New Induction Manifold Designs for High Performance and Low Emission Diesel Engine Running on Alternative Fuels

A.M. Sadiq[*], M.T. Gergawy[†], M.A. Bassiony[‡], S.F. Ahmed[§]
Thermofluids Group, Mechanical and Industrial Engineering Department, College of Engineering, Qatar University, P O Box 2713, Doha, Qatar

The demands for increasing the swirl in the combustion chamber and for decreasing exhaust emissions have increased rapidly over the past few years which attracted the researchers' attention to test new designs of the induction manifold that can match these demands since the recession of crude oil and environmental pollutions have become the main concerns in automotive industry. This can be done through varying the manifold's geometry such as outlet angle and resizing the inner diameter. This research proposes new design configurations to be replaced the standard induction manifold to enhance the air motion and turbulence in the combustion chamber. The new induction manifolds have been designed with helical and spiral shape based on varying the inner diameter and the outlet angle of the manifolds. The aim of this paper is to study the effect of each manifold design on engine performance parameters and emissions under different operating engine conditions of a single-cylinder compression ignition engine. Two fuels will be used; diesel and Gas-To-Liquid (GTL) fuels. The results are compared between the new manifold designs and the standard one.

Nomenclature

CI	Compression Ignition
HCCI	Homogeneous Charge Compression Ignition
GDI	Gasoline Direct Injection
DI	Direct Injection
GTL	Gas to Liquid fuel
PIV	Particle Image Velocimetery
LDA	Laser Doppler Anemometry
TDC	Top Dead Centre
FDM	Fused Deposition Melting
ABS	Acrylonitrile butadiene styrene
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
NDI	Nondispersive Infrared Gas Analysis

I. Introduction

The fluid motion in an internal combustion engine is induced during the induction process and later modified during the compression process. Intake charge enters the combustion chamber through the intake manifold. Then the kinetic energy of the fluid resulting in turbulence causes rapid mixing of fuel and air if the fuel is injected directly into the cylinder. The in-cylinder fluid motion governs the flame propagation in controlling the fuel-air mixing and premixed burning in diesel engines. Therefore, it is very much essential to understand the in-cylinder fluid motion thoroughly in order to optimize the combustion chambers for the modern I.C engines like GDI, HCCI engines etc. The kinetic energy of the fluid resulting in turbulence causes rapid mixing of fuel and air. In addition, Heywood [1] has stated that generating a significant swirl and/or tumble motion inside the engine cylinder during the intake process was one of

---

[*] Student, Mechanical and Industrial Engineering Department, Qatar University, Doha, Qatar

[†] Student, Mechanical and Industrial Engineering Department, Qatar University, Doha, Qatar

[‡] Research Assistant, Mechanical and Industrial Engineering Department, Qatar University, Doha, Qatar

[§] Associate professor, Mechanical and Industrial Engineering Department, University of Qatar, Qatar,.

the promising ways to obtain high in-cylinder turbulent intensity. Prasad et al [2] reviewed the PIV (particle image velocimetery) studies and had reported the basic components of PIV algorithms, optical considerations, tracer particles, illuminating lasers, recording hardware, typical errors associated and vector processing in order to investigate the induced flow motion in the induction manifolds.

In another work [3], The experiences with in-cylinder measurement using PIV, mainly with air seeding and multiple reflections on the glass liner have been described. It is reported that the PIV measurement was useful tool for evaluating in-cylinder flows especially when combined with numerical simulation. Other investigations [4-8] have conducted PIV measurements on various engines and reported that the flow structure changes substantially along the cylinder length because of the geometry of the intake valve port and the tumble motion was generated during induction process. Moreover, it has been reported that the increase in the air flow rate at higher engine speed causes the vortex center to move right-upwards compared to the lower engine speeds. Li et al[6] have investigated the instantaneous 2D velocity fields around the intake valve of an I.C engine under static and dynamic conditions by means of PIV. They have observed that for the given intake valve lift and pressure drop across the intake valve, the static analysis showed higher jet velocity than the dynamic analysis.

