IC ENGINE SUPERCHARGING AND EXHAUST GAS RECIRCULATION USING JET COMPRESSOR

by

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Original scientific paper
UDC: 621.512/.513:621.56/.59
DOI: 10.2298TSCI/10041027K

Supercharging is a process which is used to improve the performance of an engine by increasing the specific power output whereas exhaust gas recirculation reduces the NO_x *produced by engine because of supercharging. In a conventional engine, supercharger functions as a compressor for the forced induction of the charge taking mechanical power from the engine crankshaft. In this study, supercharging is achieved using a jet compressor. In the jet compressor, the exhaust gas is used as the motive stream and the atmospheric air as the propelled stream. When high pressure motive stream from the engine exhaust is expanded in the nozzle, a low pressure is created at the nozzle exit. Due to this low pressure, atmospheric air is sucked into the expansion chamber of the compressor, where it is mixed and pressurized with the motive stream. The pressure of the mixed stream is further increased in the diverging section of the jet compressor. A percentage volume of the pressurized air mixture is then inducted back into the engine as supercharged air and the balance is let out as exhaust. This process not only saves the mechanical power required for supercharging but also dilutes the constituents of the engine exhaust gas thereby reducing the emission and the noise level generated from the engine exhaust. The geometrical design parameters of the jet compressor were obtained by solving the governing equations using the method of constant rate of momentum change. Using the theoretical design parameters of the jet compressor, a computational fluid dinamics analysis using FLUENT software was made to evaluate the performance of the jet compressor for the application of supercharging an IC engine. This evaluation turned out to be an efficient diagnostic tool for determining performance optimization and design of the jet compressor. A jet compressor was also fabricated for the application of supercharging and its performance was studied.*

Key words: *jet compressor, supercharger, exhaust gas recirculation, motive stream*

Introduction

Jet compressor uses a jet of primary fluid to induce a peripheral secondary flow often against back pressure. Expansion of primary jet produces a partial vacuum near the secondary

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flow inlet creating a rapid re-pressurization of the mixed fluids followed by a diffuser to increase the pressure to the jet compressor exit value. Unlike many studies were reported on the design and performance of these jet compressors for the application of refrigeration [1-4], pump [5], and in mixing processes [6]. To the authors knowledge, no studies have been reported for the application of supercharging an IC engine.

Supercharging

Supercharging of an IC engine is the process of increasing the mass or the density of the air-fuel mixture (in spark ignition engine) or air (in compression ignition engine) induced into the engine cylinder. This is usually done with the help of a compressor or a blower known as supercharger. The objectives of supercharging are to reduce the mass, space, and the consumption of lubricating oil per engine brake power. Experimental studies have shown that supercharging increases the net power developed by the engine. For this reason, it is widely used in aircraft engines, where the mass of air sucked into the engine cylinder decreases at higher altitudes. This is due to the decrease in the atmospheric pressure with the increase in altitude.

Exhaust gas recirculation

Exhaust gas recirculation (EGR) is the most effective way of reducing NO_x emissions. EGR is a process where some of the exhaust gas is bled back into the intake system. The exhaust gas absorbs energy during combustion without contributing any energy input. The net result is a lower flame temperature. The amount of EGR can be as high as 40% of the total intake [7]. Supercharged diesel engines emit more NO_x than naturally aspirated engines due to the fact that peak temperature is high because of higher compression ratio. The effective way to reduce NO_x in such engines is to combine EGR with supercharging.

Jet compressor

The jet compressor is equipment, consisting of the motive nozzle, the mixing chamber, the throat and the divergent nozzle. Such an apparatus operates as a compressor having no moving parts and utilizing as motive the kinetic energy of the fluid in motion. A high-pressure stream of fluid expanding through the motive nozzle, which is designed to develop the highest possible velocity, provides the motive power. The jet of high velocity fluid creates a low-pressure area in the mixing chamber, thus causing the flow of the entrained fluid through the entrainment section. Thereby a mechanism of molecule to molecule collision, momentum is transferred from the molecules of the motive fluid to those of the suction fluid. The mixture then, experiences a decrease in velocity and an increase in pressure in the diffuser [8]. Thus, part of the motive power is converted into compression work. However, jet compressors have a low efficiency [9]. Figure 1 shows the various parts of the jet compressor and the corresponding static pressure variation at different locations of the jet compressor.

