Experimental Study of Direct Water Injection Effect on NOx Reduction from The Gas Fuel

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ARTICLE INFO	ABSTRACT
	Direct Water Injection (DWI) is commonly used in many nitrogen oxides (NOx) emissions control applications due to its effect to reduce the adiabatic flame temperature. In this paper an experimental test rig is designed to study the effect of water injection spray inside a simulated gas turbine combustor from the gas fuel. The practical work introduced by the chemical reaction methodology followed by the experiment which was presented and discussed carefully. Results are obtained in term of the exhaust gas temperature and different injection parameters including position, direction and fuel mass flow rate on the nitrogen oxide emission value in PPM (Parts per Million) at different conditions. The results showed that the best water injection effect was obtained at 45° degree inside the primary air zone. Injection location has a major effect on the NOx reduction as the best injected location is the Primary air zone compared with the direct fuel nozzle tip due to the increase of the water droplets residence time inside the combustor and perform a vortex that will affect the reduction of exhaust gas temperature and NOx emission respectively. The huge impact was observed at LPG (Liquefied Petroleum gas) flowrate 2.7L/min and water to fuel ratio about 0.4 as the NOx value was decreased about 73% from almost 381 PPM to 73 PPM. The chemical reaction arrangement order methodology presented good agreement with the experimental results at different fuel flow rate and equivalence ratio. The chemical Reaction equations were implemented to calculate the different adiabatic flame temperatures which is experimentally known as the exhaust gas temperature and impacted directly the NOx emission results.

1. Introduction

Nowadays, issues such as global warming and pollution are one of the highest impact concerns for human life. Trials to improve the existing fuel combustion systems to reduce emissions have created one of the most important research fields in the combustion science. With the widely usage of gas turbines in power plants, strict laws are set in order to control their pollution. For example,

according to EU law for gas turbines, the maximum amount of nitrogen oxides (NO_x) and carbon monoxide (CO) emission allowed in dry mode is 25 PPMVD [1]. Natural gas is a better choice for a clean combustion due to the percentage of carbon dioxide (CO_2) emitted resulting from the combustion of this fuel is very low [2]. However, NO_x emission is the other barrier to deal with since the greenhouse effect of NO_x is even more than CO and CO_2 [3]. In the last half of the twentieth century, it has become apparently that nitrogen oxide (NO) is a major contributor of photochemical smog, acid rain and ground level ozone in the urban air [4]. Furthermore, NO_x participates in a chain reaction that removes ozone from the stratosphere with the consequence of increased ultraviolet radiation reaching the earth's surface. Ultraviolet (UV) rays can kill plant and animal cells, because even small amounts of UV light cause cell damage and induce skin cancer [5]. Consequently, minimization of NO production becomes a necessity in combustion systems. The oxides of nitrogen are formed mostly during the combustion of hydrocarbon fuels. From the many pollutants the nitrogen oxides deserve special attention because of their wide-ranging effects on tropospheric ozone production, and also because nitrogen oxides are amenable to reduction by process modification more than other air pollutants [6]. Comparing among the different NO_x products, the NO percentage is the highest one, so the nitrogen oxide emission (NO_x) is our concern in this paper. Recently, many researchers were studied the emissions and especially NO_x reduction from the gas turbines. Direct water injection is one of the effective methods to control positively the NO_x emission by decreasing the combustion temperature [7]. So, wet cycle is a way of reducing NO_x emissions from gas turbines. The humid air including the amount of moisture has inversely proportional with NO_x production. The temperature profile of the entering gas towards the gas turbine blades is the main factor which is affected the NO_x emission characteristics [8]. DWI with $\dot{m}_w/\dot{m}_f$ about 0.15 at turbine low load led to reduce NO_x emission values around 35% [9]. Water in gas turbine can be recycled from the compressor cooling and lead to a NO_x reduction [10]. The other method is a direct water injection in the gas turbine combustor. Studies showed that with the water injection at the rate of 0.4 of the total air flows, up to 50% of NO_x emission can be reduced [11]. The other important point is the proper water injection location and direction [12]. When the water is directly introduced into the ignition region (injected into combustion air zone), the NO_x formation is effectively reduced. Although of some general guidelines on direct water spray injection in gas turbine combustors, many features of this process still remain unknown probably due to a smaller number of studies were published on this topic. The proper values of water injection mass flow rate, angle, and location encountered in gas turbines are of special interest. In this research, the effects of water spray injection in the combustion chamber on the combustor are checked including the best location and tilting water injection angle and water injection mass flowrate to determine the best conditions are recommended to use while injection the water into the gaseous combustor to control the NO_x emissions.

