PERFORMANCE OF MICRO GAS TURBINE COMBUSTION CHAMBER WITH DIESEL FUEL

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DECLARATION

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Nomenclature/symbols

CO	carbon monoxide	**LPG**	liquefied petroleum gas
DC	direct current	**MGT**	micro gas turbine
HDR	high dynamic range	**NOx**	oxides of nitrogen
HRU	heat recovery unit	**ppm**	part per million

ABSTRAK

Sejak kebelakangan ini, perkembagan mikro gas turbin (MGT) telah meningkat disebabkan kebolehpercayaan yang tinggi dan kebolehan dalam menjana kuasa dengan sendirinya. MGT juga menghasilkan kehilangan kuasa yang rendah dan ia boleh beroperasi mengunakan bahan api yang boleh diperbaharui dan bahan api yang tidak boleh perberahui. Bagaimanapun, tanpa reka bentuk ruang pembakaran yang betul, jumlah udara yang cukup dan ciri-ciri semburan minyak cecair yang baik, ia akan menyebabkan pembakaran tidak sempurna akan berlaku dan mnyebakan pelepasan gas yang berbahaya pada tahap tinggi. Dalam kertas ini, satu sistem mikro gas turbin (MGT) telah dibangunkan dengan menggunakan pengecas turbo Garret GT25 dengan ruang pembakaran untuk beroperasi dengan bahan api diesel.Ciri semburan bagi minyak diesel dengan menggunakan pelbagai jenis nozel telah dipelajari. MGT sistem ini telah dijalankan secara uji kaji dengan menggunakan bahan api gas petroleum cecair (LPG) untuk sebagai pemanasan pada ruang pembakaran dan bahan api diesel untuk operasi sepenuhnya. Sistem MGT ini telah mencapai pelepasan gas ekzos bagi CO dan NOx pada tahap rendah masing-masing sekitar 95ppm dan 31ppm. Selain itu, reka bentuk zone penyejuk di dalam ruang pembakaran dapat mengawal suhu ekzos daripada melebihi 1000^{o}C.

ABSTRACT

Development of micro gas turbine has increased in recent year due to high reliability and the ability of self-generating. MGT system also provides lower power losses and it can operate on both renewable and non-renewable fuels with low level of gas emission. However, without right design of combustion chamber, sufficient amount air and better spray characteristic of liquid fuel will causes incomplete combustion occurred and lead to high level of gas emissions. In this paper, a MGT system was developed by using a Garret turbocharger GT25 with a combustion chamber to operate with diesel fuel. A spraying characteristic was studied of diesel fuels using various nozzles. The MGT system was characterized experimentally with liquefied petroleum gas (LPG) for warm up session and diesel fuel for full operation. The MGT system has achieved low level of CO and NOx emission of about 95ppm and 31ppm respectively**.** Besides that, design of dilution zone at the combustion chamber able to prevent temperature of gas exhaust exceeding 1000^{o}C.

1.0 Introduction

Gas turbine is an internal combustion chamber consisting of a compressor coupled to a turbine with a combustion chamber (combustor) in between. One of the attractive features of the gas turbine is that it can run on a wide variety of fuel such as natural gas, kerosene, diesel and biodiesel. Currently, several countries follow new trend in the energy sector with, development of small scale generator. Micro Gas Turbine (MGT) has become an appropriate technology option for electricity generator in a small scale and independent source. MGT is small thermal machine operating on a Brayton cycle to produce electricity in the range of 25-80W [1].

In MGT, the combustor is the very important part where chemical energy is converted into thermal energy through a combustion process. A lot of studies on geometry, configuration and dimension of the combustor have been made related to wall cooling, flame stability and emission control [2-3]. Several investigations on MGT by using different design of combustion chamber with different types of fuel were conducted in previous works [4-8]. This work present an analysis of combustor with addition of pre-chamber and swirl air motion to work with LPG gas and diesel fuel.

Spray characteristics is an important study in order to achieve better combustion and fuel economy. The performance liquid fuel (diesel fuel) combustion largely depends on fuel atomization which affects the air-fuel mixture. Injection pressure, fuel density, fuel viscosity, ambient pressure and temperature are the factors that affect the spray pattern [9]. Besides that, spray characteristic also can be investigated by using numerical simulation [10].

However, low emissions of exhaust gas from the combustor without the pre-chamber and swirl air motion are difficult to achieve. This problem is due to the properties of diesel such as high of flashpoint (>62°C) and auto- ignition (>220°C) which prevent the liquid fuel to vaporize and mix with the air. Another factor that contributed in high emissions of exhaust gas is the amount of air supplied and the spray behavior. Therefore, optimized design of combustion chamber with sufficient amount of air and suitable fuel injector are presented in this paper. The main purpose of this study is to achieve complete and stable combustion and low temperature of exhaust gas with low CO and NOx emissions.

