CFD Analysis of Flow through a Throttle Body of a Spark Ignition Engine for different Throttle Valve Shaft Configurations

Kriti Gupta, Saumya Sharma, Jayashree Aseri, Anupriya

Abstract— **In a spark ignition engine, the design of air intake system is of utmost importance in order to improve its power and fuel efficiency. The amount of air entering the engine is controlled by the throttle valve. However, it also acts as a restriction to the intake air stream, causing loss of flow energy in the intake air. For this reason, the fluid flow analysis for the flow through the throttle valve for different cross-sections of the throttle shaft has been carried out using ANSYS FLUENT and a comparative study of pressure and velocity variations across the valve has been made. Different basic shapes, namely circular, oval, square, hexagonal, rectangular, rhombus and triangular have been considered and their models have been designed for analysis. Considering the different conditions that the throttle body is subjected to, the various inlet and outlet boundary conditions have been calculated in this work.**

The nature of flow through the valve was analyzed and the different regions formed in the air flow field were studied. The velocity flow vectors and pressure contours were compared and evaluated. The results obtained were interpreted on the basis of different characteristics of flow. On the basis of the results of this analysis, the hexagonal cross section has been suggested as the optimal throttle shaft cross-section with the aim of enhancing the air flow into the engine.

Index Terms— **ANSYS FLUENT, Butterfly valve, CFD, Throttle body**

I. INTRODUCTION

Performance of a spark engine mainly depends on three variables i.e. air intake, fuel injection and spark ignition. The air intake system delivers oxygenated air into the combustion chamber of an engine, where fuel injection and timely spark occurs to generate power for the vehicle. A proper air intake system delivers required amount of clean air into the engine as per the engine load, to deliver power and better gas mileage during operation. The design of air intake system requires optimization of the air flow, reduction of inertia of moving parts to improve response and reduction of losses. For ideal air flow, the intake system should increase the velocity of the air until it travels into the combustion chamber, while minimizing turbulence and restriction to flow.

Early automobile intake systems were simple air inlets connected directly to carburetors where the air and fuel were mixed. These systems posed challenges of inefficient combustion, slow response and increased pollution. These are now replaced by the modern intake system with quick response throttle coupled with electronically controlled fuel injection.

There are three main parts of the air intake system i.e. air filter, mass flow sensor and throttle body. The throttle body is usually positioned between the air filter box and the intake manifold. Its main objective is to control the amount of air flowing into the engine combustion chambers. It consists of a throttle plate that rotates on a shaft when the accelerator pedal is depressed. The throttle plate opens up and allows air into the engine and when the pedal is released the throttle plate closes and effectively chokes-off air flow into the combustion chamber. This process is used to control the rate of combustion and the speed of the vehicle. In many cars, the accelerator pedal motion is communicated via the throttle cable, to activate the throttle linkages, which rotates the throttle plate.

The disc of a throttle valve is always positioned within the flow; therefore a pressure drop is always present in the flow. Even when the throttle valve is fully open, there is a restriction to the air flow due to the thickness of the plate and shape and size of the throttle shaft, causing loss of flow energy in the intake air.

Suresh Kumar et al. have formulated a procedure to design a throttle body and bypass screw opening and verified the design through CFD analysis and experiments on prototype throttle body [1].*Chalet* and *Chesse* have developed a more effective throttle valve unsteady one dimensional model, backed by CFD and experimental results[2]. *Wojtkowiak* and *Oleskowicz-Popiel* studied flow characteristics, flow fields and pressure distribution of throttle valve by numerical analysis and experiments[3]. *Per Carlsson* has incorporated the effects of surface heating and surface wall thickness in CFD simulations of air intake and devised a method to calculate the effective flow area[5]. In this study, the fluid flow analysis been conducted using ANSYS FLUENT for the flow across different cross-sections of the throttle shaft, namely circular, oval, square, hexagonal, rectangular, rhombus and triangular. The nature of flow through the valve is analysed to identify the different regions formed in the air flow field.