2. Methodology

The chemical reaction has been done for the LPG domestic gas bottle which contains the used gas fuel (Propane- C_3H_8) in the Combustion Lab. Under Mechanical Power Department at Faculty of Engineering in Menia University, Egypt [13]. The given data is included in Table 1.

Table 1
LPG used fuel characteristics

Item	Value	Unit
Used Fuel-LPG domestic Bottle	80% propane C_3H_8	%
	20% butane C_4H_{10}	
	Assume for balanced chemical reaction, the fuel is propane C_3H_8	
Entrance Pressure Range	0.32 to 10	bar
LPG flowrate Range	5 to 1000	l/hr
	0.095 to 19	l/min.
LPG inlet Temperature	20	°C
LPG Volumetric to mass unit	1 Litre = 0.51Kg = 510 gram	L & gram
Air Volumetric to mass unit	77.3 Litre = 100 gram	L & gram
Oxygen density	1.323	Kg/m^3 at 20°C
LPG density	1.898	Kg/m^3 at 20°C

2.1 Chemical Reaction

The balanced equation for the complete combustion of propane C_3H_8 in air [23]

$$C_\alpha H_\beta + \left(\alpha + \frac{\beta}{4}\right)(O_2 + 3.76N_2) \rightarrow \alpha CO_2 + \frac{\beta}{2}H_2O + 3.76(\alpha + \frac{\beta}{4})N_2$$
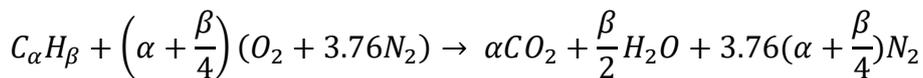
where, α is the number of carbon atoms in a molecule of fuel. β is the number of hydrogen atoms in a molecule of fuel. Then, for C_3H_8 chemical reaction balance

$$C_3H_8 + 5(O_2 + 3.76N_2) \rightarrow 3CO_2 + 4H_2O + 5*3.76N_2$$
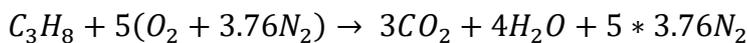
Accordingly,

The stoichiometric air to fuel by mole is

$$\frac{n_{air}}{n_{fuel}} = 4.76\left(\alpha + \frac{\beta}{4}\right) = 4.76*5 = 23.8$$

Also, the stoichiometric air to fuel by weight is

$$\frac{m_{air}}{m_{fuel}} = \frac{29.0*\left(\alpha+\frac{\beta}{4}\right)*4.76}{1*44} = \frac{29.0*5*4.76}{44} = 15.6863 \text{ kg air/kg fuel at T°Reference} = (25°C)$$

So,   (A/F) stoichiometric = 15.6863 kg air / kg fuel at T° = 25°C.
        (F/A) stoichiometric = 0.0637 kg fuel/kg air at T° = 25°C.

Then, the equivalence ratio $\varnothing$ is defined as the actual fuel/air mass ratio f divided by stoichiometric fuel/air mass ratio f_s.

$$\varnothing = \frac{F/A_{m.actual}}{F/A_{m.st}} = \frac{f_a}{f_s}$$

Accordingly, the Measured Points at Combustion Lab, Faculty of Engineering in Menia University at Egypt can be found in Table 2.

Table 2
Measured Points in the Experimental Test rig

LPG flowrate	l/min.	gram/sec.
Point 1	2.7	22.95
Point 2	4.8	40.8
Point 3	6.7	56.9
Point 4	10.5	89.2

The gas flowmeter at Faculty Lab is modified to measure the oxygen gas flowrate. So, to calibrate it to measure the LPG flowrate, the below calibration procedure calculation has been done

Qxygen Density = 1.323 kg/m^3 at temperature= 20°C
LPG density= 1.898 kg/m^3 at temperature= 20°C
So, Q Corrected (LPG)= Q Scale (Oxygen) * factor

$$Factor = \sqrt{\frac{\rho Scale}{\rho Corrected}} = \sqrt{\frac{1.323}{1.898}} = 0.83$$

Hence, the air flowrate in g/sec at Different Equivalence Ratio Ø and gas flowrate are included in Table 3 and the data summary at different equivalence ratio and measured combustion air supply flowrate can be found in Table 4.