2.0 Design of optimum combustion chamber and experiment setup

2.1 Design of the combustion chamber

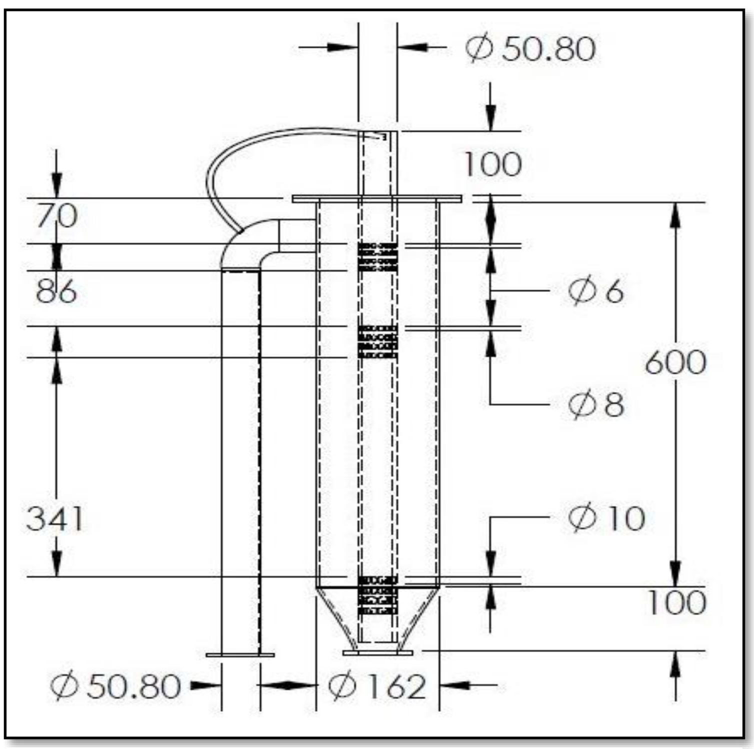

Figure 2.1(a): Dimension of the combustion chamber

Figure 2.1 shows the design of the combustion chamber used in the experiment. The combustion chamber consists of flame holder, air jacket and a bypass tube. Diameters of the air inlet manifold and exhaust of the chamber were fixed at 50.8mm to match with the diameters of the compressor and turbine outlet of the turbocharger. Diameter of the flame holder and overall height are about 50.8mm and 800mm respectively. The air jacket is 162mm diameter stainless steel cylinder with a cone shape at the end and an overall height of 700mm. On the surface of the flame holder, are 4 zones identified such as partially premixed zone, premix zone, primary combustion zone and dilution zone. A pre-chamber is an extension of the flame holder with 100mm and diameter 50.8mm. One of the end of the bypass tube is fixed to the inlet manifold and the other end is fixed tangentially to the pre-chamber. The diameter and length of the bypass tube are about 8mm and 398mm respectively. High pressurized air from the compressor flow into the air jacket, however small amount of air will pass through the bypass tube. The low flow rate of pressurized air enters the partially premixed zone in a form of swirl motion. This swirl air increases the mixing of fuel and air and helps to vapourize diesel partially before entering the premixed zone. The diameters on the flame holders were set to 6,8,10 mm in respective to the zones except partially premixed zone. Pressurized air inside the air jacket will enter each zone with different volume flow rate due to the different size of diameter of the holes. Pressurized air enters the premixed zone to help the remaining diesel vapour to vaporize completely before entering the primary combustion zone. Pressurized air will then enter the combustion chamber to undergo combustion reaction and combustion process. The operating range air fuel ratio (AFR) for diesel fuel is in the range 14 to 40. In the dilution zone, more pressurized air enters the flame holder to reduce the temperature before the exhaust strikes the turbine blades. This procedure is necessary to preserve the life of the turbine blades.

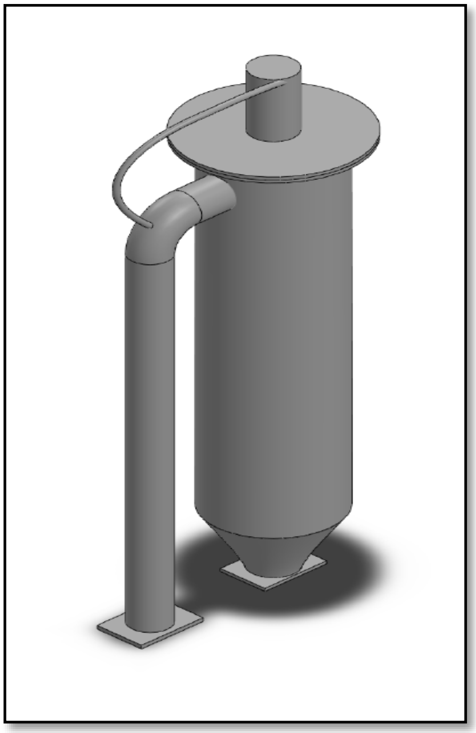

Figure 2.1(b): Design of combustion chamber.

2.2 Experiments Setup

The experiment setups to study the spray characteristic and the combustion chamber performance were develop at the school of mechanical engineering, Universiti Sains Malaysia (USM) as shown in Figures 2.2.1, 2.2.2(a) and (b).

2.2.1 Experimental setup for spray characteristic

The test rig consists of a fuel pump with inverter, fuel tank, fuel distribution pipe and different sizes of fuel injector. In this experiment, five liters of diesel fuel and suitable fuel pump was used with specification 0.37kW, frequency range up to 50/60 Hz and maximum speed of the motor of about 2800rpm. Steinen Nozzle with different sizes (1, 2, 3, 4 US gal/h) fuel injector was used. The injectors were indicated as injector 1, 2, 3and 4 according their capacity in US customary unit and their capacity in SI unit are about 63.09, 126.18, 189.27 and 252.36 ml/min respectively. The fuel pipe was made from copper connecting the fuel tank, fuel pump and injector. The purpose of installing backflow fuel pipe is to return unused fuel back to the tank. Two units of halogen lamp (1000w of each) were needed to provide enough lighting for the photo session.

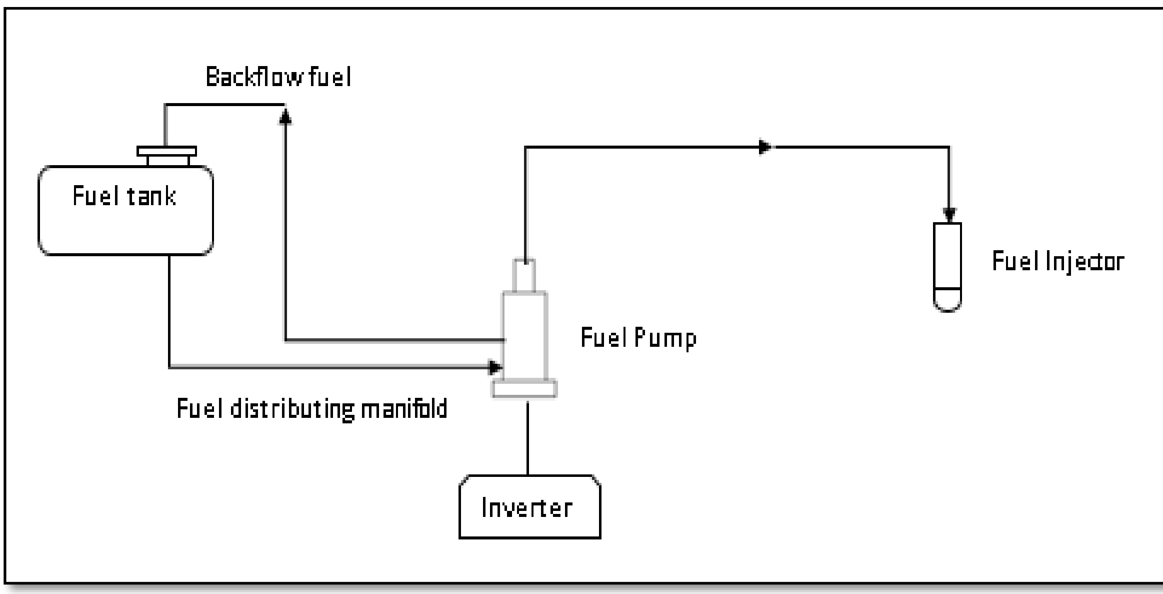

Figure 2.2.1: Schematic diagram of the setup.