Experimental investigations using the LDA technique have been carried out to study the engine in-cylinder flow characteristics [7]. The results showed that the flow structure during the intake was very much affected by the intake valve lifts with the formation of up and down flows and a strong flow reversal below the intake valve generated during the intake closure period. Also, the addition of swirl into the engine was altering the flow structure, particularly below the intake valve.

Swirl is one of the principal means to ensure rapid mixing between fuel and air in Diesel Injection diesel engine, and is used in gasoline engines to promote rapid combustion. The swirl level at the end of the compression process depends upon the swirl generated during intake process and how much it is amplified during the compression process. In direct injection diesel engine, as fuel is injected, the swirl converts it away from the fuel injector making fresh air available for the fuel about to be injected. The induction swirl is generated either by tangentially directing the flow into the cylinder using directed ports or by pre-swirling the incoming flow by the use of a helical or spiral or helical-spiral ports. Helical ports are more compacted than normal manifold. They are capable of producing more swirl than directed ports at low lifts, but are inferior at higher lifts. Either design creates swirl at the expense of volumetric efficiency. In trying to optimize the port design for both good swirl and volumetric efficiency, current high swirl ports are in part of both directed and different technique inlet manifolds.

Controlling of flow through the manifold is critical for meeting the emission regulations and fuel economy requirements. Parameters like engine speed, manifold and combustion chamber configuration are directly influence the swirl in DI diesel engines and subsequently it plays a vital role in mixing air and fuel inside the cylinder [9]. Bugrake[10] presented a flow model to predict the swirl vortices and turbulence in an open chamber cup-in piston engine. The work was compared with experimental data over a range of engine intake manifold and combustion chamber configurations. A number of studies have been conducted on engine flow and the parameters that affect the turbulence, performance and emissions in a DI diesel engine. Kajiyama and Nishida [11] carried out the modeling of flow distribution in exhaust manifold. Modifications were made on the inlet and exhaust manifolds based on the results obtained. They also conducted experiments and validated the performance and emissions of the engine.

Akira et al [12] presented an experimental analysis for turbulence inside the combustion chamber of direct injection diesel engine. This study has showed clearly the effects of piston bowl shape, engine speed, manifold shape and compression ratio on the flow fields in a DI diesel engine. It was concluded that the manifold shape has a considerable effect on the flow structure inside the cylinder. Martin [13] conducted a study on the flow behavior in intake and exhaust system of an internal combustion engine and observed that the flow phenomenon inducts closely affecting the volumetric efficiency of the engine.

Other parameters such as the outlet angle of the manifold plays a major rule of increasing engine efficiency in terms of brake specific fuel consumption (BSFC), brake means effective pressure (BMEP) and volumetric efficiency. Moreover, swirl induction and turbulence level are enhanced by varying the outlet angle to different degrees

All of these previous investigations studied using conventional diesel fuel. On the other hand, fewer studies investigated the use of GTL Diesel with design parameters. It can be analyzed that the design of inlet manifold configuration is very important to improve the efficiency and reduce emissions in IC engines and in particular diesel engines. Hence, this work develops new designs of helical, spiral, and helical-spiral combined configuration of the induction manifold and calculate the induced mean swirl velocity and the generated swirl number. Therefore, the main objectives of the study are to understand the effect of different (helical, spiral, helical-spiral) inlet manifold configurations on combustion performance and emissions in a DI diesel engine fueled with GTL fuel. The experimental methods are presented next while the results are presented and discussed in Section III

II. Experimental Methods

The experiments were carried out on a T85D single cylinder, four stoke, water cooled, direct injection, compression ignition engine attached to DIDACTA ITALIA engine test bed. An electric dynamometer with motor and a load cell was coupled to engine. Engine specifications are shown in Table.1. Two fuel tanks were assembled in the test bed; one tank was used for convention diesel fuel and the other was used for GTL Diesel. The properties of the used fuel are mentioned in Table.2 [14].

The engine test bed and the measuring devices are shown schematically in Fig. 1. The in-cylinder pressure was measured by using a water cooled piezoelectric pressure transducer AVL QH 33D which was mounted flush at cylinder head and connected via AVL charge amplifier. The output signal was displayed on Instek GDS-3152 Digital Storage Oscilloscope with 150 MHz sampling rate. Then, the data was transferred to a laptop which saved for further analysis. The crank shaft position was measured using a digital shaft encoder.

