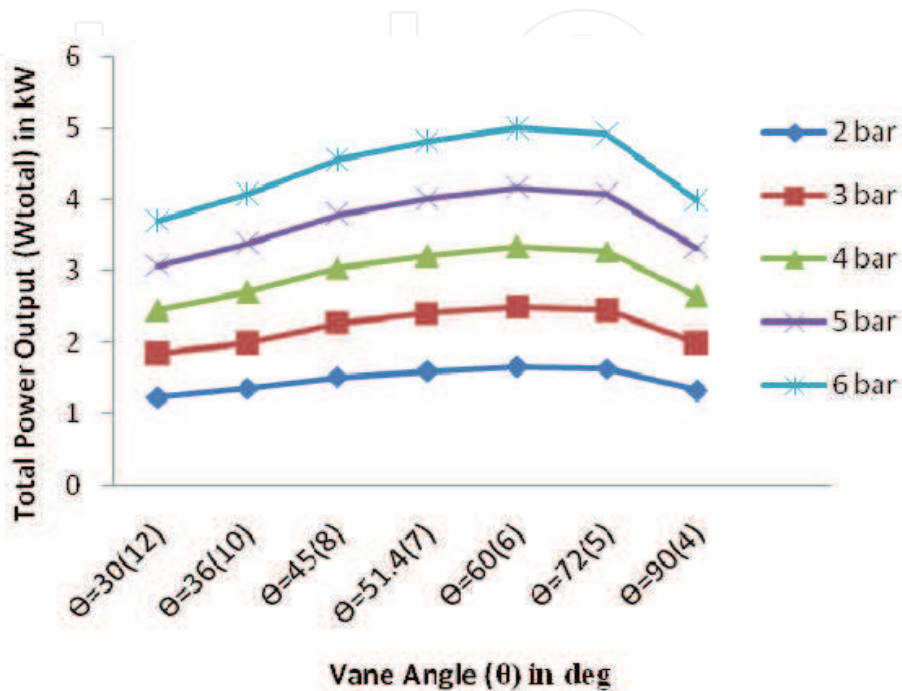


Fig. 5. Total power output versus different vane angles, at injection air pressure 2-6 bar, injection angle of 30° and speed of rotation 2500 rpm

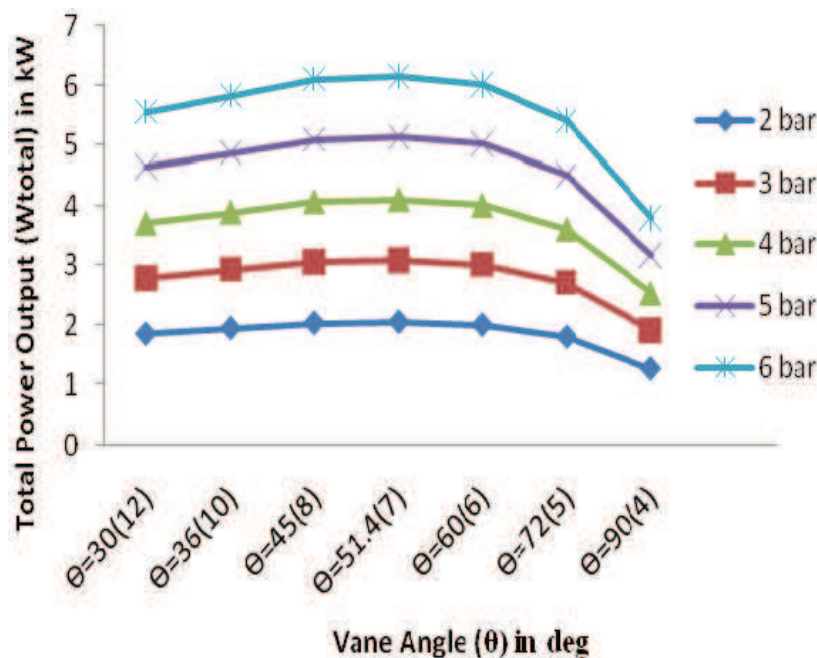


Fig. 6. Total power output versus different vane angles, at injection air pressure 2-6 bar, injection angle of 45° and speed of rotation 2500 rpm