2.2.2 Experimental setup for performance of combustion chamber

The experimental setup as shown in Figure 2.2.2 consists of a combustion chamber, Garrett turbocharger GT 25 (170-270 horsepower) [4] and a Heat Recovery Unit (HRU) to form a Micro Gas Turbine (MGT) system. Double tube counter flow heat exchanger was used, with 100 small pipe in this HRU. In this application, one fluid flows inside the smaller tube while the other fluid flows in the annular space between two tubes. Other auxiliary units include, oil pump, oil cooling, liquid fuel pump with inverter, air blower, and high volt DC transformer for spark plug.

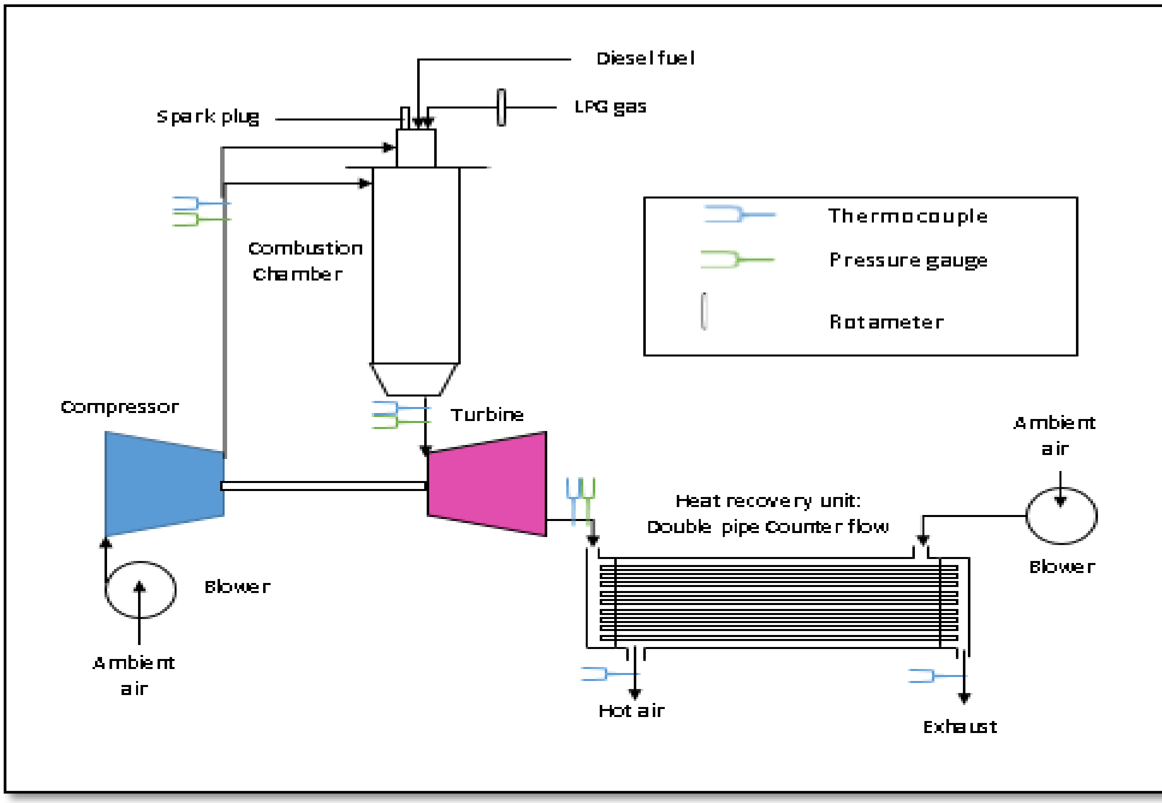

Figure 2.2.2(a): Schematic drawing of performance of combustion chamber experiment setup.

PrThe flowchart of this project is shown in the Figure 2.2.2(b) below:

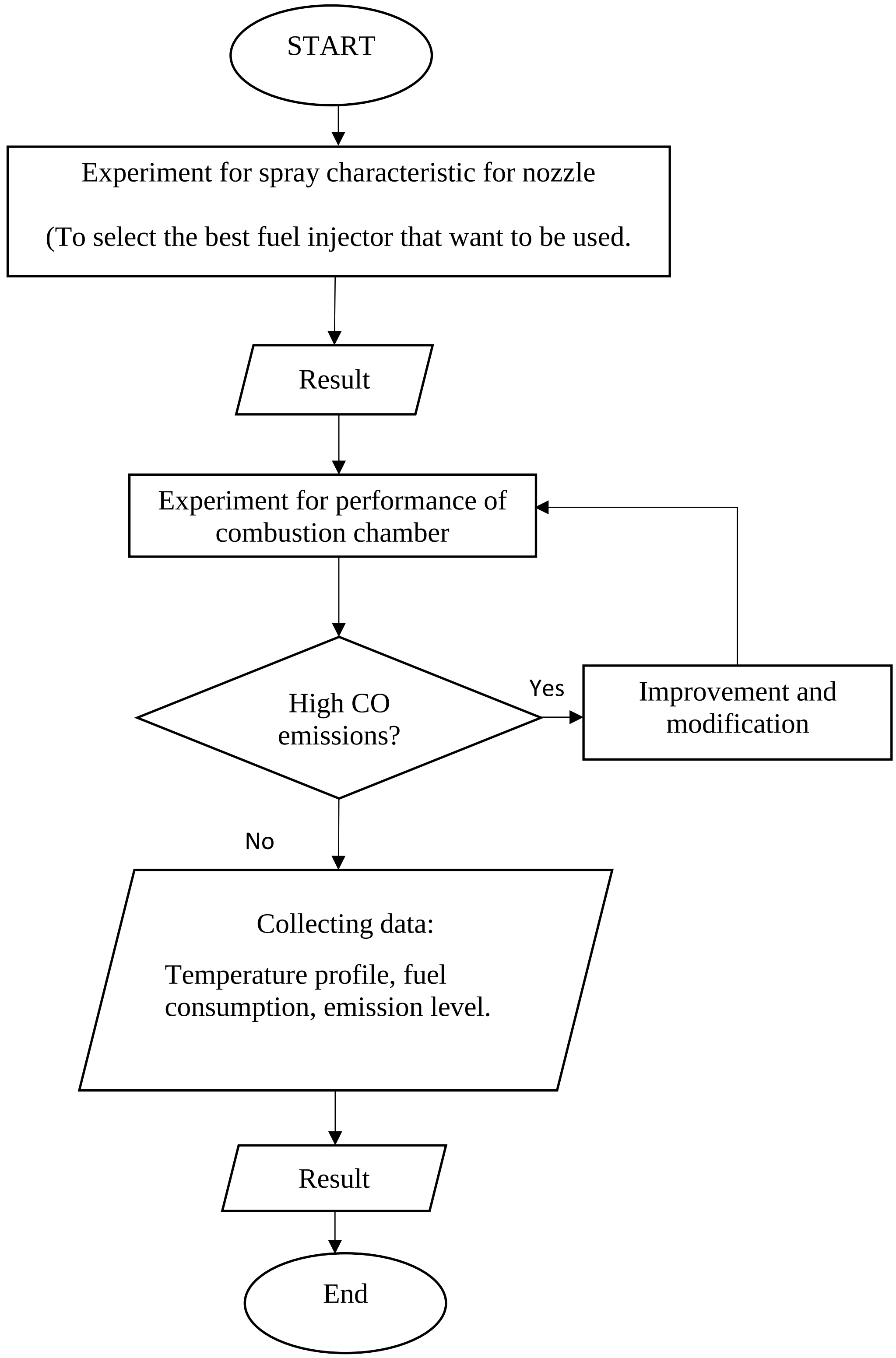

Figure 2.2.2(b): Project flowcharts.