The engine speed was measured by using a speed tachometer that used the pulse counting principle to detect the crank shaft speed, while the fuel flow rate was measured by using a calibrated burette and a stop watch. The engine torque was measured by using a load cell. Engine NO_x emission was measured by a long life electrochemical sensor at NOVA-7465PK portable engine exhaust emission analyzer .This electrochemical sensor has anodes, cathodes and suitable electrolyte sealed inside it which, when exposed to gasses, produces a small output current. This output is directly proportionally to the amount of NO gas in the sample. A Pre-Amplifier board directly mounted on the top of the sensor boosts the small signal and converts it to an output of 1 mV per PPM .This output is then sent the main microprocessor board, corrected for the calibration then displayed on the LCD display meter. The resolution of the NOx sensor is ± 1 PPM. The test rig is also equipped with a type-K thermocouples to measure air inlet manifold, engine cooling temperatures and exhaust temperatures which were mounted at relevant points. Normal engine test bed safety features are also included .Atmospheric conditions (temperature and pressure) were monitored during the tests.

The new induction manifold have been 3D designed using SolidWorks software which have helical and spiral shapes. The outlet angle of the manifold, relative to the inlet port are set to be 0°, 30° and 60° with two configurations of inner diameter; the red one is with one inner diameter turn of the standard intake manifold and the white one is with double inner diameter turn of the standard intake manifold, as shown in Fig. 2. The goal is to investigate not only the effect of main manifold configuration designs on the generated air swirl, but also the outlet angles of these manifolds relative to the inlet port. The modified intake manifolds have been manufactured using Fused Deposition Modeling (FDM) additive manufacturing Technology with a 3D printer for built our rapid prototype. UPrint SE Plus 3D printer with .254 mm layer thickness 203 x 203 x 152 mm working space was used. The material of manufactured parts from ABS filament which has a good mechanical and thermal properties. ABS has a lot of advantages strength, flexibility, machinability, and higher temperature resistance properties which was the most proper rapid prototyping. This material is suitable for the new manifolds since the induced air passes through these manifolds at nearly ambient temperature and pressure.

III. Results and Discussion

In this section, a comparison between the new manifold designs and the standard manifold of the engine in terms of engine performance and emissions is presented. A number of experiments have been conducted when the engine runs at different loads and different speeds. In addition, the results of the best performance designs of the white color manifolds and the the red color ones are shown when the engine uses diesel and GTL fuel to show the fuel effect with these new designs.

A. Engine Performance

Table 3 shows the values of the new design configurations with respect to the inner diameter, outlet angle and calculated geometrical swirl numbers. It can be observed that, the swirl number of helical-spiral manifold with 60° and double inner diameter is about 1.34, which is the highest value comparing to the other configurations. This indicated that this particular design configuration is expected to create high mixing level of the air-fuel mixture inside the combustion chamber.

Preliminary results have been obtained for the in-cylinder pressure versus crank angle when the engine runs with different manifold designs and different fuels. Figure 3 shows an example of the pressure profile inside a cylinder when the engine was running on diesel fuel at 1300 rpm at 3 N.m load. Similar curves will be obtained in the future work to compare the maximum in-cylinder pressure, pressure rise rate, knocking tendency and cycle-by-cycle variations for all the conditions under consideration. The comparisons of curves such as that in Fig. 3 helps to study the combustion characteristics of the new intake manifolds. Further improvement of the noise filter and analyze the output data of these curves will be included in the final submission of this paper.

