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Effect of Nozzle Vane Shape on Performance of Variable Geometry Turbocharger.

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Abstract - Now a day's tightening of emissions regulations, the turbochargers used to supercharge air into engines are now essential products for automotive diesel engines. Variable Geometry (VG) turbochargers capable of controlling boost pressure with a variable nozzle vane on the turbine side are becoming the mainstream. The turbocharger performance has a direct impact on fuel consumption and the variable nozzle mechanism uses a airfoil shape vane to guide the flow inside the volute casing of turbocharger. The controlling of vanes is depending upon engine rpm. Here paper describes the effect of airfoil shape vane on turbine rpm of turbocharger. Presently the VG turbocharger uses a un-camber vane shows a more static pressure on the turbine blades hence rotating with less rpm. The aim is predication of turbine rpm and velocity magnitude within the volute casing of VG turbocharger by using cambered vane with the use of CFD analysis.

Index Terms – *Turbocharger, Variable nozzle mechanism.*

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I. INTRODUCTION

Turbochargers are employed to achieve higher specific engine power output by converting some of the energy in the exhaust gas stream into energy in the inlet system in the form of raised inlet pressure (boost). This raised inlet pressure forces more air into the engine cylinders, allowing more fuel to be burned and thus resulting in higher power output. Thus turbochargers are finding increasing application to automotive diesel engines as cost effective means for improving their power output and efficiency, and reducing exhaust emissions; these requirements have led to the need for highly loaded turbocharger turbines. The advent of the turbocharger marked a large jump in the break mean effective pressure (BMEP) of the engine. At start of engine the amount of exhaust gas is less and turbine of turbocharger rotate with less rpm hence compress of turbocharger unable to provided required amount of air for complete combustion fuel in cylinder in short we can say that A/F ratio does not meet to design standard value which cause to be low boost pressure. On other hand, at high rpm of engine the amount of exhaust gas are more and hence turbine of turbocharger rotate at high speed cause to be more amount of compress air supplied to engine because of this the engine efficient lowering down at high speed. To avoid such fluctuations in rpm of turbocharger a nozzle ring vane assembly is introduce to control the speed of turbine of turbocharger at low and high rpm of engine. Here the work is carried out for modification of vane shape for achieving controllability. Now a day's a straight vane is used in turbocharger nozzle ring but it is found to a larger circumferential static pressure variation which lowering down the turbine efficiency which need to be change in shape of vane. The shape of existing vane is based on the NACA airfoil 0015 which is further modified based on NACA airfoil 6412 with reduction in nose radius and i.e 1.87 to 1.59 and using computerized fluid dynamics software such as fluent analyze the performance of turbocharger by observing pressure, velocity and mass flow rate.

II. LITERATURE REVIEW

A turbocharger acts in a similar way as a supercharger and pressurizes the air at the inlet manifold. As the inlet valve in the cylinder opens, a greater mass of air is drawn into the cylinder to be burnt with the fuel. More power is generated at each engine speed. Unlike the supercharger it does not feed off the power output of the engine. The turbocharger uses the waste energy from the exhaust gas to drive a turbine wheel that is linked to the compressor through a shaft. At high altitudes, there is insufficient oxygen to burn the fuel, resulting in low power and black smoke.

At high altitudes the turbocharger rotates faster to increase delivery of air to the engine to compensate. So a turbocharger maintains power from the engine and produces clean emissions. Fitting a turbocharger and an air cooler can increase engine power even more. An Intercooler removes the heat of compression between the stages of a compressor whereas an after cooler reduces the temperature of the air leaving the compressor. Delivering cold air means that there is more oxygen per cylinder (cold air has a higher density than warm air) thus more engine power. In a turbocharger it is often desirable to control the flow of exhaust gas to the turbine to improve the efficiency or operational range of the turbocharger. Variable geometry turbochargers (VGTs) have been configured to address this need. A type of such VGT is one having a variable exhaust nozzle, referred to as a variable nozzle turbocharger. Different configurations of variable nozzles have been employed in variable nozzle turbochargers to control the exhaust gas flow. One approach taken to achieve

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exhaust gas flow control in such VGTs involves the use of multiple pivoting vanes that are positioned annularly around the turbine inlet. The pivoting vanes are commonly controlled to alter the throat area of the passages between the vanes, thereby functioning to control the exhaust gas flow into the turbine.