Many factors affect the jet compressor performance, including the fluid molecular weight, feed temperature, mixing tube length, nozzle position, throat dimension, motive velocity, Reynolds number, pressure ratio, and specific heat ratio [10]. Hence, all the geometric parameters of the jet compressor are to be optimally designed to meet the above requirements.

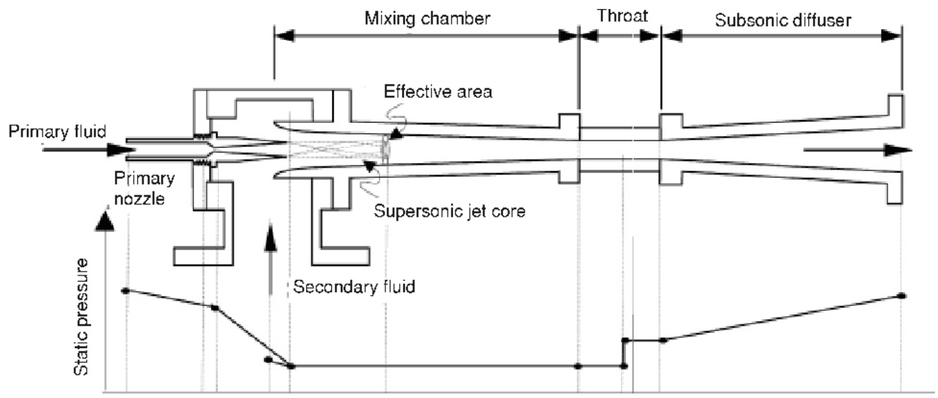

Figure 1. Variation of static pressure at different zones of the jet compressor

Description of the supercharging system using jet compressor

Figure 2 shows the schematic layout of an IC engine supercharger using a jet compressor. The exhaust gas from the engine which is at 700 K and 1.5 to 3 bar pressure [11] is fed as motive stream into the jet compressor. The motive stream expands in the nozzle and enters into the convergent section of the secondary nozzle at vacuum pressure with very high kinetic energy. The other end of the convergent nozzle is open to atmosphere. Due to the low pressure created at the convergent section by the motive stream, atmospheric air is sucked in as secondary stream, and it is mixed with the motive stream till they attain a uniform velocity. In this process an exchange of momentum occurs between the two streams as well as the static pressure of the secondary stream is increased. This mixture is further pressurized at the diffuser section of the jet compressor at the expense of the kinetic energy.

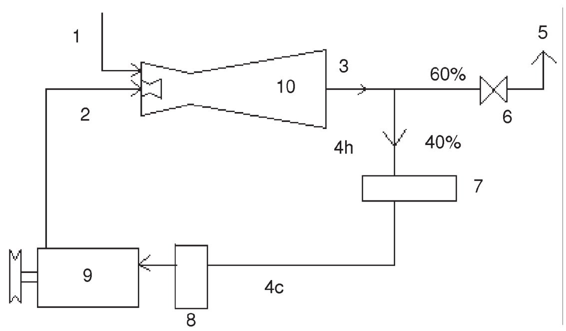

Figure 2. A schematic lay-out of an IC engine supercharger using jet compressor with auxiliary components
1 – atmospheric air, 2 – exhaust gas, 3 – exhaust gas + atmospheric air, 4h – hot exhaust gas + atmospheric air, 4c – cooled exhaust gas + atmospheric air, 5 – net engine exhaust gas, 6 – back pressure valve, 7 – air cooler, 8 – air filter, 9 – engine, 10 – jet compressor

A percentage of the pressurized mixture from the jet compressor is inducted into the engine as fresh charge and the remaining mixture of gas is expelled out as exhaust. A back pressure valve is fixed to maintain the required boost pressure for the engine. Before inducting the gas mixture into the engine, it is filtered and cooled to the required inlet temperature of the engine. Thus, supercharged gas air mixture with required boost pressure and temperature is supplied to the engine which contains about 40% of exhaust gas.

Design of the jet compressor

The performance of a jet compressor is mainly affected by turbulence, friction, and energy consumption that occur during pressurizing the propelled stream. Even though enhancing turbulent mixing plays an important roll and needs a major consideration in improving the performance, the jet compressor design should be optimized so as to minimize the turbulence effects [12]. This is achieved by optimizing the nozzle geometry where complete blending is obtained by boosting the tangential shear interaction between the propelled and motive stream. The energy consumption is taken care off by avoiding the shock waves generated at the diffuser section at the design point operating condition using the method of constant rate of momentum change (CRMC) [13]. Here, the momentum of the flow is allowed to change at a constant rate as it passes through the diffuser passage by gradually increasing the static pressure, from entry to exit, thus avoiding the total pressure loss due to shock process encountered in conventional diffuser. Figure 3 describes the geometric parameters of a jet compressor.