The bsfc is a measure of engine efficiency. In fact, bsfc is inversely related to engine efficiency, so that the lower the bsfc the better the engine efficiency. The variations of brake specific fuel consumption at different loads and speeds for standard, spiral, helical and helical spiral inlet manifolds fueled by diesel and GTL fuels are shown in Fig. 4. It can be observed that brake specific fuel consumption of new inlet manifolds have a similar trend to the standard one. In general, bsfc decreases with load and speed. This trend is well established in the literature [15]. It can be noted from Fig. 4 that brake specific fuel consumption for all new manifolds is less compared to the standard manifold . The values of brake specific fuel consumption of standard, spiral, helical with doubled diameter and 60 degree outlet angle was decreased significantly specially with increasing speeds and loads. This may be related to the high mixing enhancement with this new design, which improve the combustion efficiency of the fuel. As a result, the engine thermal efficiency increases specially when GTL diesel is used. This can partially attributed to the higher calorific value of GTL, which increases the engine power at the same fuel consumption. Moreover, the GTL has a lower density and viscosity and high cetane number in comparison to conventional diesel fuel as demonstrated in Table. 2. All these properties are in favor of improving fuel evaporation and mixing with air, which lead to better combustion efficiency.

B. Engine emissions

Nitrogen oxides NOx emissions is one of the major pollutants of diesel engine due to high pressure and temperature inside the cylinder. The majorly of this pollutant comes from nitrogen oxide (NO). Figure 5 shows the comparison of NOx emission with different speeds and loads between the best performance new inlet manifolds and the standard inlet manifold. The NOx emissions for diesel engine with the new inlet manifolds No. 2c and No. 3c with GTL fuel are the lowest emissions among all other manifold designs, including the standard one. This is due to the low level of fuel injected with these cases, which tends to decrease the maximum temperature in the cylinder by the leads to less NOx formation.

Figure.6 depicts the variation of exhaust gas temperature for diesel engine of different inlet manifolds. As before, the new manifold designs are compared with the standard manifold No. 1 at variable loads and speeds. Exhaust gas temperature is an indication for conversion of heat into work that takes place in the cylinder. The exhaust gas temperature is higher for diesel engine with the standard manifold than that of the new designs. At various load conditions, it is observed that the exhaust gas temperature increases with load because more fuel is burnt to meet the power requirement. Moreover, It can be seen that, in the case of the engine with the standard inlet manifold, the exhaust gas temperature is about 298°C, while temperature decreases to 214°C with manifold No. 2c with GTL fuel.

IV. Conclusions

In this work, new induction manifolds have been developed to enhance the induction air motion inside the cylinder of a diesel engine. In addition, the effect of changing the design of the intake manifold on the swirl ratio , engine performance and emissions of a single cylinder compression-ignition engine fueled by diesel and GTL fuel was experimentally investigated under different operating experiments of loads and speeds. It was found that that using the helical and spiral induction manifolds with 60 degree outlet angle and doubled inner diameter (Manifold No. 3c) produces the lowest bsfc, highest efficiency and lowest NOx emissions among all other manifold designs. The performance of the engine with GTL fuel is comparable with that of diesel fuel. However, GTL fuel produces less NOx emissions and lower exhaust gas temperature in comparison with those of diesel fuel.

Acknowledgments

The authors would like to thank Qatar University for the support.