II. CALCULATIONS

The following calculations have been performed to find the velocity at inlet and pressure at oulet which are used to set the boundary conditions.

Kriti Gupta, Department of Mechanical and Automation Engineering, Indira Gandhi Institute of Technology, New Delhi, India.

Saumya Sharma, Department of Mechanical and Automation Engineering, Indira Gandhi Institute of Technology, New Delhi, India.

Jayashree Aseri, Department of Mechanical and Automation Engineering, Indira Gandhi Institute of Technology, New Delhi, India.

Anupriya, Department of Mechanical and Automation Engineering, Indira Gandhi Institute of Technology, New Delhi, India.

The surrounding temperature was considered as 294 K i.e. 529.47 °R and pressure at inlet equal to the atmospheric pressure (101325 Pa i.e. 14.7psia).

A. Calculation of Inlet Velocity

Using the Continuity Equation, the inlet velocity has been calculated as shown,

$$V_t = \frac{4 \times V_{disp} \times N/2}{C_d \times \pi \times D^2} \quad (1)$$

where,

V_t = Velocity at inlet (m/s)

V_{disp} = Displacement volume of engine (litre) = 0.6 litre

N = Maximum Engine Speed (rpm) = 5500 rpm

C_d = Coefficient of Discharge = 0.9

D = Diameter at inlet (m) = 0.038 m

Substituting these values in eq. (41), we obtain,

$$V_t = \frac{4 \times 0.6/1000 \times 5500/2 \times 60}{0.9 \times \pi \times 0.038^2}$$

$$= 40.32 \text{ m/s}$$

B. Calculation of Outlet Pressure

The pressure drop between inlet and outlet is governed by the type of valve used and its valve flow coefficient. For butterfly valve, the value of C_v is specified using the standard tables. The calculation of pressure difference is as shown,

$$\Delta P = \frac{T_1 \times G_g}{P_1} \times \left(\frac{Q}{\gamma \times 1360 \times C_v}\right)^2 \quad (2)$$

where,

ΔP = Pressure difference between inlet and outlet (psi)

T_1 = Absolute upstream temperature (°R) = 529.47 °R

G_g = (Molecular weight of gas)/(Molecular weight of air) = 1

P_1 = Upstream absolute static pressure (psia) = 14.7 psia

P_2 = Downstream absolute static pressure (psia)

Q = Volumetric flow rate (standard cubic feet per hour)

Γ = Gas constant = 1.4

C_v = Valve flow coefficient (for 38mm diameter butterfly valve

For the calculation of volumetric flow rate, Q,

$$Q = \text{Area of cross section} \times \text{Velocity at inlet} \quad (3)$$

$$Q = \frac{\pi}{4} \times (0.038^2) \times 40 \text{ m/s}$$

$$= 163.312 \text{ m}^3/\text{hr}$$

$$= 5767.308 \text{ scfh}$$

Substituting the values in eq (43), we get

$$\Delta P = \frac{529.47 \times 1}{14.69} \times \left(\frac{5767.308}{1.4 \times 1360 \times 57.6}\right)^2$$

$$= 0.09967 \text{psi}$$

Outlet pressure is calculated as follows

$$P_2 = P_1 - \Delta P \quad (4)$$

Therefore,

$$P_2 = 14.7 - 0.09967 = 14.5903 \text{ psi} = 100596.57 \text{Pa}$$

C. Calculation of Reynolds Number to predict the type of flow

$$R_e = \frac{\rho \times V_t \times d}{\mu} \quad (5)$$

where,

R_e = Reynolds Number

ρ = Density of air

v = Velocity of air entering the valve

μ = Dynamic viscosity of air

$$R_e = \frac{1.225 \times 40 \times 38 \times 10^{-3}}{1.846 \times 10^{-5}}$$

$$R_e = 100866$$

As the Reynolds Number is greater than 4000, the flow is turbulent.