3.0 Experiment procedure and measuring equipment

3.1 Spray characteristic of nozzle

In this experiment, the manipulated variable is the volume flow rate 100 - 200ml/min of the liquid fuel. The inverter was used to control the speed of the motor in the fuel pump in order to achieve desired fuel flow rate. Initially low value frequency was set based on the desired volume flowrate, then photos were taken with High Dynamic Range (HDR) setting and lowest shutter speed to study the fuel spray pattern. This experiment was repeated several times with different values of fuel volume flow rates and different sizes of fuel injector.

3.2 Performance of the combustion chamber

Initially, the LPG fuel was used to warm up the MGT engine because diesel fuel will not burn effectively in cold condition and to prevent formation of carbon inside the combustor that will decrease the performance of combustor. Air flow entering the compressor was measured using a hot wire anemometer while LPG flow rate was measured using a rotameter. The mixture of pressurized air with LPG inside the combustor was ignited with high-volt spark plug at 0.2 bar compressed air. The LPG fuel will be replaced with diesel fuel when the temperature at inlet turbine was above 600°C. The inverter was set at a certain frequency to operate the fuel pump and start spraying. The fuel volume flowrate was recorded every 100ml by using stopwatch. Air blower with capacity of 750W was used to draw air into the compressor. The MGT was tested in the range of 0.2-1.0 bar and measurement of air and diesel flowrates, acoustic, temperature and pressure profile and gas emission were taken every 0.1bar increment.

Five type-K thermocouples with scanning thermometer were used to record the temperature profile for the MGT system with HRU. Also, 2 pressure gauge was used to measure pressurized air from the outlet and the pressure at the outlet of the combustor. Furthermore, automotive gas exhaust analyzer was used to measure the level of various types of gas emissions.

4.0 Results and discussions

4.1 Relationship between flow rate and the fuel spray behavior.

Table 1 shows the range of the diesel flow rate for each injector. As the fuel flow rate increases, the liquid fuel discharge from the hole at the tip of nozzle faster and thinner (atomize into small-sized droplets). Besides that, the cone angle of the spraying also increases with increasing fuel flow rate. Therefore, the atomize fuel can vaporize completely in a very short time before entering the primary combustion zone.

Table 4.1: Performance of the each injector for certain range of flow rate.

No of	Volume flow rate (ml/min)										
Injector	50	60	70	80	90	100	120	140	160	180	200
1				X	X						
2	X	X	X	X	X	X	X	X	X	X	X
3		X	X	X	X	X	X	X	X	X	X
4						X	X	X	X	X	X

Reference X: Spraying

Injector 1 revealed that it cannot form the spray at very low and high flow rates (below 80 and above 90ml/min). The fuel pump will shut down automatically if the experiment runs below 80ml/min, while above 90ml/min the injector does not spraying anything. Figure 4.1 (a) shows the spraying pattern discharge from the injector 1. It shows 90ml/min flow rate as the best spray because the fuel discharges more tiny droplets.

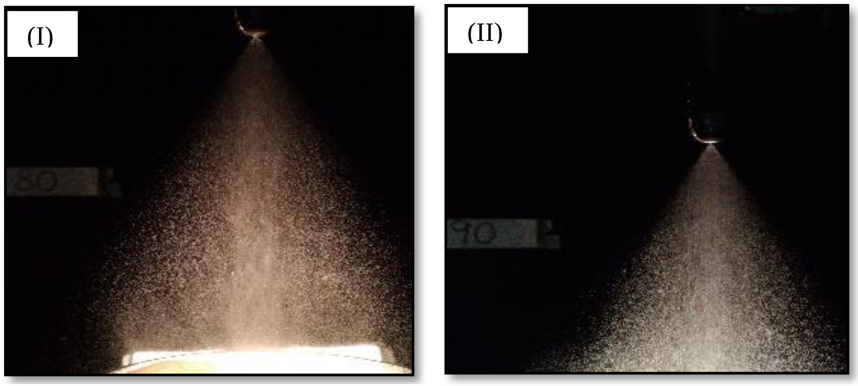

Figure 4.1(a): Injector 1at (I) 80ml/min, (II) 90ml/min.

For the 2US gal/h injector, it can perform at a wide range of flow rates from 50 to 200ml/min, this injector can sustain at low flow rate (below 80ml/min). Figure 4.1(b) shows the spraying pattern for this injector. At low flow rate (below 80ml/min), the spray pattern does not show good result, the liquid fuel does not atomize well. As the flow rate increases to 200ml/min, the better the fuel atomization (more tiny droplets).