References

1. Heywood, J. B., (1988), Internal Combustion Engine Fundamentals, McGraw-Hill, Singapore, 1988.
2. A. K. Prasad (2000), "Particle image velocimetry-review", University of Delaware, Newark, DE 19716-3140, USA, Current Science, Vol. 79, NO. 1, 10.
3. P. Hatschbach, J. Novotny, P. Baumruk, (2004), "Measurement of Flow in Model of Internal Combustion Engine Cylinder using PIV", Research Center project LN00B073 of Ministry of Education, Czech Republic.
4. V. Gerardo, D. Kaufman, P. Farrell (1993), "Intake Valve Flow Measurements Using PIV", SAE Paper No. 932700
5. M. Reeves, M.J Haste, N.A Halliwell, (1999), "Barrel swirl breakdown in spark-ignition engines: insights from particle image velocimetry measurements" Applied Optics Laboratory, Leicestershire, UK, Proc I MechE, Vol 213, Part D.
6. Y. Li, H. Zhao, Z. Peng, N. Ladommatos, (2001), "Particle image velocimetry measurement of in-cylinder flow in internal combustion engines experiment and flow structure analysis", Proc Instn. Mech Engrs Vol 216 Part D.
7. A. Yasar, B. Sahin, H. Akilli, K. Aydin, (2006), "Effect of inlet port on the flow in the cylinder of an internal combustion engine", Cukurova University, Adana, Turkey, Proc. I MechE Vol. 220 Part C: J. Mechanical Engineering Science.
8. P. Stansfield, G. Wigley, T. Justham, J. Catto, G. Pitcher, (2007), "PIV analysis of in-cylinder flow structures over a range of realistic engine speeds", Exp Fluids 43:135–146, Springer.
9. A .Chen, A. Veshagh, intake Flow prediction of a Transparent DI Diesel Engine, SAE Paper 981020.
10. Bugrake, The effect of induced swirl pattern on TDC flow field in a HSDI Diesel Engine, SAE Paper 2005-26-319.
11. K. Kajiyama, k. Nishida, An analysis of swirling Flow in cylinder for Predicting D.I .Diesel Engine performance, SAE Paper 840518
12. Akira et al, Experimental Analysis for Turbulence Inside the Combustion Chamber of Direct Injection Diesel Engine, 1990
13. Martin B.Link ,The combustion laboratory retrieved from http://www.enme.umd.edu/combustion/underwater_propulsion.h
14. Fuel Characterization Lab, Texas A&M University at Qatar, Doha, Qatar.
15. M. Y.E. Selim, M.S. Radwan, H.E. Saleh, Improving the performance of dual fuel engines running on natural gas/LPG by using pilot fuel derived from jojoba seeds, Renewable Energy 33 (2008) 1173–1185.

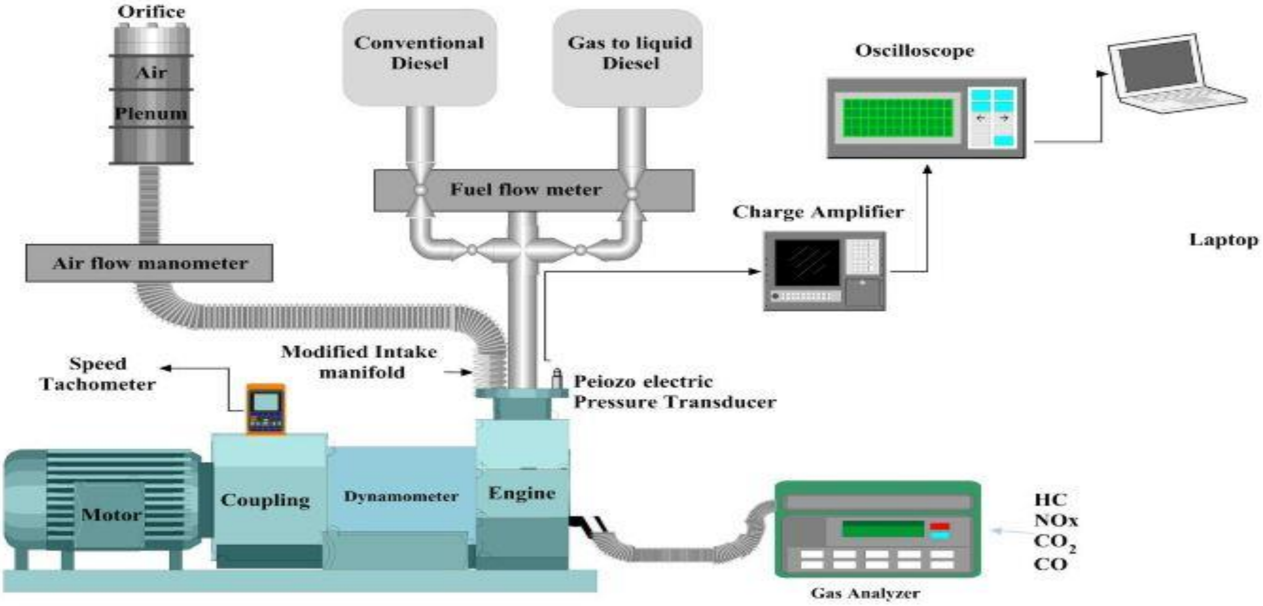

Figure 1. A schematic diagram of the diesel engine test rig and the experimental setup.

Table 1. Engine specifications.