D. Calculation of Turbulent Intensity (%)

Turbulent Intensity is defined as the root mean square of the velocity fluctuations. An idealized flow of air with absolutely no fluctuations in air speed would have hydraulic intensity as 0%. A turbulent intensity of 1% is considered low whereas turbulent intensity of 10% is considered high.

$$\text{Turbulent Intensity} = 0.16 \times R_e^{-\frac{1}{8}} \times 100 \quad (6)$$

$$= 0.037 \times 100 = 3.7 \%$$

For carrying out the flow analysis, different models, corresponding to different cross sections of the shaft were created in the ANSYS design modeler. The different cross sections of throttle shaft that were modeled were, Circular, Square, Triangular Rhombus, Rectangular, Oval and Hexagonal. The models were then meshed and the flow problem was specified in Setup.

Here, the properties of air and various boundary conditions at inlet and outlet have been tabulated.

Table. I Properties of Air

Property	Value
Density	1.225 kg/m^3
Specific Heat (C_p)	1006.43 J/kg-K
Viscosity	1.7894e-05 kg/m-s

Table. II Boundary Conditions

At inlet	
Velocity	40 m/s
Turbulent Intensity	3.7 %
Hydraulic Diameter	38mm
Temperature	294 K
At outlet	
Absolute Pressure	100596.57 Pascal
Turbulent Intensity	3.7 %
Hydraulic Diameter	38 mm
Temperature	294 K

III. RESULTS

The variation in velocity and pressure have been computed and displayed for comparison.

RECTANGULAR SHAFT

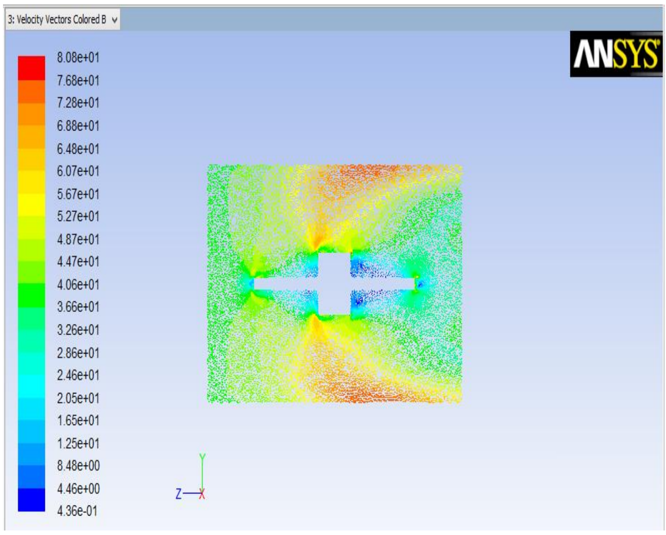

Fig. 1 Velocity contour of flow through throttle body with rectangular cross-section of the shaft.

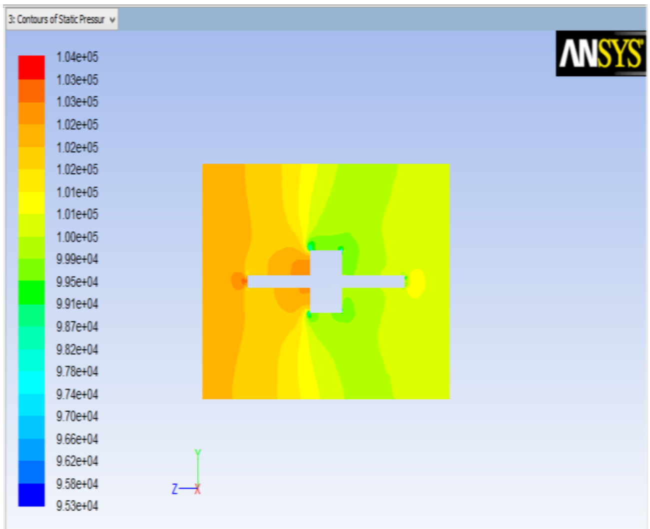

Fig. 2 Pressure contour of flow through throttle body with rectangular cross-section of the shaft.