Table 3
Combustion air measured points versus LPG fuel at Different Equivalence Ratio (φ)

Point No.	LPG g/sec.	Ø	Air g/sec.	Air g/sec. calculation = (A/F) stoichiometric * LPG g/sec.
1	22.95	1.1	325.5	= 14.11 * 22.95
		1.0	360	= 15.686 * 22.95
		8.0	432	= 18.82 * 22.95
		7.0	468	= 20.39 * 22.95
2	40.8	1.1	575.6	= 14.11 * 40.8
		1.0	640	= 15.686 * 40.8
		0.8	767.85	= 18.82 * 40.8
		0.7	831.9	= 20.39 * 40.8
3	56.8	1.1	802.8	= 14.11 * 56.8
		1.0	892.5	= 15.686 * 56.8
		0.8	1070.8	= 18.82 * 56.8
		0.7	1160.1	= 20.39 * 56.8
4	89.2	1.1	1258.6	= 14.11 * 89.2
		1.0	1399.2	= 15.686 * 89.2
		0.8	1678.7	= 18.82 * 89.2
		0.7	1818.7	= 20.39 * 89.2

Table 4
Volumetric flowrates of LPG fuel and Combustion air measured points

LPG l/min.	Ø	Air l/min.	LPG l/min.	Ø	Air l/min.
2.7	1.1	4.19	6.7	1.1	10.34
	1.0	4.64		1.0	11.53
	0.8	5.56		0.8	13.81
	0.7	6.03		0.7	14.91
4.8	1.1	7.42	10.5	1.1	16.22
	1.0	8.25		1.0	18.03
	0.8	9.89		0.8	21.62
	0.7	10.72		0.7	23.44

Afterwards, to calculate the adiabatic flame temperature of propane C_3H_8 air mixture flames at different equivalence ratios (0.7,0.8,1.0,1.1) complete and in-complete combustion. The following calculations were implemented as follow.

Chemical equation for stoichiometric burning of hydrocarbon in air for complete combustion is as follow.

$$C_xH_y + \left(x + \frac{y}{4}\right)(O_2 + 3.76N_2) \to x.CO_2 + \frac{y}{2}.H_2O + \left(x + \frac{y}{4}\right).(3.76N_2)$$
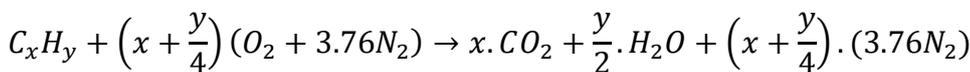
Stoichiometric Chemical equation for in-complete hydrocarbon combustion [28]

$$z.C_xH_y + \left(z.\left(\frac{x}{2} + \frac{y}{4}\right)\right)(O_2 + 3.76N_2) \to z.xCO + \left(\frac{z.y}{2}\right)(H_2O) + (z.\frac{x}{2} + \frac{y}{4})(3.76N_2)$$
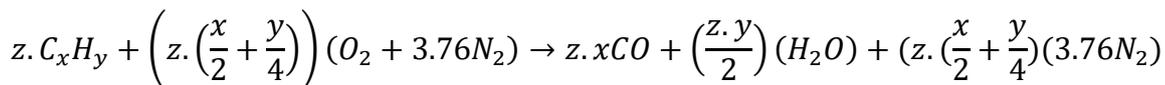
Then for adiabatic flame process,

$$\sum_R n_i \, (h_f^o + \Delta h)_i = \sum_P n_e \, (h_f^o + \Delta h)_e$$

Accordingly, $(\Delta h)_e$ is got at adiabatic flame temperature. Where

$$R \to Reactant \quad , \quad P \to Product \quad , \quad i \to initial$$

$$e \to exit \;\; , \;\; h_i \to initial \; enthalpy \left(\frac{kj}{kmol}\right)$$

$$h_f^o \to enthalpy \; of \; formation \left(\frac{kj}{kmol}\right)$$

$\Delta h_i = 0$ due to the initial temperature which equal the Reference temperature (Ti = 25°C).

At equivalence ratio $\emptyset = 1.0$

The balanced chemical equation

$$C_3H_8 + 5(O_2 + 3.76N_2) \to 3CO_2 + 4H_2O + 18.8N_2$$
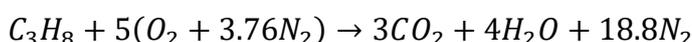
Hence,

$$h_f^o = 3(h_f^o)_{CO_2} + 4(h_f^o)_{H_2O} - (h_f^o)_{C_3H_8} + 18.8 \, N_2 \text{ - } 18.8 \, N_2$$

$$h_f^o \to the \; values \; of \, h_f^o \; can \; be \; get \; from \; the \; steam \; tables \; for \; h_f^o$$

$$h_f^o = 3kmol\left(-\frac{393,252kj}{kmol}\right) + 4kmol\left(-\frac{241,827kj}{kmol}\right) - 1kmol\left(\frac{104,700kj}{kmol}\right) = -2.043 * 10^6 \; kj$$