III. Working of Turbocharger

In simple terms, a turbocharger comprises of a turbine and a compressor connected by a common shaft supported on a bearing system's shown in fig. 1. The turbocharger converts waste energy into compressed air which it pushes into the engine. This allows the engine to produce more power and torque and improves the overall efficiency of the combustion process. In the above-described procedures, the engine operates as a naturally aspirated engine. The combustion air is drawn directly into the cylinder during the intake stroke. In turbocharged engines, the combustion air is already pre-compressed before being supplied to the engine. The engine aspirates the same volume of air, but due to the higher pressure, more air mass is supplied into the combustion chamber. Consequently, more fuel can be burnt, so that the engine's power output increases related to the same speed and swept volume.

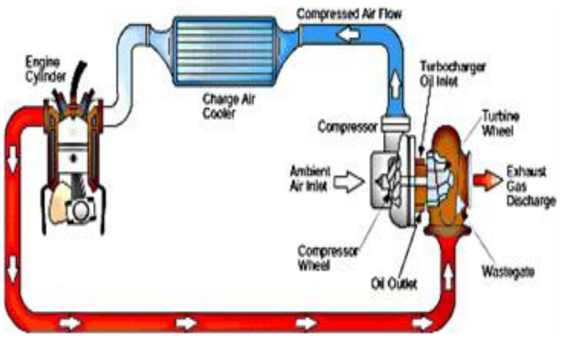

Fig..1- Turbine and a Compressor connected by a common shaft supported on a bearing

The turbocharger is bolted to the exhaust manifold of the engine. The exhaust from the cylinders spins the turbine, which works like a gas turbine engine. The turbine is connected by a shaft to the compressor, which is located between the air filter and the intake manifold. The compressor pressurizes the air going into the pistons. The exhaust from the cylinders passes through the turbine blades, causing the turbine to spin. The more exhaust that goes through the blades, the faster they spin.

IV. Variable Geometry Turbocharger (VGT)-

A Variable Geometry Turbocharger is also called as Variable Nozzle Turbochargers (VNT) or Variable Turbine Geometry (VTG). It is primarily used to reduce turbo lag at low engine speed, Ordinary turbochargers cannot escape from turbo lag because at low engine rpm the exhaust gas flow is not strong enough to push the turbine quickly. A Variable Geometry Turbocharger is capable to alter the direction of exhaust flow to optimize turbine response. It incorporates many movable vanes in the turbine housing to guide the exhaust flow towards the turbine. An actuator can adjust the angle of these vanes; in turn vary the angle of exhaust flow.

VGT are turbochargers control the width of the nozzle directing exhaust gas onto the turbine wheel. By narrowing the width of the nozzle opening shown in figure 2, the turbine speed increases as does exhaust backpressure. An electric or air type actuator operates a sliding nozzle ring to regulate the nozzle opening. As the actuator closes the nozzle to narrow its width, turbine speed and boost pressure rapidly increase. This effect can be accomplished with minimal engine load or exhaust energy. So at low speed and load operation, relatively higher boost pressure is achieved than with using fixed geometry or even wastegate turbochargers.

Fig.2. VGT vane position when exhaust supply is low.

Opening the nozzle produces the opposite effect, more exhaust gas flow will take place across the turbine but turbine speed will decrease and exhaust backpressure drops. By varying the width of the nozzle opening with an actuator, turbine power can be set to provide just sufficient energy to drive the compressor at the desired boost level wherever the engine is operating. VGT is implemented in different ways.

One system uses a series of movable vanes around the periphery of the turbine wheel, as shown in Figure 2. Each vane pivots on an axis parallel with the rotor axis. When the exhaust gas supply is low, the vanes pivot to a position which is a few degrees from perpendicular to the turbine wheel inducer vanes. That gives the incoming gasses a strong tangential component to drive the turbine more effectively.