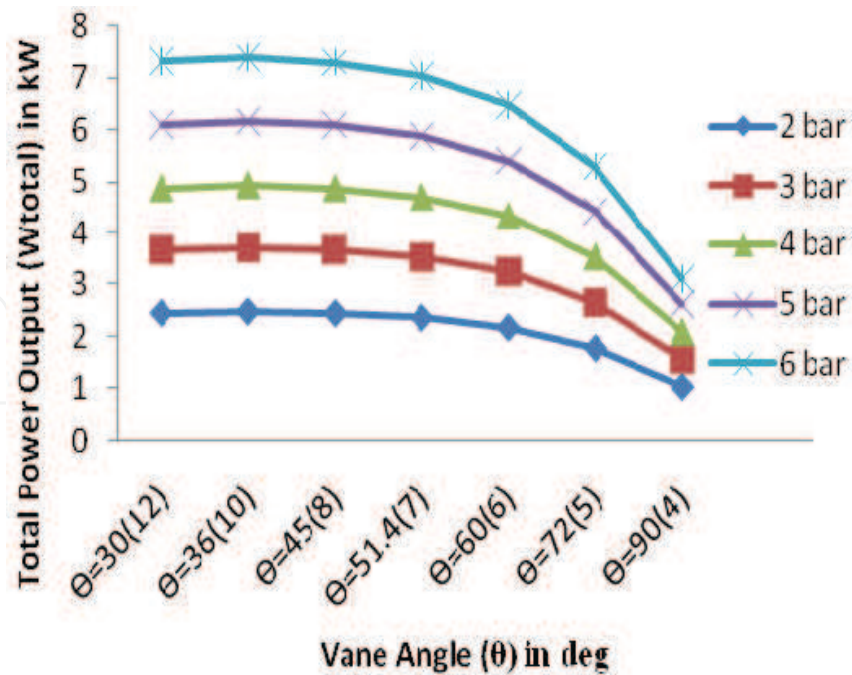


Fig. 7. Total power output versus different vane angles, at injection air pressure 2-6 bar, injection angle of 60° and speed of rotation 2500 rpm

Thus, total optimum power is observed as:

Case-1: 5.00 kW at vane angle (θ) = 60° (i.e. 6 vanes) when injection angle is kept 30°,

Case-2: 6.1-6.15 kW at vane angle (θ) = 45°, 51.4° (i.e. 8-7 vanes) when injection angle is 45° and

Case-3: 7.39 kW at vane angle (θ) = 36° (i.e. 10 vanes) when injection angle is 60°.

4.2 To optimize the power by selection of injection angle (θ)

4.2.1 Input parameters for investigation of injection angle

Symbols	Parameters
D=2R	200 mm (outer)
d=2r	160 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	$(v_1 / v_4)^\gamma \cdot p_1 > p_5$ assuming adiabatic expansion
θ	45° (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°, 15°, 20°, 25°, 30°, 45°, 60°, 75°, 90° angles at which compressed air enters through nozzle into rotor

Table 3. Input Parameters for Investigation of Injection angle

4.2.2 Results and discussion

From the Fig. 8 it is observed that total power 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.