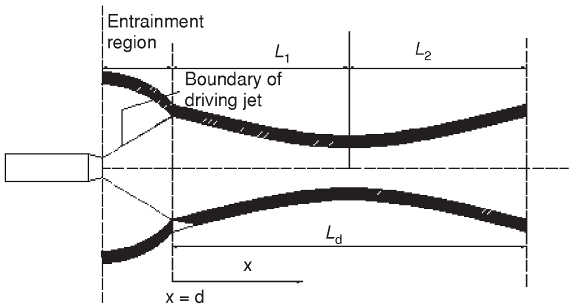

Figure 3. Schematic diagram showing the geometric parameters of a jet compressor

Determination of design parameters of the jet compressor

In the CRMC method, the momentum of the flow is allowed to change at a constant rate as it passes through the diffuser passage by gradually raising the static pressure from entry to exit, thus avoiding the total pressure loss due to shock waves encountered in the conventional diffusers. Accordingly the change in momentum along the flow direction is given as [13]:

$$\frac{\mathrm{d}M_\mathrm{o}}{\mathrm{d}x} \quad m_\mathrm{g}(1 \quad R_\mathrm{m})\frac{\mathrm{d}c}{\mathrm{d}x} \quad \beta \tag{1}$$

where β is constant.

The following assumptions are made for determining the geometric parameters of the jet compressor:

– the flow inside the jet compressor is steady and one-dimensional,
– the working fluid is assumed to be ideal gas,
– heat loss from the jet compressor is negligible,
– the entrainment process is carried out at constant static pressure $P_\mathrm{s} = P_\mathrm{ne} = 0.5$ bar (absolute),
– the primary flow (m_g) and the required entrainment ratio (R_m), are known,
– secondary flow velocity (c_s) at the entry to the entrainment region is specified, and
– local Mach number at the throat is unity.

From the mass balance equation and using the boundary conditions at $x = 0$, $c_{\mathrm{d,x}} = c_1$ and at $x = L_\mathrm{d}$, $c_{\mathrm{d,x}} = c_\mathrm{de}$, the diameter of the diffuser along its axis is given as:

$$D_{\mathrm{d,x}} \quad 2\sqrt{\frac{m_{\mathrm{g}}(1 \quad R_{\mathrm{m}})\mathrm{R}T_{\mathrm{x}}}{\pi P_{\mathrm{x}} c_{\mathrm{d,x}}}} \tag{2}$$

The length of the diffuser $L_{\mathrm{d}} = L_1 + L_2$, is determined by assuming the wall included angle as 8° in order to minimize the pressure loss caused by friction and recirculation, where:

$$L_1 \quad \frac{L_2 \dfrac{c_1 \quad c_{\mathrm{d,x}}^*}{c_1 \quad c_{\mathrm{de}}}}{1 \quad \dfrac{c_1 \quad c_{\mathrm{d,x}}^*}{c_1 \quad c_{\mathrm{de}}}} \tag{3}$$

and

$$L_2 \quad D_{\mathrm{d,x}}^* \frac{\dfrac{D_{\mathrm{de}}}{D_{\mathrm{d,x}}^*} \quad 1}{2\mathrm{tg}(\theta)} \tag{4}$$

Numerical analysis of the jet compressor

The flow field inside the jet compressor before entering the supercharger has been simulated using FLUENT software. The simulated results have helped in understanding the local interactions between shock waves and boundary layers, their influence on mixing and recompression rate which in turn made it possible for a more reliable and accurate geometric design and operating conditions. Many numerical studies about supersonic ejectors have been reported since 1990s in predicting ejector performance and providing a better understanding of the flow and mixing processes within the ejector.