At Low Exhaust Flow VGT Position the angle of the blades can be varied continuously, and at high exhaust flow they are nearly aligned radically with the outer contour of the turbine blades, as shown in Figure 3 giving the incoming gasses a strong radial component to drive the turbine, while offering a relatively large flow area to reduce backpressure. At

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low rpm the vanes are partially closed, reducing the area hence accelerating the exhaust gas towards the turbine. Moreover, the exhaust flow hits the turbine blades at right angle. Both makes the turbine spins faster.

Although many such systems. Currently use non-cambered vanes (the chord line is straight), future developments will include cambered vanes to increase VGT efficiencies at the top and bottom ends of the operating range.

Fig.3–VGT vane position when exhaust supply is more.

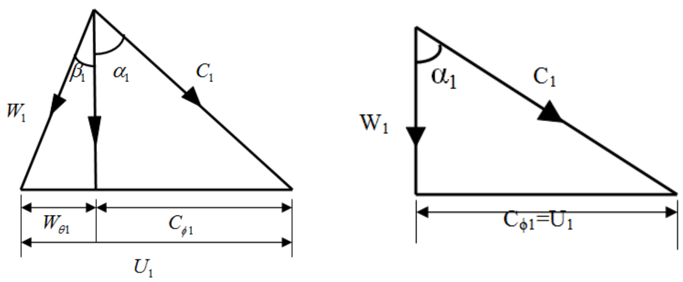
V. NOZZLE VANE IN TURBOCHARGER.

The axial turbine blade design method was used to decide on the nozzle vane's geometries and the arrangement was consequently converted to a circumferential nozzle ring. The nozzle vane in the current used is an un-cambered. The nozzle vane's profile was designed based on the NACA (The National Advisory Committee for Aeronautics) airfoil 0015. The volute used in this study is based on a commercial turbocharger (HOLSET H3B) which content sufficient enlargement for a nozzle vane ring fitting. The volute has an inlet area over radius ratio (A/R) of 30 mm and an exit flow angle of 70º [2]. To calculate the mass flow rate of exhaust gas that entering the turbocharger, flow velocity over turbine, RPM of turbine and power output of turbocharger. In order to calculate the above parameter theoretically, construction of velocity triangle at inlet and outlet condition is done.

Here as turbine of turbocharger is radial turbine $\therefore \beta_2 = 0$

and hence $C_{\phi 1} = U_1$ and $\overrightarrow{W_{\theta 1}} = 0$

$\therefore$ Inlet velocity triangle (A) is reduce to triangle (B)

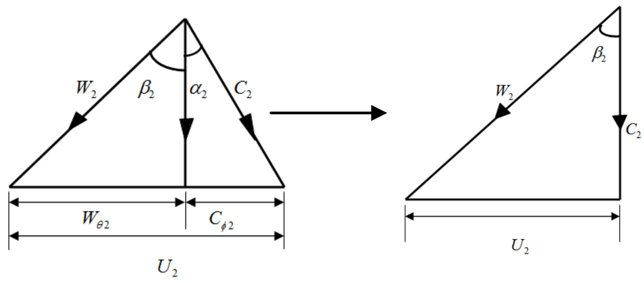


(A) (B)

Here as turbine of turbocharger is radial turbine

$\therefore \alpha_2 = 0$ And hence $C_{\phi 2} = U_1$ and

$\therefore$ Outlet velocity triangle (C) is reduce to triangle (D)



(C) (D)

From above calculation it is clear that in idle condition of an engine, for the 0.209 kg/s mass of rate of exhaust gas the flow velocity is found to be 25.12 m/s and rotor velocity is found to be 23.60 m/s and calculated turbine rpm is 7513. This mass flow rate of exhaust gas used as a boundary condition for the analysis of existing turbocharger geometry with un-cambered nozzle ring vane for the prediction of pressure and velocity profile with the volute casing of the turbocharger.