Then, the exit state at the adiabatic flame temperature is specified by

$$\sum_P n_e \, \Delta h_e = 2.043 * 10^6 \; kj$$

To calculate C$_P$, $\Delta h = C_P . \Delta T$, C_P can get from the steam tables,

$$\Delta h = \sum_P n_e \, \Delta h_e = \Delta T (3(C_P)_{CO_2} + 4(C_P)_{H_2O} + 18.8(C_P)_{N_2}$$

$$2.043 * 106 = \Delta T \, (3 * 40 + 4 * 30 + 18.8 * 30)$$

$$\Delta T = 2268 \; C$$

$$\Delta T = T_{Final} - T_{ref.(25 \, C)} = 2268 - 25 = 2243$$

Hence, the adiabatic flame temperature for propane-air mixture is 2243°C at $\emptyset = 1.0$. At Equivalence Ratio $\emptyset = 1.1, 0.8$ and 0.7 respectively and reference to the above chemical reaction equations, the adiabatic flame temperature results will be as described in Table 5.

Table 5
Adiabatic Flame Temperatures in Celsius Degrees (C) at Different Equivalence Ratio

Equivalence Ratio (Ø)	Adiabatic Flame Temperature (C)
1.1	2228
1.0	2243
0.8	2083
0.7	1924

3. Experimental Setup and Testing

3.1 Apparatus

An experimental test rig has been designed and constructed in the Combustion Lab, Mechanical Power Department, Faculty of Engineering, Menia University to study the effect of water injection at fuel nozzle tips and primary air with different operating conditions on NO$_x$ emissions from a prototype small gas combustor. In the present work, a water injection kit has been added to the setup model aiming to validate the effect of injected water at ambient air temperature on the NO$_x$ emissions from the gaseous flames. Water has been added through a clean calibrated stepwise glucose lash. Water is entered through a combustor with a different flowrates and different

inclination angles in the primary air and accordingly the NO$_x$ is examined. A schematic arrangement of the experimental test rig which is illustrated in Figure 1.

1. LPG Commercial Bottle.
2. Air Compressor.
3. Potable water Supply.
4. Digital Thermometer.
5. Flue Gas Analyzer.
6. Fuel Nozzle Tip.
7. Fuel Gas flow-meter&Flow Control.
8. Tap for Water injection in the fuel Nozzle tip.
9. Spare Tap.
10. Exhaust Temp, measurement tap.
11. Exhaust flue gases tap..
12. downstream LPG fuel inlet valve.
13. Upstream LPG fuel outlet valve.
14. Water interjection outlet valve into primary air.
15. Water injection outlet valve into the fuel Nozzle tip.
16. Water inlet supply valve.
17. Primary combustion air outlet valve.
18. Head water glucose lashes.
19. Combustion Chamber.
20. Gaseous Flame.

Fig. 1. Schematic of the Experimental Test Rig

The experimental setup consists of a combustion chamber (19), a fuel circuit, a combustion air circuit and a water injection unit. Combustion chamber is a tubular type premixed one [22]. It is mainly consisting of two parts. The first part is called the body of combustion chamber which consists of carbon steel cylinder of 10 cm diameter and 100 cm length with 5 mm thickness. There is one hole on the circumference with a 3 cm diameter of the body to fix the fuel nozzle. The second part of the combustion chamber is called the fuel nozzle (6) [18,19]. It is free with the casing of the combustion chamber and can be accessible for insertion and retract. It has an inlet diameter of 2 mm thickness and connected with stainless steel pipe considering the length is 50 cm and 2 cm diameter. Also, the top of the combustion chamber body is tapped and welded with a thread nut for 10 mm diameter for 4 holes, the distance between each hole to the other is around 20 cm and those holes used as measured points. In the fourth hole is connected with a small T- 90-degree pipe with diameter 1 cm and length 40 cm to be the measuring point (11) for the exhaust flue gas analyzer probe. The other holes are used for exhaust gas temperature recording, water injection hole (8) at the fuel nozzle fuel tips, one hole as a spare (9) and the last hole for the flue gas exhaust measuring point (10) to record the NO$_x$ [20]. Related to the fuel system, the LPG fuel is supplied from the commercial gas bottles (1) showed in (90% propane, 8% butane and 2% other species) through rubber hose and injected at fuel nozzle. The nozzle diameter is 5 mm. The fuel flow rate is regulated by control valve and its flow rate is measured by a rotameter from the medical regulators common type used to measure the oxygen gas (7), scale type is direct, high capacity and glass tube with the accuracy ± 5%. Also, the air is supplied to the combustion chamber from an air compressor (2) at the combustion faculty lab which manufactured by Ingersoll rand with a power of 150 kW and a centrifugal type. It provides the air to the combustion chamber for a fuel burning combustion. The discharge from the air compressor end is connected with the primary air pipe which is fitted into the fuel nozzle pipe by 45 degree angle and 10 cm before the nozzle tips, the connection is through a flexible hose and an air control valve (17)