A 2-D model of the jet compressor is created in AUTOCAD using the theoretical design values obtained from CRMC method. This model is then imported into GAMBIT software for meshing the flow domain. For accurate computation of near wall phenomena, precise placement of high quality cells is critical which is achieved using the boundary layer meshing tool. Initial simulations were carried out with a tri-elemental grid of mesh size 1 mm. It was observed that the solution did not converge. This could be due to the inability of this mesh to capture the large velocity and pressure gradients in the flow domain. Later simulations were carried out with structured quadrilateral mesh of size 0.25 mm, for which a converged solution was obtained. Table 1 below shows the details of the flow domain meshing and fig. 4 shows the meshed geometry of the 2-D jet compressor.

Table 1. Flow domain meshing of 2-D JET compressor

Type of meshing	Elements of meshing	Interval size	No. of zones	No. of cells	No. of nodes
Structured map	Quadrilateral	0.25	9	54314	55367

The jet compressor developed using GAMBIT consists of a primary nozzle, secondary nozzle, diffuser, and storage chamber.

The boundary conditions are:

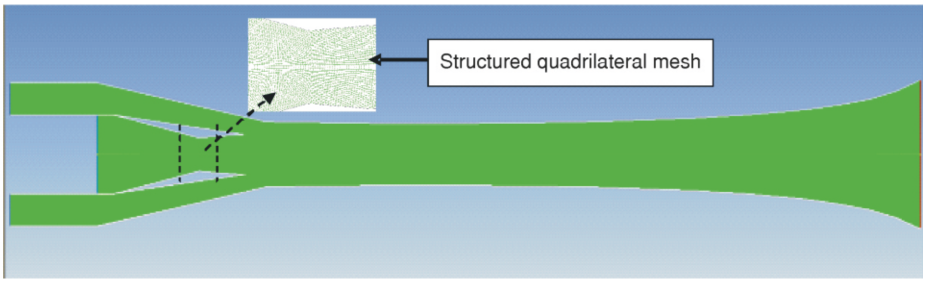

Figure 4. Meshed model of the jet compressor. The insert shows the uniform type of quadrilateral structured mesh used to mesh the jet compressor

Table 2. Parameter used for simulation in FLUENT

Versions	2-D
Solver	Segregated – pressure based
Formulation	Implicit
Space	Axi-symmetric
Gradient option	Green – Gauss node based
Energy equation	Yes
Viscous model	k-ε, standard, standard wall function
Material	Air – ideal gas
Operating pressure	1.01325 bar

– mass flow inlet at nozzle inlet,
– pressure inlet at secondary flow inlet, and
– pressure outlet at exit of the jet compressor.

Axi-symmetric solver is chosen in the FLUENT, 3-D effects can be reflected by 2-D jet compressor model. The flow inside the jet compressor is governed by the compressible steady-state turbulent equations. Table 2 describes the various parameters used for simulation in FLUENT.

Results and discussion

Figure 5 shows the velocity vector map inside the jet compressor. It is seen from the vector plot that maximum velocity occurs at the entrance of the throat of the compressor, after which it is reduced because of mixing with the secondary fluid stream. It is also observed that due to the boundary layer effect a velocity gradient is observed from the wall to the center line flow velocity. In the diffuser section this kinetic energy is converted to pressure energy.

The absolute pressure at various points in the jet compressor is shown in fig. 6. Exhaust gas from the internal combustion engine enters the jet compressor as motive stream at 3.5 bar absolute pressure. It expands in the nozzle and comes out at a reduced pressure of 0.5 bar. Due to the low pressure developed at the nozzle exit, atmospheric air is sucked through the convergent portion of secondary nozzle. Both the streams gets mixed in the mixing chamber at approximately constant pressure and enters into the diffuser. Shock waves developed in the diffuser section increases the pressure of the mixed stream to outlet pressure of 1.5 bar (absolute).

The absolute pressure variation along the axis of the jet compressor is shown in fig. 7. It was observed from the graph that the maximum pressure drop of the motive stream takes place at the primary nozzle exit where it is reduced below the atmospheric pressure. This low pressure causes the secondary fluid to be sucked into the mixing chamber where the motive and the sec-