VI. FLOW ANALYSIS

A flow analysis in volute casing of VG turbocharger is carried out by using existing profile of vane with the help of CFD software. The flow analysis is carried out mainly to observer the nature of flow on turbine blade due to aerofoil shape of vane. Also vane surface static pressure survey, steady state turbine performance for vane setting at 700 which is best as per literature survey[1], pressure variations at all nozzle opening and the exciting force of the turbine moving blade during nozzle wake resonance. In order to this, for creating geometry and meshing to this geometry a Gambit software is used and for analysis computational fluid dynamics software is used for calculation and simulation purpose. The vanes are generally designed having an airfoil shape that is configured to both provide a complementary fit with adjacent vanes when placed in a closed position, and to provide for the passage of exhaust gas within the turbine housing to the turbine wheel when placed in an open position. It has been observed that the airfoil shape of conventional vanes used in such application creates an undesired back-pressure within the turbine housing that does not contribute to the most efficient turbocharger operation. It is, therefore, desired that the vanes for use with a variable geometry turbocharger be configured in a manner that minimizes any unwanted aerodynamic pressure effects within

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the turbine housing to facilitate and promote efficient turbocharger operation. Thus, the basic idea behind modern airfoil design was conceived: the desired boundary layer characteristics result from the pressure distribution which results from the airfoil shape. The velocity (pressure) distribution is specified at one angle of attack and the airfoil shape that will produce that velocity (pressure) distribution is computed. Thus, the airfoil is designed at a single point. The required inlet velocity and swirl can only be obtained by providing a set of adjustable nozzles around the turbine wheel. Nozzles should be located at the optimal radial location from the wheel to minimize vaneless space loss and the effect of nozzle wakes on turbine performance. Nozzle shapes can be optimized by rounding the noses of nozzle vanes and are directionally oriented for minimal incidence angle loss.

VII. CFD Analysis with Un-Cambered Vane

An analysis is carried out with the help of Fluent 6.2 software. The geometry with meshing created in Gambit in now importing in fluent. The data used for analysis of nozzle ring vane is taken from engine specifications are mansion an appendix.

For analysis purpose the boundary conditions are employed as below.

1) Selection of 2-D, Full Simulation using Ansys Fluent 6.3.26 Version software.

2) Exported mesh file from Gambit is imported in fluent as reading the case file for analysis purposes.

3) Checking of grid, information Size. Here analysis carried out with 21609 nodes for 20710 cells.

4) Scaling is performing for conversion of measurement in mm.

5) Defining Model solver is density based with Formulation Explicit. Space -2D, time steady, velocity formulation is absolute, gradient option is Green-Gauss Cell based, porous formulation is supercritical velocity.

6) Model -Viscous - Inviscid.

7) Material property selected is Air, with density – 0.457 (Kg/m3)

8) Operating condition- operating Pressure is 202650 Pascal.

9) Boundary condition for Inlet is Mass flow rate of exhaust gases that entering in turbocharger is taken as 0.209kg/s with initial gauge pressure is 101325 pascal. Direction specification method is direction vector, reference frame is absolute with X-component of flow direction is 1 and Y-component of flow direction is 0. For outlet rotator_circle a pressure outlet is selected with gauge pressure 0 and backflow direction specification method is normal to boundary.

10) Solver –controls- solution – equations for flow with discretization of flow is second order upwind, solver parameters i.e. courant number 0.5, flux type is Roe-FDS, Multigrid levels 4 and residual smoothing iterations is taken as 0.

(For detail please refer fluent tutorial – solving transonic flow over a turbine blade with turbo-specific NRBCs) [10].

11) Initialization - Compute from inlet which gives initial values of Gauge pressure 101326 pascal, x velocity 9.146605 m/s, y velocity 0 m/s. reference frame is relative to cell zone.

12) Monitors – Residual with option print and plot, storage iterations 1000, plotting window as 1, Normalization is scale, Convergence criteria is absolute residual are continuity, x-velocity, y-velocity with absolute criteria – 0.001

13) Monitors force for Drag coefficient, and Lift coefficient for wall zones as vane wall. The Drag coefficient is saved in cd_history whereas lift coefficient is saved in cl_history file. The force factor for Drag is x=1, y=0 and for lift x=0, y=1. And complete case check is performing.

14) Iterate – iteration are taken about 6500 for complete

convergence of solution.