Parameter	**specification**
No. Cylinders	single cylinder,4-stroke
Engine Type	Compression ignited
Type of Cooling	Water-Cooled Engine
Bore (m)	0.082 m
stroke (m)	0.068m
Max.Power (H.P.)	6.5 H.P.
Used Fuel	Diesel or GTL

(a) (b) (c) (d)

Figure 2. Samples for the new intake manifold configurations, (a) red helical and spiral manifold with one manifold diameter turn, (b) white helical and spiral manifold with doubled manifold diameter turn, (c) the final assembly of a white configuration installed on the engine and (d) standard manifold.

Table. 2 Fuel properties [14].

Property	Diesel	GTL
Density at 15 C (kg/m^3)	866	760
Kinematic viscosity at 40 C (cSt)	1.6-7.0	1.5
Flash point (1C) (closed cup)	55	>55
Calorific value (MJ/kg)	44.3	47.3
Cetane No..(min)	55	70
Carbon content (% by weight)	86.98	94
Hydrogen content (% by weight)	12.99	1.6

Table. 3 New intake manifold configurations used in the current experiments.

Configuration	Color	Manifold type	Outlet angle	Manifold No	Swirl number
1	black	Standard	0	1	0.091
2	Red	Helical and spiral with same inner normal diameter	0	2.a	0.093
			30	2.b	0.385
			60	2.c	1.155
3	White	Helical and spiral with doubled normal inner diameter	0	3.a	0.097
			30	3.b	0.29
			60	3.c	1.34

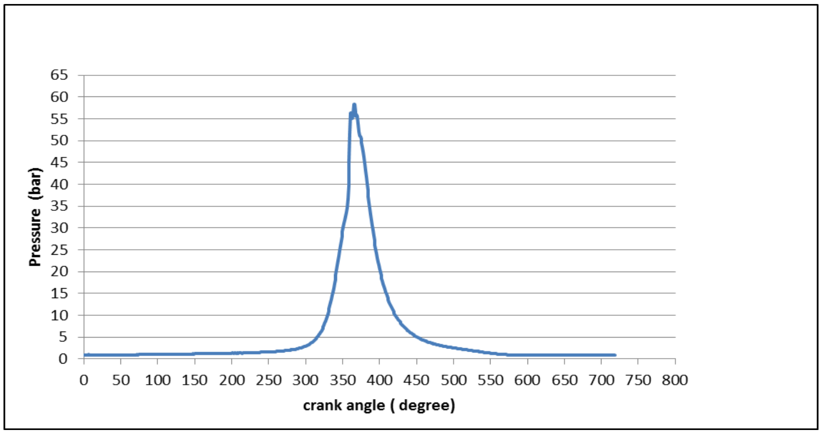

Figure 3. In-cylinder pressure versus the crank angle degree for the standard intake manifold. The engine runs on diesel fuel at 1300 rpm.

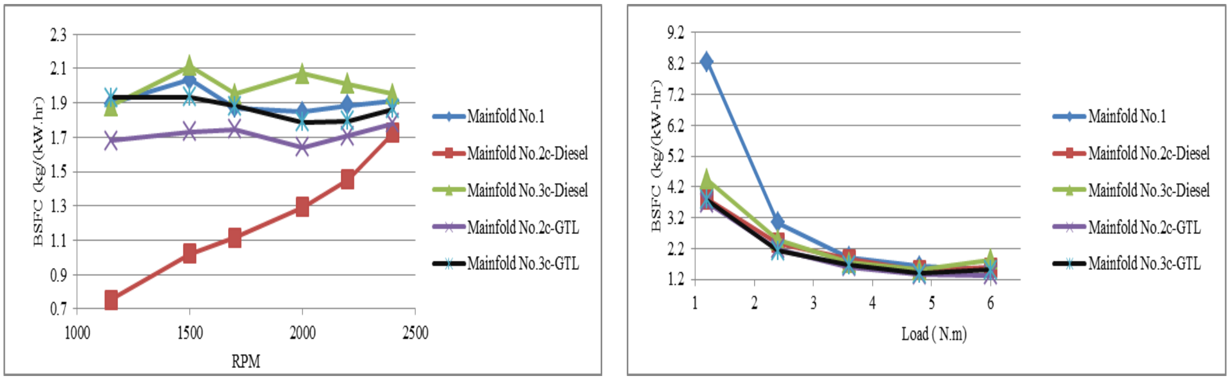

Fig. 4(a) **Fig. 4(b)**

Figure 4. BSFC comparison between the best performance red manifolds No. 2 and the best performance white manifolds No. 3 with diesel and GTL fuel. 3(a) at constant load and 3(b) at constant speed 1300 rpm.