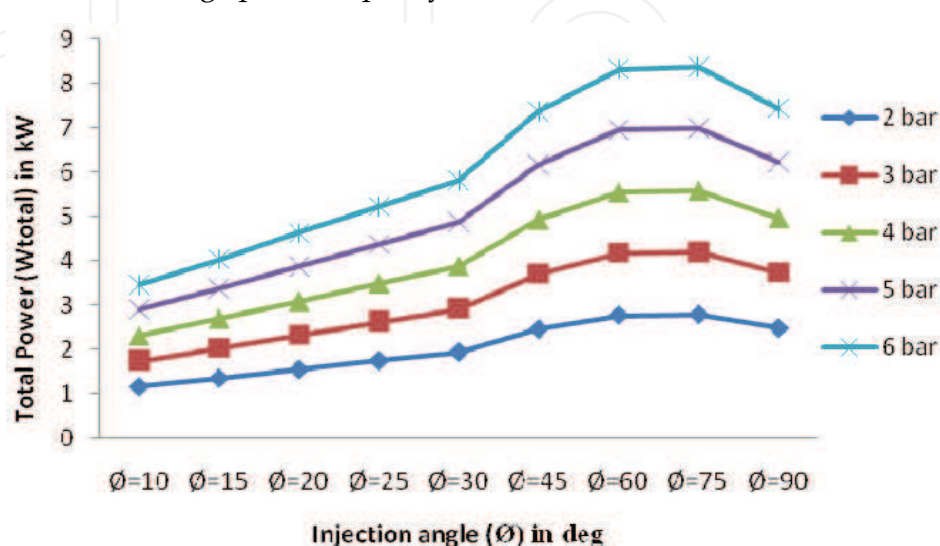


Fig. 8. Total turbine power output versus different injection angles, at injection air pressure 2-6 bar and speed of rotation 2500 rpm

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 in the range of 2-6 bar.

4.3 To optimize the power by critically selecting vane and injection angles

4.3.1 Input parameters for investigation of vane and injection angle

Symbols	Parameters
D=2R	150 mm (outer)
d =2r	100 mm (inner) corresponding
p_1	2bar (=30psi), 3bar (=45 psi), 4bar (=60 psi), 5bar (=75 psi), 6bar (=90 psi)
p_4	$= (v_1 / v_4)^\gamma . p_1$ assuming adiabatic expansion
p_5	1 atm = 1.0132 bar
θ	30°, 36°, 45°, 51.4°, 60°, 72° and 90° angles between 2- consecutive vanes (i.e. rotor contains correspondingly 12, 10, 8, 7, 6, 5 and 4 vanes)
N	3000 rpm
L	45 mm length of rotor
γ	1.4 for air
n	(360 / θ) Number of vanes
\emptyset	30°, 45° and 60° Injection angles at which compressed air enters through nozzle into rotor

Table 4. Input Parameters for Investigation of Vane and Injection Angles Both

4.3.2 Results and discussion

From Fig. 9, it is noted that optimum total power output is obtained as:

- 5.0 kW when vane angle (θ) = 60° (i.e. 6 vanes) and injection angle (ϕ) = 30° ,
- 6.1-6.15 kW when vane angle (θ) = 45° - 51.4° (i.e. 8-7 vanes) and injection angle (ϕ) = 45° and
- 7.39 kW at vane angle (θ) is 30° - 45° (i.e. 12-8 vanes) and injection angle (ϕ) = 60° .