15) Following result is displayed for. - Pressure- static pressure, Velocity- velocity magnitude and total pressure in turbocharger, showing in fig no.4.3,fig. no. 4.4

Fig 4.3 – Static Pressure

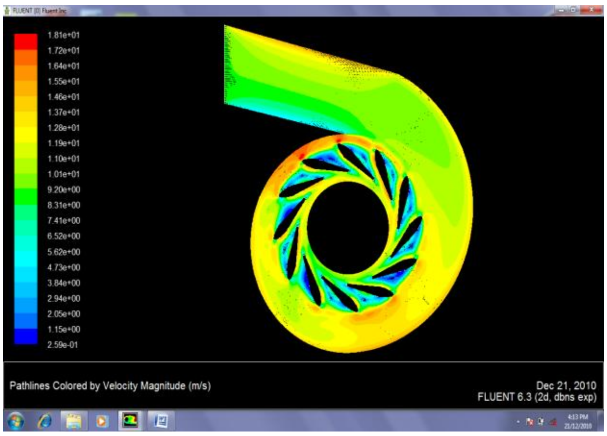

Fig 4.4 - velocity magnitude

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VIII. Modification of Vane Profile and Analysis with CFD

Here modification is done in vane of turbocharger for aim, to minimize the static pressure in clearance zone i.e. area between trailing edge of nozzle and turbine blade tip. This will help to reduce the circumferential pressure on turbine blade which leads to increment in velocity magnitude of flow over turbine blade give improvement in rotation of turbine for low velocity of entering exhaust gas. In order to avoid incidence loss, the flow from the nozzle should come on to the vane at correct angle i. Hence, a well-designed nozzle is very necessary for an efficient turbine. As the turbine blades pass under the jets emanating from the stationary guided vanes, there will be periodic excitation proportional to the inlet nozzles and the speed of the turbine. To reduce the effect due to this periodic excitation a thumb rule is that the number of nozzles should not be integral multiple of the number of turbine blades.[5] The blades angles at entry to and at exit from the cascade are denoted by and respectively. A most useful blade parameter is the camber angle _ which is the change in angle of the camber line between the leading and trailing edges and equals in the notation of Figure 4.7 for circular arc camber lines the stagger angle is for parabolic arc camber lines of low camber as used in some turbocharger turbine cascades. Here we are not going to change inlet angle it remain constant for modified vane also stagger angle ξ. In case of existing straight vane which is un-cambered means camber angle 00 and angle of attack is of 40. The interest in giving camber angle to vane and reduce the value of incidence i.e angle of attack to 00. Refer Figure D, So that flow is directed over the vane surface and stagnation pressure loss is avoided. As well as pressure distribution above and below the vanes surface is equal which avoid the chocking of flow in close position of vanes. The camber angle is calculated by equation given below.

$$\alpha = \xi + \tan^{-1}\frac{t/c}{(a/c)^2}$$

$$70 = 35 + \tan^{-1}\frac{18/34}{(a/34)^2}$$

$$\therefore a = 21.50^0$$

Fig. D Modified vane showing camber angle

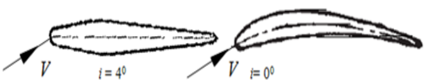

Fig. E showing comparison between un-cambered and cambered vane with Arrow showing flow direction.

IX. CFD Analysis with Modified Vane-

The effect of cambered vane on flow of exhaust gas with in VG turbocharger can be analyze by creating geometry with same dimension but instated un-cambered vane there is a cambered vane. The gambit software is used for creating geometry with same methodology as prescribed above. Meshing is done and this meshed geometry is the exported to fluent software for analysis purpose. Figure no. 4.3 and Figure no. 4.4 shows the geometry and meshing with modified vane profile respectively. Computational fluid dynamics analysis is carried out on imported geometry from gambit with modified vane profile adopting same boundary condition and solver. All parameters for analysis are same which used for analysis of un-cambered vane. Figure no. 4.5, 4.6 showing analysis with modified vane profile

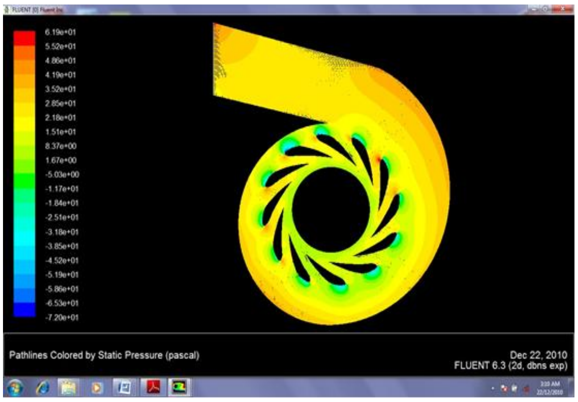

Fig. 4.5 – Static pressure variation with in VG turbocharger with cambered Nozzle Vane