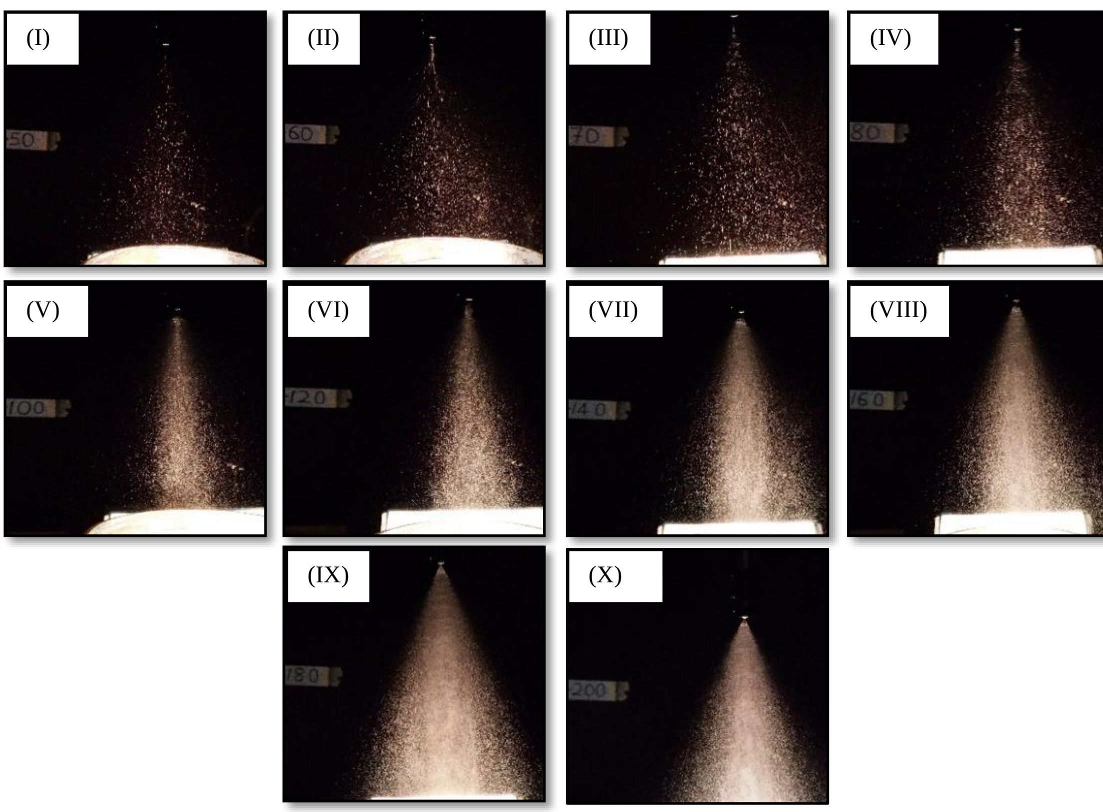

Figure 4.1(b): Injector 2 at (I) 50ml/min, (II) 60ml/min, (III) 70ml/min, (IV) 80ml/min, (V) 100ml/min, (VI) 120ml/min, (VII) 140ml/min, (VIII) 160ml/min, (IX) 180ml/min, (X) 200ml/min.

Figure 4.1(c) shows spray characteristic for injector 3 with good spray pattern at high flow rates (above 140ml/min) but decreasing flow rate decrease the atomization of the fuel until the pump shut down automatically. The minimum flow rate of this injector is 60ml/min with bad spray behavior. At low flow rate (below 100ml/min) injector 2 has better atomization than injector 3. Thus, injector 2 is more suitable to be used at low fuel flow rate.

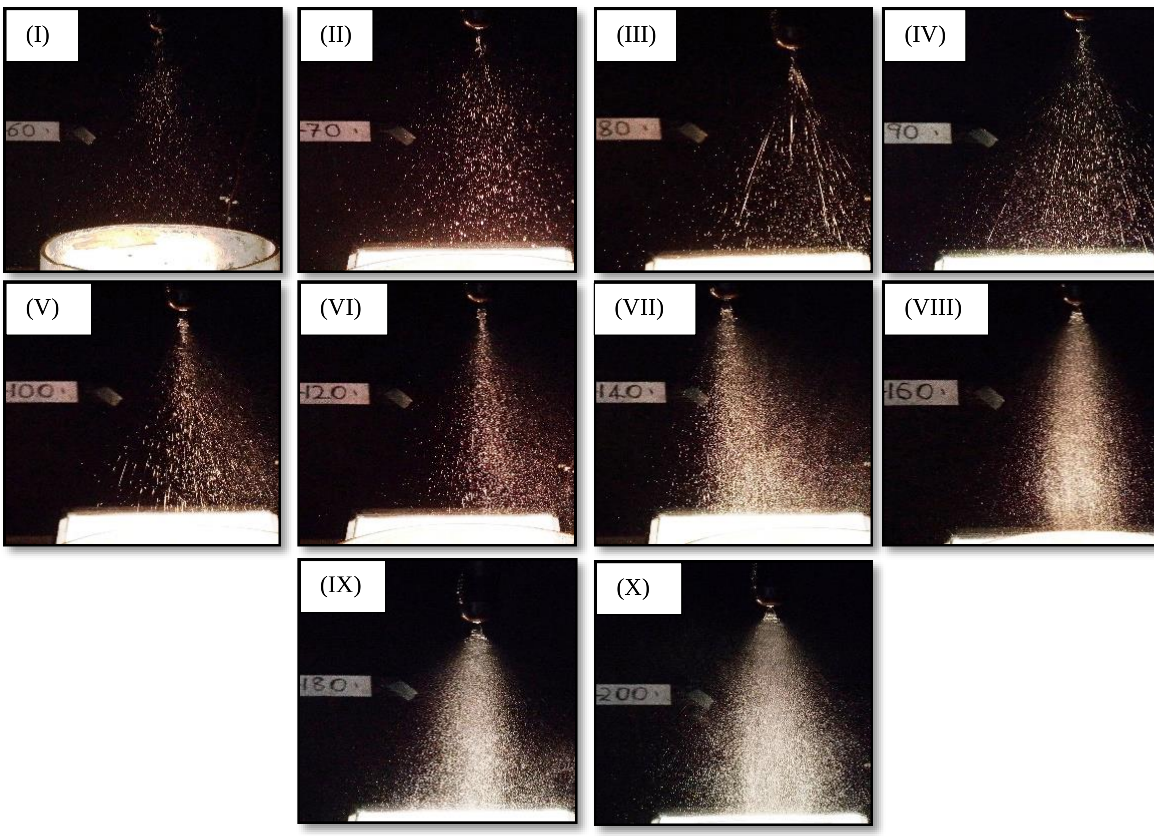

Figure 4.1(c): Injector 3 at (I) 60ml/min, (II) 70ml/min, (III) 80ml/min, (IV) 90ml/min, (V) 100ml/min, (VI) 120ml/min, (VII) 140ml/min, (VIII) 160ml/min, (IX) 180ml/min, (X) 200ml/min.

Injector 4 is the biggest injector used in this experiment, it show bad spray behavior at low flow rate (below 140ml/min) injection compare to the injector no 2 and 3. Figure 4.1(d) shows good spray characteristic starting from 180ml/min. Thus, this injector is more convenient for high flow rate of injection (above 180ml/min).