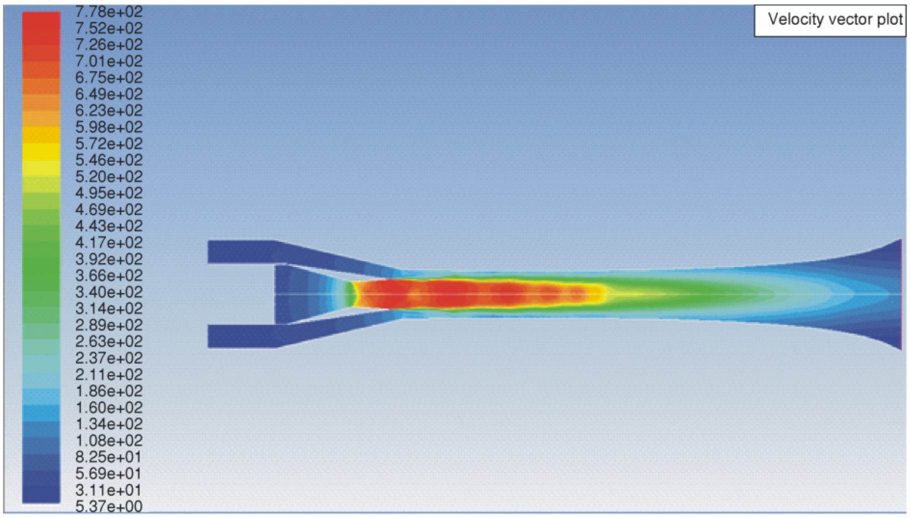

Figure 5. The velocity vector map showing the maximum velocity occurring at the primary jet nozzle of the jet compressor (color image see on our web site)

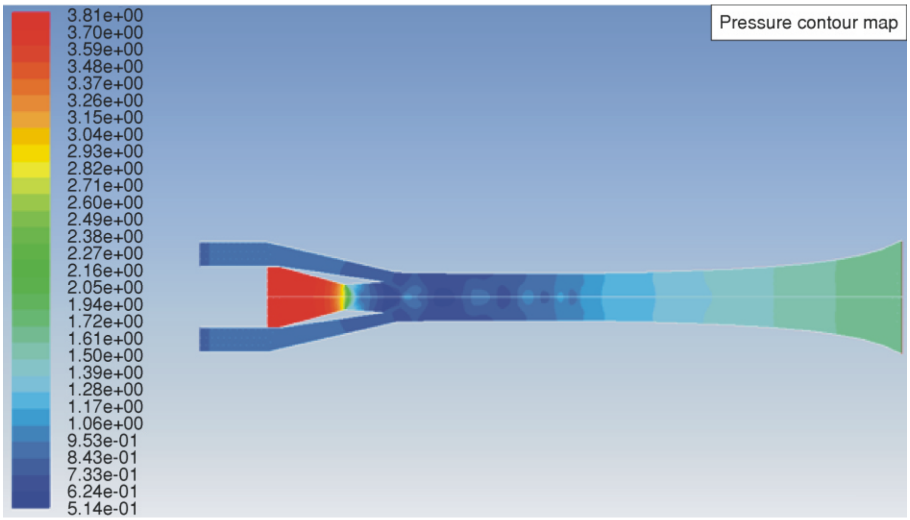

Figure 6. Variation of absolute pressure at different zones inside the jet compressor. Maximum pressure occurs at the entry to the primary nozzle where the exhaust stream from the engine enters (color image see on our web site)

ondary streams are mixed, thereby increasing the pressure to nearly atmospheric pressure. As explained above, the shock waves are avoided by modifying the geometric parameters of the converging and diverging sections of the jet compressor as per the values calculated using the CRMC method. Hence, the pressure rise in the diffuser section was gradual till it reaches the