CIRCULAR SHAFT

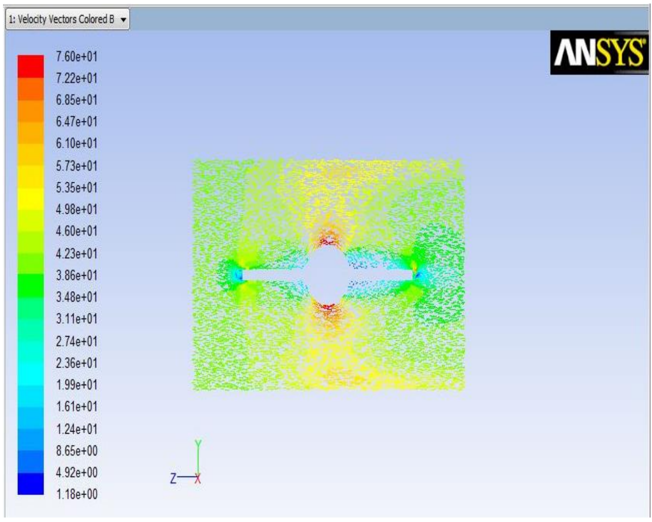

Fig. 3 Velocity contour of flow through throttle body with circular cross-section of the shaft.

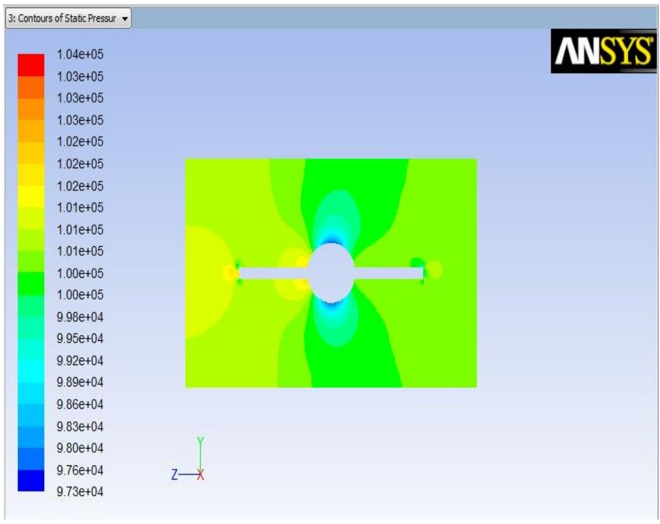

Fig. 4 Pressure contour of flow through throttle body with circular cross-section of the shaft.

HEXAGONAL SHAFT

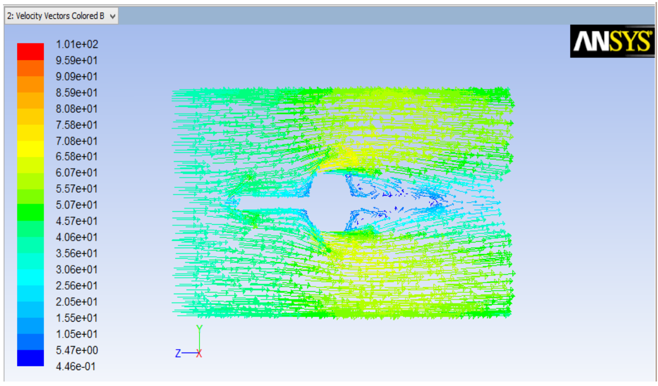

Fig. 5 Velocity contour of flow through throttle body with hexagonal cross-section of the shaft.