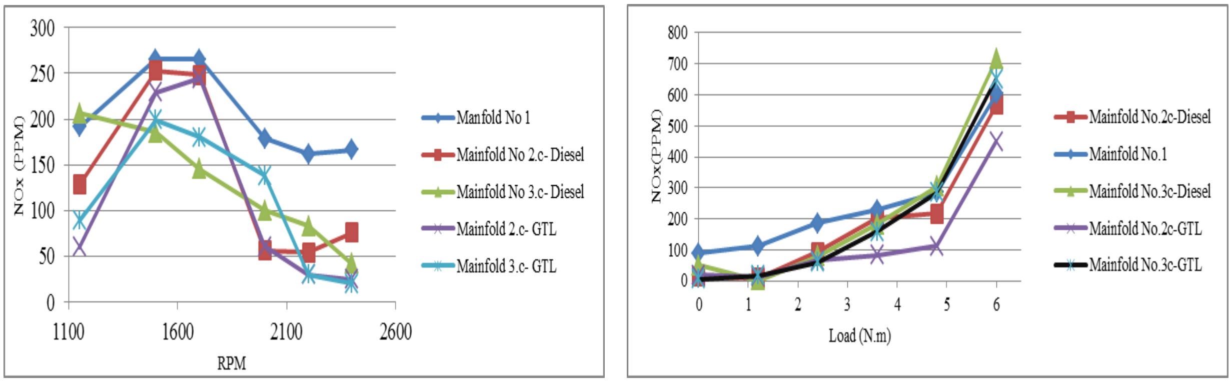

Fig. 5(a) **Fig. 5(b)**

Figure 5. NO$_x$ emissions comparison between the best performance red manifolds No. 2 and the best performance white manifolds No. 3 with diesel and GTL fuel. 3(a) at constant load and 3(b) at constant speed 1300 rpm.

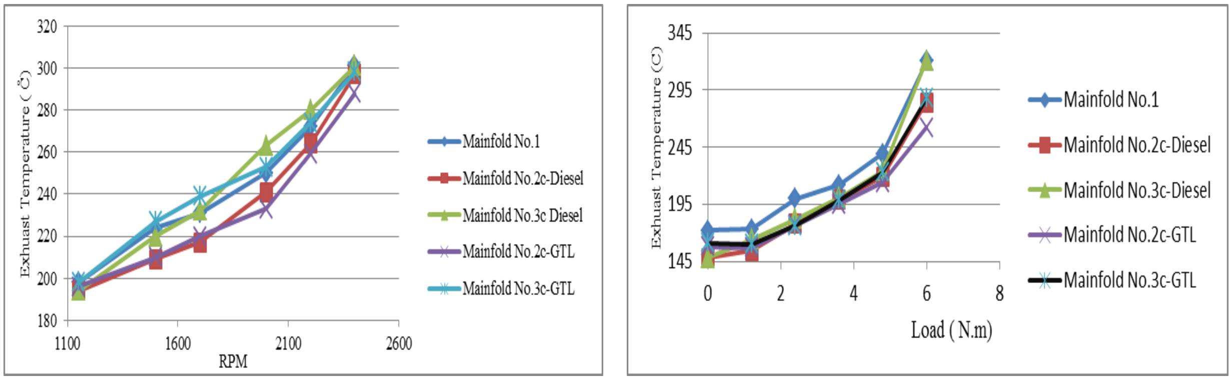

Fig. 6(a)

Fig. 6(b)

Figure 6. Exhaust gas temperature comparison between the best performance red manifolds No. 2 and the best performance white manifolds No. 3 with diesel and GTL fuel. 3(a) at constant load and 3(b) at constant speed 1300 rpm.