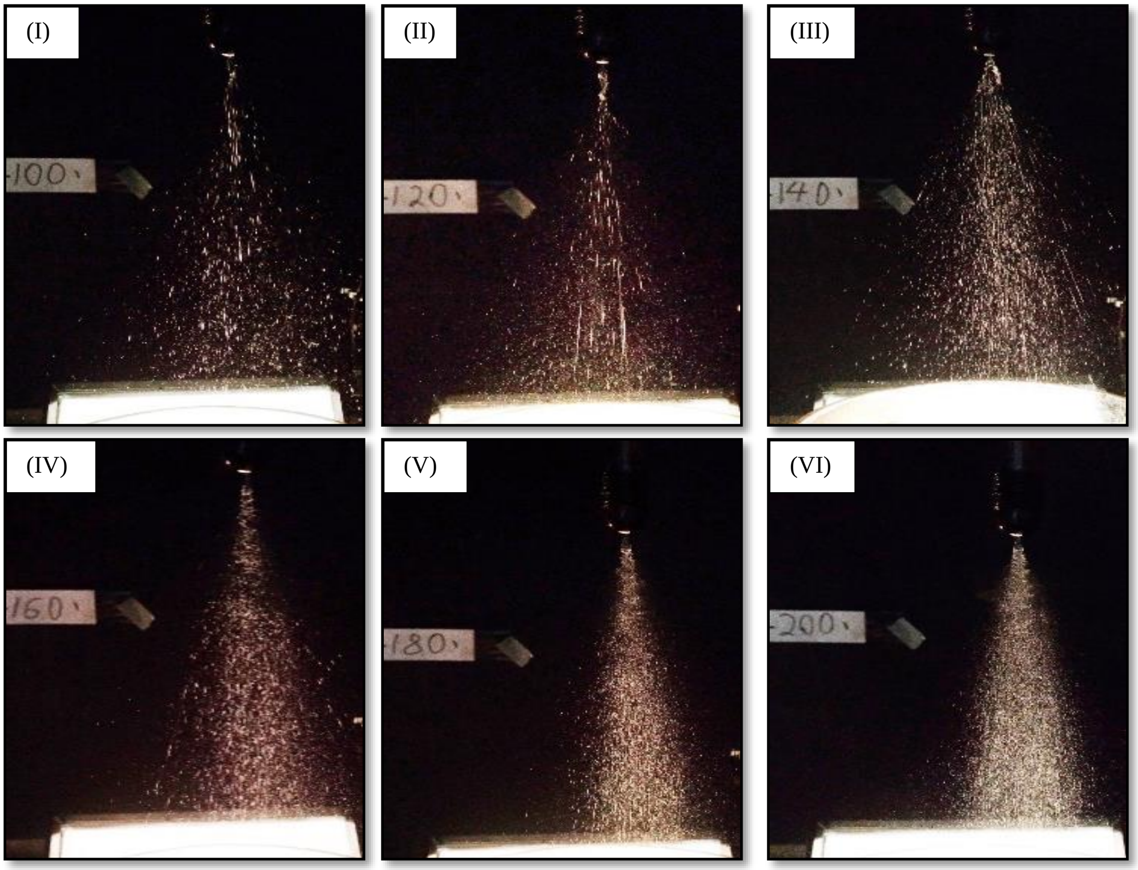

Figure 4.1(d): Injector 4 at (I) 100ml/min, (II) 120ml/min, (III) 140ml/min, (IV) 160ml/min, (V) 180ml/min, (VI) 200ml/min

Generally, as the flow rate of diesel inside the combustor increases, the speed of compressor coupled with turbine also increases and hence increase the air pressure and velocity into the combustor. Large pressure differences across the injector nozzle are required to have better spraying characteristic. In conclusion, injector 2 ,3 and 4 were selected to be used in combustion experiment. Both of the fuel injectors selected can perform well in the range of air pressure needed in the combustion experiment.

4.2 Relationship between the air pressure inlet combustion chamber with temperature, gas exhaust emission and fuel flow rate.

All the responding variables were measured experimentally using the described apparatus. Pressure of air inlet to the combustor depends on the resulting turbo-compressor regime, while the fuel flow rate was controlled manually by adjusting the frequency on the inverter. Table 4.2 shows the values of the responding variables for the combustion experiment.

Table4.2: Responding variable recorded from the experiment of performance of combustion chamber.

		Variables					
Air Pressure Inlet (bar)		Fuel flow rate (ml/min)	Air velocity (m/s)	CO emissions (ppm)	NOx (ppm)	Average Temperature (℃)
Injector 2 (2 US gal/h)	**0.2**	85.71	9.15	1500	07	756
	0.3	115.38	11.02	1300	07	746
	0.4	122.45	12.37	1700	05	813
	0.5	130.43	13.77	1400	01	977
Injector 4 (4 US gal/h)	**0.5**	123.83	14.02	1500	05	668
	0.6	141.2	14.40	1600	06	653
	0.7	157.89	17.10	1400	08	764
	0.8	173.95	18.02	770	08	867
	0.9	187.69	18.85	350	22	910
	1.0	203.45	19.70	95	31	997

Figure 4.2(a) shows trend of the fuel flow rate when the pressure of air inlet was increased. The fuel flow rate increases with the pressure air inlet for both injectors used. The maximum fuel flow rate for injector 2 was 130.43ml/min at 0.5 bar. This limitation of fuel flow rate is due to the pressure and temperature inside the combustor decrease the performance of the nozzle. For injector 4, the maximum value of the fuel flow rate at 0.5 bar was 123.83ml/min which is lower than value for injector 2 at 0.5bar.