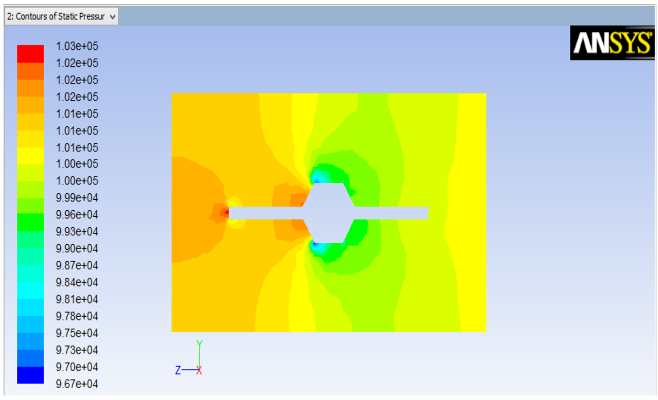

Fig. 6: Pressure contour of flow through throttle body with hexagonal cross-section of the shaft.

IV. DISCUSSION ON THE RESULTS FOR DIFFERENT VALVE SHAFT CROSS-SECTIONS

The following different characteristics of the velocity and pressure contours can be used to compare and analyze the flow across different shaft cross-sections.

1. The throttle plate and the throttle shaft provide restriction to the flow of intake air. Lesser is the restriction across the flow, lower is the loss of energy. This increases the velocity at the outlet of throttle body.
2. Throat region has the minimum area available for the air to flow. In order to reduce energy loss, the flow should be accelerated at the throat. Hence, the pressure drop at throat should be minimum.
3. The region of re-circulating flow, formed downstream of the throttle shaft, is known as the wake region. The recirculation of air is caused by the viscous air flow around the throttle plate surface. The medium is displaced when it leaves the surface of throttle shaft, resulting in turbulent eddies being formed. The presence of eddies make the flow through the wake region turbulent and hence, it should be minimum.
4. There is a region of adverse pressure gradient formed due to excessive loss of momentum near the flow contacting surface. Due to adverse pressure gradient, the flow near the surface of a body is decelerated. Thus, this pressure gradient precludes the flow from progressing downstream past a certain point, called the point of separation. At this point, the flow becomes separated from the contacting surface of the throttle plate. The position of the point of separation is also an important factor to be considered while analyzing the pressure contours.
5. Stagnation point is a region formed in air flow field where the local velocity of air approaches zero. In the throttle flow, stagnation point is formed at the tip of leading edge of the throttle plate where the air is brought to rest due to sudden obstruction in flow. In this region, the static pressure increases as the velocity drops.

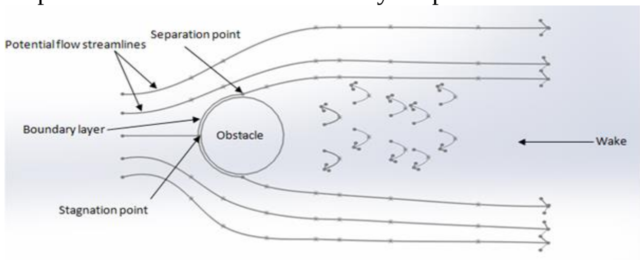

Fig. 7 Regions of Air Flow in Throttle

Based on the above mentioned parameters, the results obtained for various cross sections of throttle shaft were compared and analysed. The results are tabulated here.

Table. III Result Tabulation

S No	Parameter	Circular Shaft	Rectangular Shaft	Hexagonal Shaft
1	Velocity at outlet (m/sec)	23 – 38	24 - 40	25 – 50
2	ΔP_{throat} (Pascal)	61 – 76	48 - 68	50 – 70
3	Wake region	Maximum	Moderate	Minimum
4	Pressure drop (Pascal)	$10^5 - 9.76$ 10510^4 9.95 24 10^4 9 × 1005 − 9.7×10^4		

V. EFFECT OF THROTTLE OPENING ON FLOW FIELD

The contours of air flow regime inside the throttle body for two positions of the throttle valve i.e. at 30° and at 60° from the completely closed position have been computed. The analysis has been performed for circular cross-section of the shaft which is most commonly used configuration in automobile engines. Also, by the previous analysis, as the hexagonal configuration is found to be the most advantageous out of all the suggested configurations, the further analysis has been performed only for the hexagonal valve shaft cross-section.