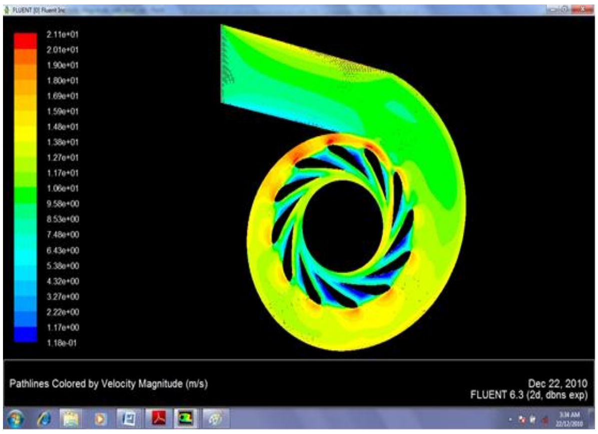

Fig. 4.6.- Velocity Magnitude variation with in VG turbocharger with Cambered Nozzle vane.

The above analysis with cambered vane is carried out for 21609 nodes & 20710 cells. The complete convergence of solution for convergence criteria 10-3 is obtained with 3407 iterations. The comparison between un-cambered and cambered nozzle vane profile is done on the basics of performance of turbocharger. The performance of turbocharger is predicated on the basis of power out delivered by turbocharger. With same mass flow of exhaust gas the power output in KW is calculated for both a turbocharger with un-cambered nozzle ring vane and with cambered nozzle ring

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vane. Also subsequently increase in mass flow rate by unit factor calculating the power output for both conditions. Following table shows the statically comparison for above said conditions. The flow velocities at rotor tip circle are taken from CFD analysis.

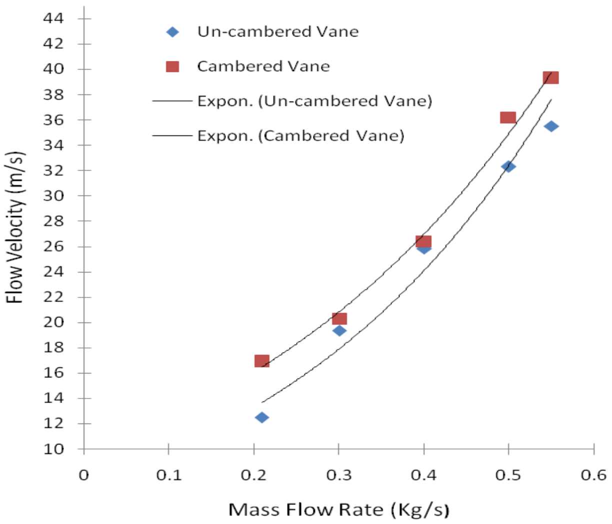
Inlet Mass flow rate of Exhaust Gas (Kg/s)	Flow Velocity (m/s)	Turbine speed (RPM)	Power Output (W)
0.209	12.5	3742	28.8668
0.3	19.37	5797	99.48
0.4	25.84	7285	235.81
0.5	32.3	9661	460.57
0.55	35.52	10625	613.2

Table 1 - Power Output By Un-Cambered Nozzle Vane.

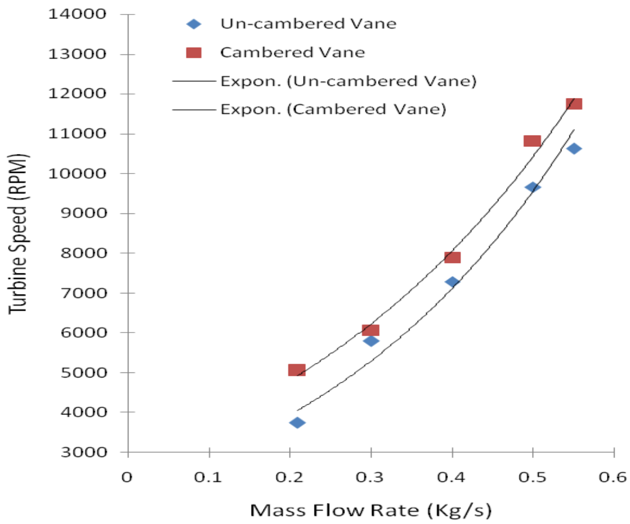
INLET MASS FLOW RATE OF EXHAUST GAS (KG/S)	FLOW VELOCITY (M/S)	TURBINE SPEED (RPM)	POWER OUTPUT (KW)
0.209	16.9	5054.75	52.71
0.3	20.3	6072	109.16
0.4	26.4	7898	246.17
0.5	36.2	10828	578.57
0.55	39.3	11755	750.1