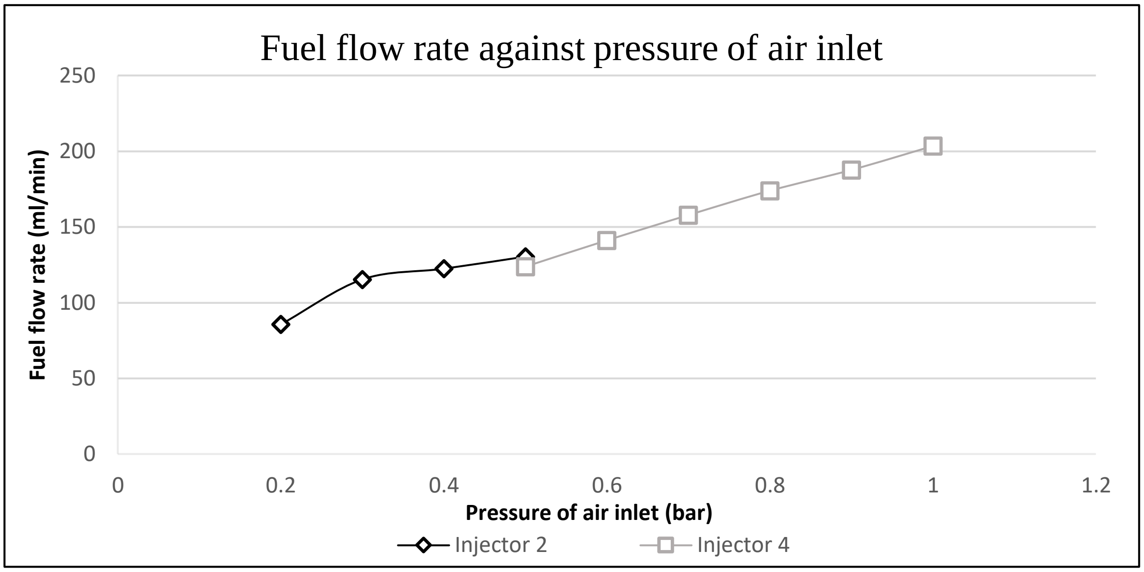

Figure 4.1(a): Diesel fuel flow rate

Figure 4.2(b) shows the air velocity with increasing air inlet pressure for both injectors. For injector 2 the minimum air velocity is 9.15 m/s and increases up to 13.77m/s, while the minimum air velocity for injector 4 was 14.02m/s and increases up to 19.70m/s. By referring Table 4.2 at 0.5 bar, the speed of air enter the inlet manifold by using injector 2 and 4 was about 13.77 and 14.02 respectively. These slight difference (about 0.25m/s) proves that the spraying performance does not affect the air velocity enter. Both of air velocity and fuel flow rate graphs show same pattern. When the fuel flow rate increases, it causes more intense combustion process inside the combustor, resulting in high kinetic energy forcing the turbine and compressor blades to spin faster. High speed of rotation by the compressor blade forces more air to enter the inlet manifold.

Figure 4.2(c) shows the graph of average temperature by increasing the pressure of air inlet. The MGT system underwent warming up session until the temperature at the primary combustion achieved above 600°C. The experiment was started at minimum air pressure at inlet for both injectors when the temperature display on the scanning thermometer was stable. For injectors 2 and 4 the experiments started the operation at 756°C and 668°C respectively. The temperature at the outlet of the combustor increases gradually with increases of fuel flow rate and pressure of air inlet but not more than 1000°C. The dilution air at the dilution zone managed to control the outlet temperature of the combustor from exceeding 1000°C. These range of temperature is matching with the temperature designed of the turbine blades, thus preventing the blades from damage.

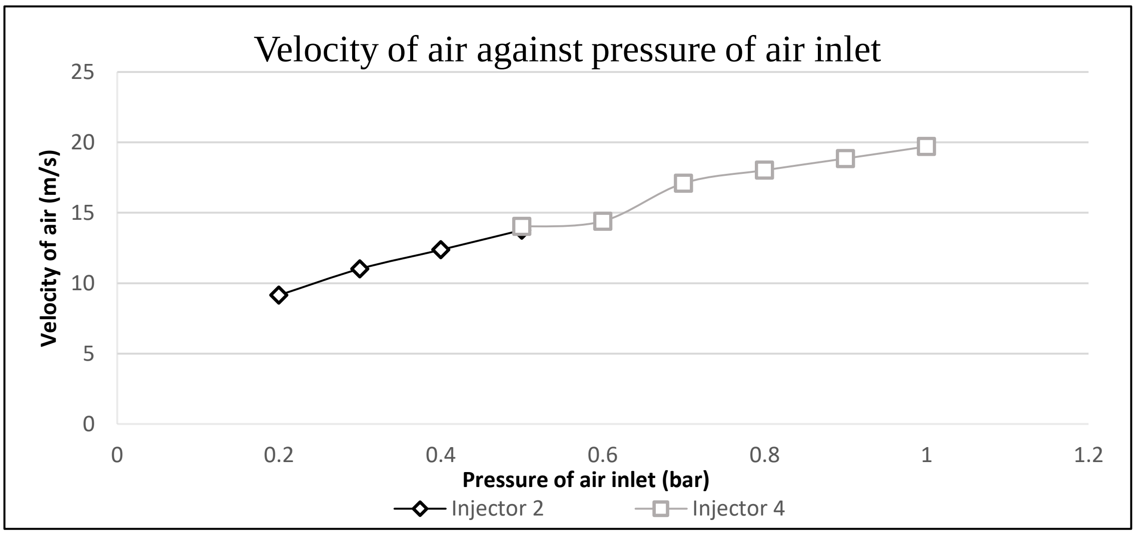

Figure 4.2(b): Velocity of air inlet

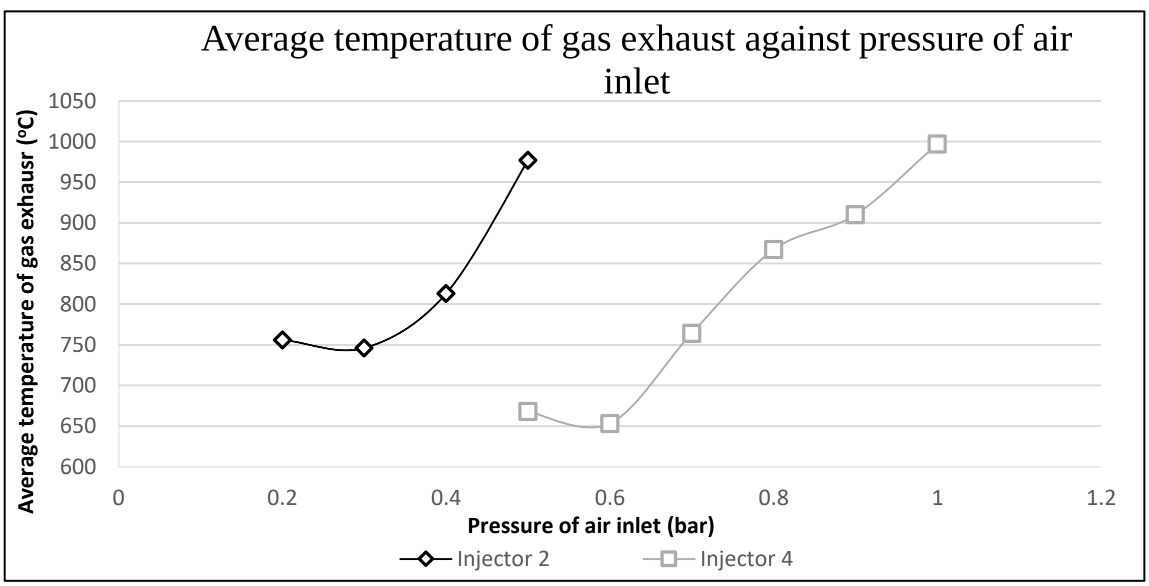

Figure4.2(c): Average temperature of the combustor outlet.

Figure 4.2(d) show the graph of CO emissions measured at the exhaust of the HRU exit. CO concentrations in this experiment was controlled primarily by the air/fuel ratio. For the experiment with injector 2, the value of CO concentration measured was high in the range of 1200 - 1700 ppm. This results indicates the combustion process insufficient oxygen and causes incomplete combustion. On other hand, the graph for injector 4 show decreasing trend from 1500ppm to 95ppm with increasing the air inlet pressure. This indicates the optimum pressure of air inlet of 1bar needed by the combustor for complete combustion. The lowest value of CO emission for this experiment is in the acceptable range of gas emission according to Department of Environment of Malaysia.