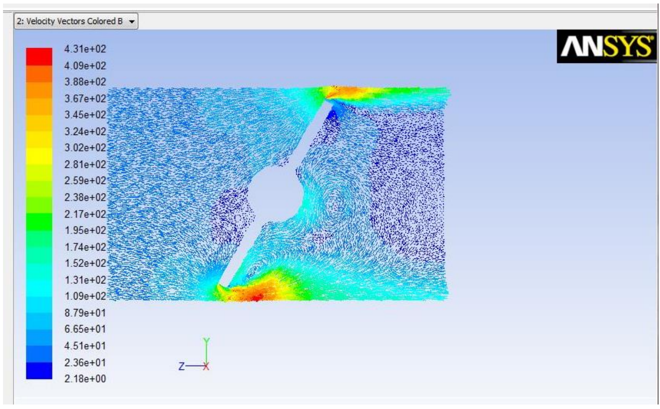

Fig. 8 Velocity contour of Flow through Throttle Body with Circular Cross-Section of the Shaft and 30° Open Position of the Valve.

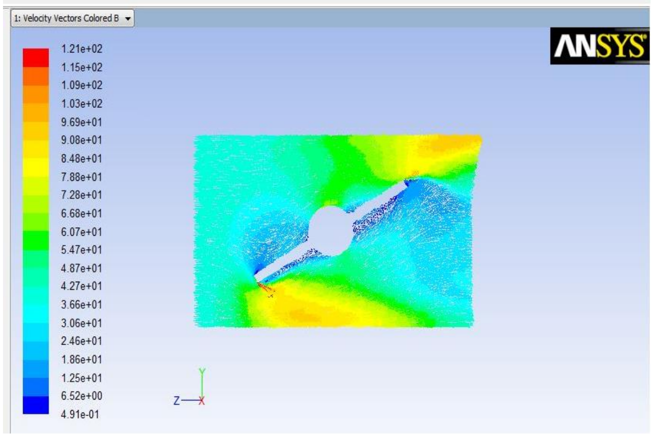

Fig. 9 Velocity contour of Flow through Throttle Body with Circular Cross-Section of the Shaft and 60º Open Position of the Valve.

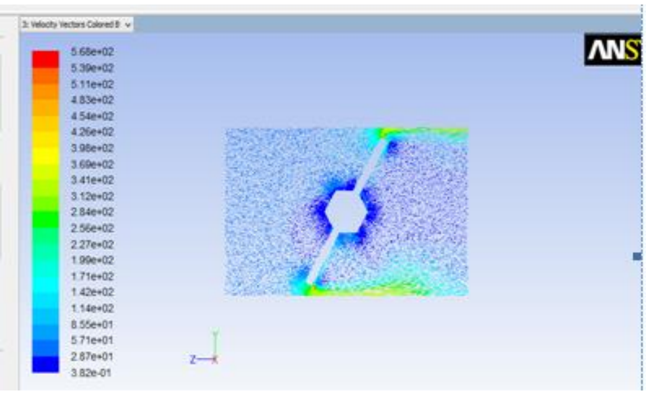

Fig. 10 Velocity contour of Flow through Throttle Body with Hexagonal Cross-Section of the Shaft and 30º Open Position of the Valve.