Table 2 – Power Output By Cambered Nozzle Vane.

From table no. 1 and table no. 2 it is clearly shown that as mass flow rate increases the flow velocity magnitude increases. As the flow velocity over turbine increases ultimately the RPM of turbine increases as found in table .It shows significant improvement in power delivered by turbocharger. The comparative graph between mass flow rate and flow velocity also mass flow rate and RPM of turbine for both un-cambered and cambered are plotted as below.



Graph 1 – Mass Flow Rate Vs Flow Velocity



Graph 2 – Mass Flow Rate Vs Turbine Speed

From above graph no. 1 and 2, it is observed that the flow velocity of exhaust gas increases exponentially and speed of turbine also increase exponentially with the use of cambered Vane in nozzle ring of variable geometry turbocharger.

CONCLUSION

It is observed that, with use of un-cambered vane in nozzle ring, the flow is separated at the leading edge due to a higher incidence angle i.e angle of attack is of 40. But the separation effect is lesser in case of cambered vane compared to straight vane because the positive lean adapts better to incoming flow. The trailing edge region of the pressure surface forms the nozzle throat with the leading edge region of the suction surface, hence the drastic acceleration in this region, with the cambered vane showing stronger convergence than the un-cambered vane. The bigger pressure difference between the surfaces at the trailing edge indicates a possibility of higher wake loss in the un-cambered vane. This is because the pressure at the suction surface needs to rise sharply to meet the pressure at the vane surface. The effect is more evident with cambered vane which can be attributed to the influence from the high velocity flow after the throat. This increased velocity of flow leads to give more spin the turbine rotor and hence turbine rpm increases, further more we can say that as rpm of turbine increases, the compressor impeller will rotate with more rpm as they are mounted on same shaft ultimately increase in density of air within combustion chamber will produce more boost pressure because of complete combustion of charger this will benefits to increase starting torque of an engine. It is also desired that an improved vane configuration be constructed that provides a throat area that is similar or better than that of the conventional slim airfoil vane configuration, while at the same time provide a throat area turndown ratio that is improved, and an improved turbine

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efficiency throughout the range of vane movement, when compared to the conventional slim airfoil vane configuration.

REFERENCES

[1] Katsuyuki Osako And Yasuaki Jinnai, “Development of the High Performance and high reliability VG Turbocharger for Automotive Applications”.

[2] Corky Bell, “Maximum Boost, Designing, Testing and Installing Turbocharger System”. BENTLEY PUBLISHERS, 1734 Massachusetts, Avenue, Cambridge, MA 02138 USA..

[3] Srithar Rajoo And Ricardo Martinez-Botas, “Variable Geometry Mixed Flow Turbine for Turbochargers: An Experimental Study”. International Journal of Fluid Machinery and Systems Vol. 1, No. 1, October-December 2008B. Simpson, et al, “Title of paper goes here if known,” unpublished.

[4] G. Descombes, J.F. Pichouron, F. Maroteaux, N. Moreno, J. Jullien, “Simulation of the Performance of a Variable Geometry Turbocharger for Diesel Engine Road Propulsion”. Int.J. Applied Thermodynamics, ISSN 1301-9724 Vol.5 (No.3), pp.139-149, September-2002

[5] FAHUA GU AND MARK R. ANDERSON, “Cfd-Based Through flow Solver In A Turbomachinery Design System”. Proceedings of GT2007 ASME Turbo Expo 2007: Power for Land, Sea and Air May 14-17, 2007, Montreal, Canada. GT2007-27389M.