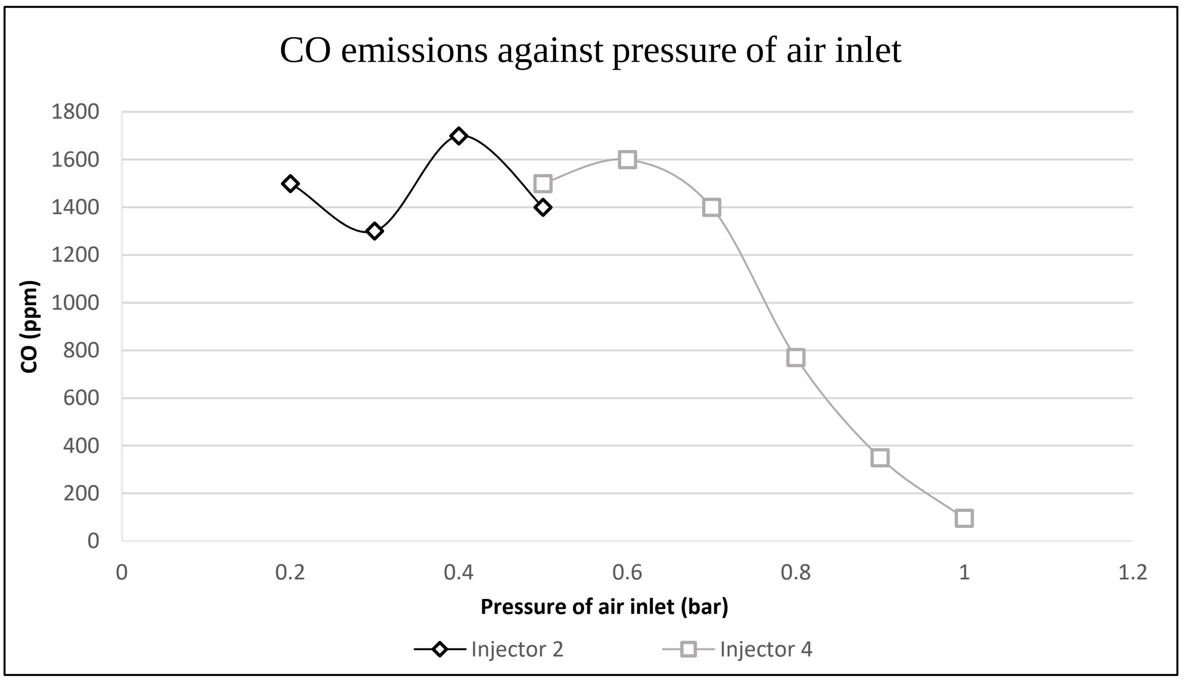

Figure 4.2(d): CO emissions.

Figure 4.2(e) shows the graph of NOx emission for both injectors. Theoretically, NOx formation will increase with excess air in the combustion zone due to the increasing flame temperature which is one of the factor of NO formation. Usually, thermal NOx is formed in the flame near the adiabatic temperature of about 1925°C [11].

For injector 2, the operating pressure (0.2 to 0.5bar) causes insufficient amount of air and does not contribute in the formation of NOx, the graph shows decreasing trend with increasing air inlet pressure. The highest value and lowest of NOx emission for this injector was about 7ppm and 1ppm respectively. However, injector 4 shows increasing trend with increasing air inlet pressure from5ppm to 31ppm. This range of pressure consist of high concentration of oxygen which causes the formation NOx.

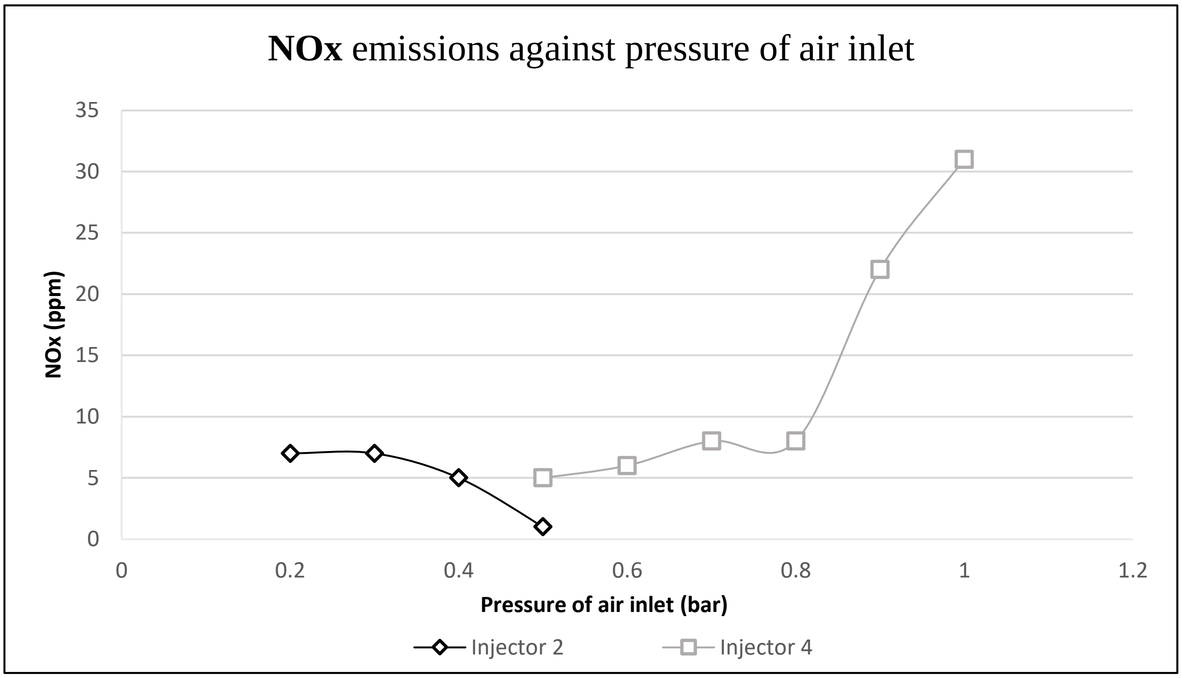

Figure 4.2(e): NOx emissions.

5. Conclusions

Optimum design of combustion chamber was fabricated and tested with Garrett turbocharger GT25. The system has been characterized with diesel fuel. The test showed low emission of CO and NOx can be achieved with sufficient amount of air and using high performance of liquid fuel injector (4US gal/h). The combustor design also managed to control the temperature outlet of the combustor from exceeding 1000^{o}C which can damage the turbine blade of the turbocharger. However, additional support for cooling at the dilution zone is needed to be studied as safety precaution if pressurized air entering the dilution zone is not enough. One of the suggestion is to install water injector with low flow rate at the dilution zone.

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