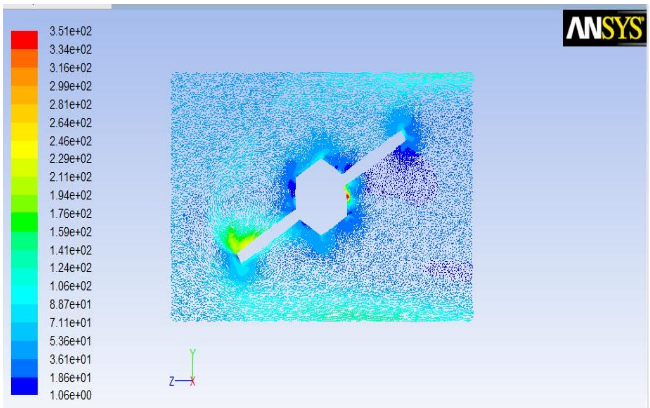

Fig. 11 Velocity contour of Flow through Throttle Body with Circular Cross-Section of the Shaft and 60º Open Position of the Valve.

VI. DISCUSSION ON THE RESULTS FOR DIFFERENT THROTTLE OPENINGS

The following different characteristics can be observed from the velocity contours obtained for different throttle openings –

1. The spread of the wake region decreases as the throttle opening increases.
2. Stagnation region can be observed at the upstream face of the throttle valve for all the valve positions.
3. The velocity increases at the throttle valve edges and the velocity of airflow through the clearance between the valve edge and the throttle body increases as the throttle valve opening angle increases.
4. The total airflow rate through the throttle body increases with increase in the throttle valve opening angle.

VII. CONCLUSION

1. *The pressure and velocity variation over different cross-sections of throttle valve shaft were analysed. The study of different regions formed showed that the hexagonal cross-section is the most optimal for throttle shaft, among all other analysed shapes.*
2. *The hexagonal cross-section allows the most efficient flow of air with minimal velocity drop between the inlet and outlet. Also, the wake region is less for this configuration and hence, the air flow is better. Thus, valve shafts with hexagonal cross-section can be advantageously employed for use in throttle bodies of automobile engines.*
3. *The analysis of air flow across valve opened at different angles showed that the flow rate is more at higher throttle opening angles and the wake region decays as the throttle opening increases.*

VIII. VALIDATION AND INTERPRETATION

The results obtained for the circular and rectangular cross-section of the shaft are similar to the results computed for these geometries in the research paper- Design and optimization of a throttle body assembly by CFD analysis, by J Suresh Kumar, V Ganesan, J M Mallikarjuna and S Govindarajan[1]. As interpreted in the research paper, rectangular configuration of valve shaft is more advantageous than the circular configuration.

Also, from this analysis based on the above mentioned factors, it can be interpreted that the hexagonal configuration, is even more advantageous than the rectangular configuration. Thus, valve shafts with hexagonal cross-section can be advantageously employed for use in throttle bodies of automobile engines.

REFERENCES

[1] J Suresh Kumar, V Ganesan, J M Mallikarjuna and S Govindranjan, Design and optimization of a throttle body assembly by CFD analysis, Indian Journal of Engineering and Material Sciences.20 (2013)350-360

[2] David Chalet and Pascal Chesse, Analysis of unsteady flow through a throttle valve using CFD, Engineering Applications of Computational Fluid Mechanics Vol. 4, No. 3, pp, 378-395(2010)

[3] Janusz Wojtkowiak and Czeslaw Olekowicz-Popiel, Investigation of butterfly control valve flow characteristics, Foundations of Civil and environmental Engineering, No. 7, 2006

[4] Fluid flow basics of throttling valves, Cashco

[5] Fluent Inc. Fluent 6.1 User's guide.

[6] Per Carlsson, Flow through a throttle body. A comparative study of Heat Transfer, Wall Roughness and Discharge Coefficient,.Linkopings University Electronic Press, Linkopings University, Sweden(2007)

[7] John D. Anderson, Computational Fluid Dynamics, The Basics with Applications, McGraw Hill Book Company, Indian Edition (1995).

[8] V Ganesan, Internal Combustion Engines, ISBN 1-25-900619-0,McGraw Hill Book Company, (2012).

[9] http://www.carmudi.com.ng/journal/the-air-intake-system-and-how-it-works/ visited and downloaded on - 03-Mar-2015

[10] http://www.smithvalve.com/ visited and downloaded on - 10-Mar-2015