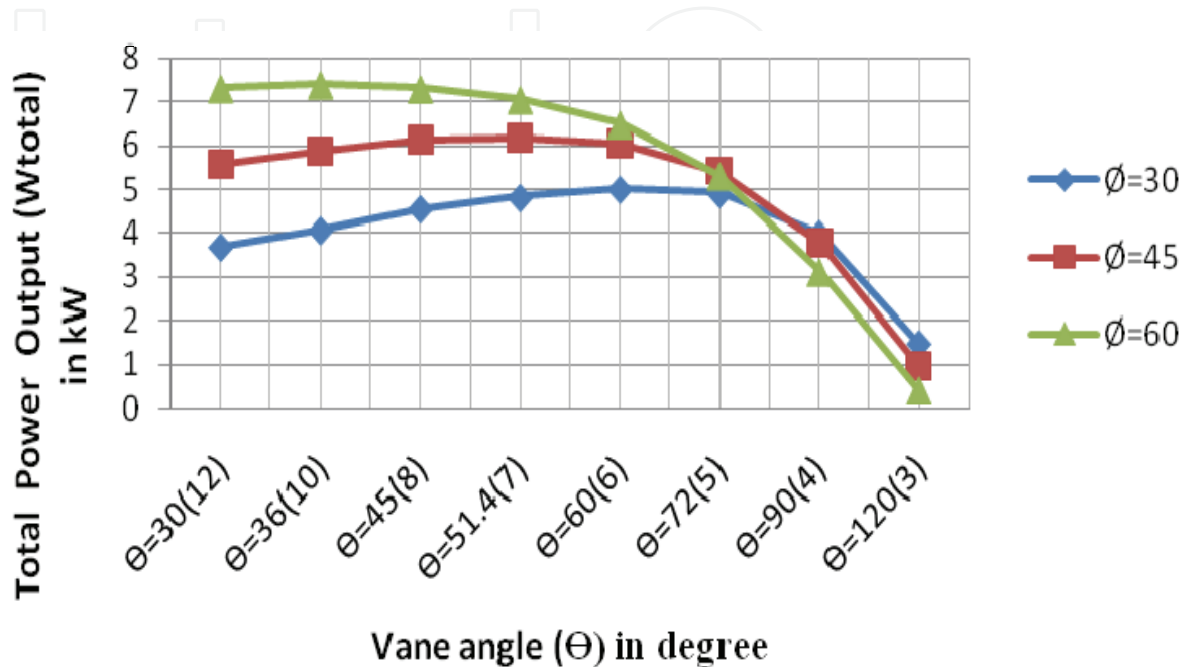


Fig. 9. Total power output versus different vane angles at air injection pressure 6 bar, at injection angle of 30° , 45° , 60° , and speed of rotation 3000 rpm

Thus the maximum shaft power output 6.1 kW to 7.39 kW is achievable at 60° injection angle when number of vanes of rotor is kept between 12-8 (vane angle is 30° - 45°). Such type turbine can be used as replacement to internal combustion engines and it can easily be used to run light vehicle or motorbikes with zero pollution.

5. Conclusions

From the above study, it is noticed that the heavy consumptions of fossil fuel in the transport sector is causing serious threat to mankind causing global warming and damage to the environment and ecology. Following conclusions are observed from the study:

- Fossil fuel reserves are depleting due to growing energy requirements.
- Vehicular pollution is estimated to increase many fold in near future.
- Energy storage system could be utilized for the clean energy future.
- The shaft power output of small air engine is achievable from 6.1 kW to 7.39 kW, which is sufficient to run motorbikes or any light vehicle.
- Compressed air technology is going to be the most economical and dominating energy source for running light vehicles / motorbike as tail pipe emission is zero.

The air engine technology, if implemented widely in developing countries to run the light vehicles / motobikes, it might reduce 50-60% global warming issues which is a big challenge of 21st century.

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7. 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 = $(360/\theta)$
 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

- $1, 2, \dots, 4, 5$: subscripts - indicates the positions of vanes in casing
 exp : expansion
 min : minimum
 max : maximum

Greek symbols

- α : angle BOF (see Fig.3)
 α_1 : angle LOF ($=180 - \phi$) (see Fig.3)
 α_2 : angle KOF ($=180 - \theta - \phi$) (see Fig.3)
 β : angle BAF (see Fig.3)
 γ : 1.4 for air
 θ : angle between 2-vanes (BOH) (see Fig.3)
 ϕ : angle at which compressed air enters into rotor through nozzle
 ξ_d : eccentricity ($R-r$)

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The Impact of Air Pollution on Health, Economy, Environment and Agricultural Sources

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This book aims to strengthen the knowledge base dealing with Air Pollution. The book consists of 21 chapters dealing with Air Pollution and its effects in the fields of Health, Environment, Economy and Agricultural Sources. It is divided into four sections. The first one deals with effect of air pollution on health and human body organs. The second section includes the Impact of air pollution on plants and agricultural sources and methods of resistance. The third section includes environmental changes, geographic and climatic conditions due to air pollution. The fourth section includes case studies concerning of the impact of air pollution in the economy and development goals, such as, indoor air pollution in México, indoor air pollution and millennium development goals in Bangladesh, epidemiologic and economic impact of natural gas on indoor air pollution in Colombia and economic growth and air pollution in Iran during development programs. In this book the authors explain the definition of air pollution, the most important pollutants and their different sources and effects on humans and various fields of life. The authors offer different solutions to the problems resulting from air pollution.

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