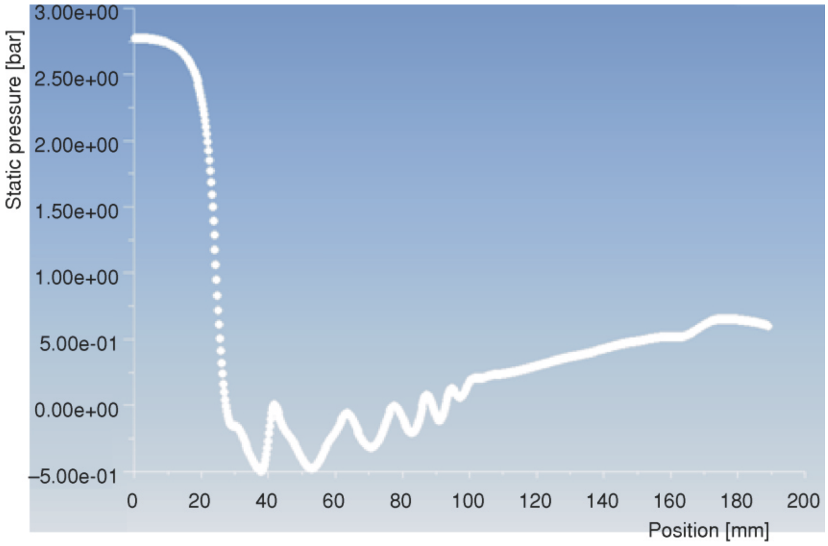

Figure 7. Variation of absolute pressure along the axis of the jet compressor

outlet pressure. Figure 8 shows the values of Mach number inside the jet compressor. At the throat of the primary nozzle, the Mach number is 1 to get the maximum mass flow rate of the motive stream without chocking. At the exit of the primary nozzle the Mach number is 1.55 in order to create the low pressure required for the suction of the secondary stream. After which the Mach number is maintained constant close to 1 throughout the mixing chamber. The flow is

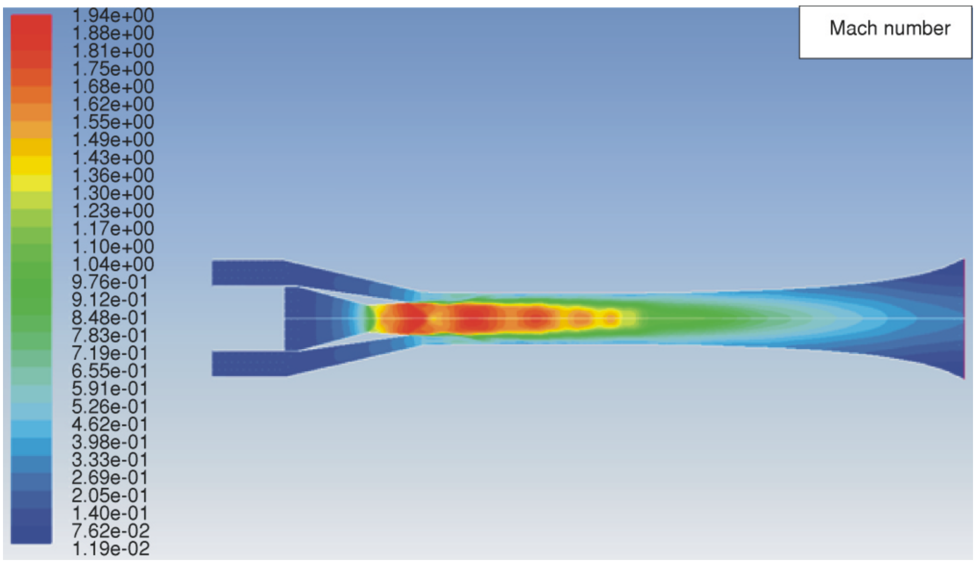

Figure 8. Contours of Mach number inside the jet compressor. The maximum Mach number is found to occur at the primary nozzle exit where the velocity is maximum (color image see on our web site)

maintained sub-sonic in the diffuser section which is again increased at the exit of the jet compressor.

The entrainment ratio of the jet compressor was computed from the mass flux analysis and it was found to be 1.5 which was above the required value.

Experimental validation

Using the results obtained from FLUENT simulation as well as the theoretical design parameters from CRMC method, a jet compressor was fabricated. This jet compressor was fitted on a multi-cylinder diesel engine whose specification details are given in tab. 3.

Table 3. Multicylinder diesel engine specification detaile

Fuel	Diesel
Number of cylinders	4
Swept volume	1990 cm^3
Speed	3000 rpm
Exhaust gas mass flow rate	0.0238 kg/s
Exhaust gas average pressure	2.5 bar (gauge)
Exhaust gas temperature	673 K
Super charger boost pressure	0.5 bar (gauge)

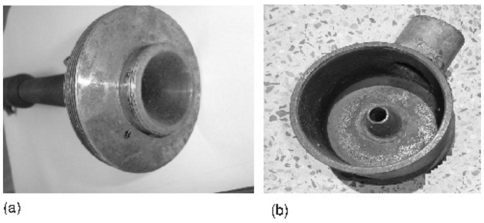

Figure 9. (a) secondary nozzle; (b) primary nozzle

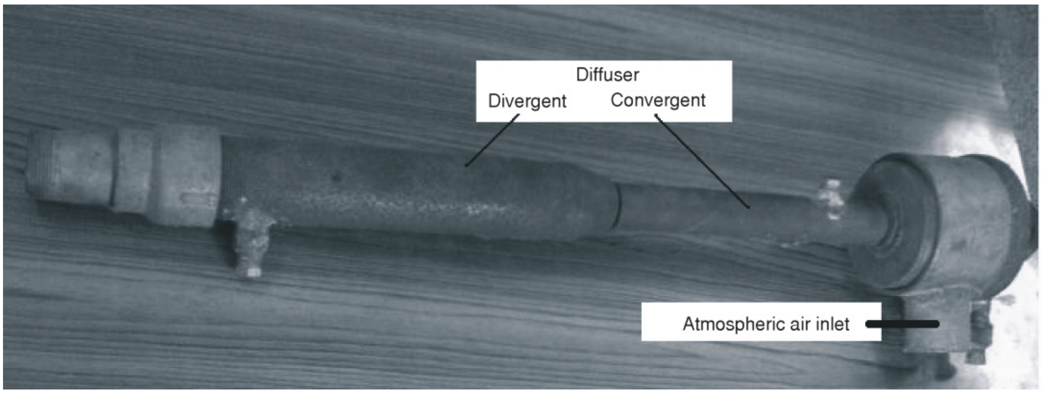

Figure 10. Assembled view of the Jet compressor

Performance test was carried out to study the diesel engine's operating characteristics fitted with the fabricated jet compressor supercharger as shown in figs. 9, 10, and 11. The experimental results showed that jet compressor delivers only 0.4 bar boost pressure whereas it is designed to produce 0.5 bar boost pressure. The drop in boost pressure was due to frictional losses and losses due to entropy generation at the mixing of two streams of different velocities at the throat. The engine retrofitted with jet compressor was able to produce only 30 HP where as the

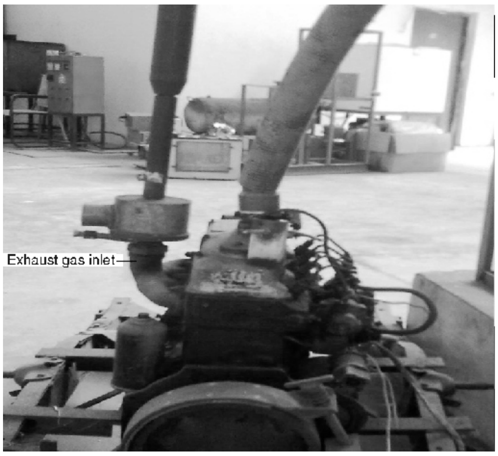

Figure 11. Experimental set-up showing a jet compressor fitted to a diesel engine

same engine fitted with turbo charger produced 35 HP. The reason for drop in power developed could be due to the low boost pressures delivered by the jet compressor. In order to increase the boost pressure delivered by the jet compressor a blower was fixed at the entrance of secondary nozzle to get the required forced draft thereby increasing the boost pressure to 0.5 bar. By this method the velocity of secondary stream is increased and loss due to mixing of fluid at the throat was brought to a minimum. As a result, the engine fitted with the forced draft jet compressor was found to produce the same power as that of a turbo charged engine.

Conclusions

Jet compressor driven by the exhaust gas of an internal combustion engine can effectively supercharge the engine by delivering a boost pressure of 0.5 bar (gauge) and an EGR of about 40%. This could be a very effective alternative for the mechanical superchargers in terms of both by energy conservation as well as a measure of reducing exhaust noise and dilution of exhaust pollutants in the atmospheric air.

Nomenclature

c – velocity, [ms^{-1}]
D – diameter, [m]
L – length, [m]
L_d – length of diffuser, [m]
M_o – momentum, [kgms^{-1}]
m – mass flow rate, [kgs^{-1}]
P – static pressure, [Pa]
R – gas constant, [Jkg^{-1}K^{-1}]
R_m – entrainment ratio, [msmg^{-1}]
T – static temperature, [K]

Greek letters

β – constant
θ – diffuser half-angle, [°]

Subscripts

d – diffuser
de – diffuser exit plane
g – primary nozzle inlet
ne – primary nozzle exit
o – total or stagnation condition
s – secondary flow
x – co-ordinate along central axial of the jet compressor

Superscripts

* – critical condition at diffuser throat

Acronims

CRMC – constant rate of momentum change
EGR – exhaust gas recirculation

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Paper submitted: June 30, 2009
Paper revised: September 22, 2009
Paper accepted: April 4, 2010