to adjust the inlet air for the combustion process and measured the air flowrate with a similar rotameter of the gas fuel as well [23]. For the water injection kit, the water is injected through a clean glucose lashes with a calibrated ruler from 1 to 500 mm/min (18) and hanged on an ironed stand with a height 130 cm from the injection point to be simulated as a head tank [21]. A flexible hose is exit from the lash with a small injector at the end. Water supply into the lash is coming through a normal water source (3) at the combustion faculty lab and connected to the lash with a normal flexible hose (16).

3.2 Experiment (Test) Description

In the experiment, LPG commercial bottle was used as the fuel source. Flowmeter regulator was used to control the fuel flow rate through the fuel nozzle tube. Also, the fuel flow rate was measured using rotameter which is built up in the flowmeter regulator. The combustion air was supplied to the combustion chamber from a 150kW air compressor and was controlled the flow rate by butterfly valve and measured by a similar flowmeter of the gas fuel one. Water injection kit which consists of glucose lashes drops the injected water flow through a medical injector to make sure the droplets is entered the combustor directly in the fuel nozzle tips with a right angle 90 degree and also in the primary combustion air with a different inclination angles 30, 45, 90 and 135 degree in the shape of atomizing droplets to make sure no stagnation of the water flow inside the combustor and quenching the flame. The water droplets flowed into the combustor from a 130 cm height. Exhaust temperature was measured by using Chromel-Alumel thermocouple (K-type), their wires have 200 µm diameter and its normal measuring range is from 0 to 1370°C with digital thermometer (4). The thermal NO formation was measured by using the gas emission analyzer from the port of gas sample heated handle with length 0.9 ft and hose 11.5 ft and measure the NO_x through a gas emission analyzer (5) [24,25].

3.3 Experimental Procedures

The main specified measurements in the present work are the recording of the NO_x emission concentration in ppm, Exhaust Temperature in degree C, LPG flowrates in l/min and injected water in l/min as well. This is to establish experimentally the effect of normal water injection on NO_x emission at different water injection flowrates related to LPG fuel and also diff inclination injected angles at different locations at fuel nozzle tips and primary air from a typical small gas combustor. Some of preparations have been carried out before starting the experimental test, such that

   i.   The zero-level reading for the LPG pressure regulator rotameter was checked.

   ii.   The digital temperature thermometer was checked by transfer the push button from C to F and in opposite and also connected the K type thermocouple in both TC1 and TC2 to make sure the accurate reading.

  iii. NO_x analyzer was checked by pressing zero calibration pushbutton which is taking around 5 minutes, then it will be ready for measuring the NO_x readings.

Just make that preparation, the air compressor is running, then its control valves were partially opened that give the specified combustion air related to the different LPG fuel flowrates per the measuring points. The LPG fuel valve was opened until the combustion takes place and then adjusts the fuel flow rate such that rotameter read the specified different flow rate needed from of 2.7 to 10 l/min. In addition, the water injection kit was checked externally at first by make sure it's filled and a source of water is available and make sure the injector is discharged an atomized water droplet, then the injector was put in the targeted location whether directly at fuel nozzle tips or at the primary

combustion air. It may take care to give enough time for the stability of all measuring instrument and the test rig every time for each experiment test conditions.

4. Results and Discussion
4.1 Introduction

In this study, commercial LPG propane is considered for combustion at different values of fuel flowrates and percentage of volumetric injected water related to the fuel flowrate in both direct fuel nozzle tip and the primary combustion air stream at different inclination angle. Global reaction was schemed with the propane-air mixture at stoichiometric to study the chemical reaction of the products from the hydrocarbon fuel.

4.2 Effect of NOₓ And Exhaust Temperature at Different LPG Fuel Flowrates

Figure 2 showed that by increasing the LPG fuel flowrates from 2.7 l/min to 15 l/min. The Exhaust Temperature is proportionally increased from 233 to 499°C alongside will get the NO_x emission is proportionally increased from 215 to 477 ppm as part of the thermal NO which is directly affect proportionally with the adiabatic flame temperature that results experimentally in the Exhaust Temperature. This result is in agreement with Serrano *et al.,* [14].
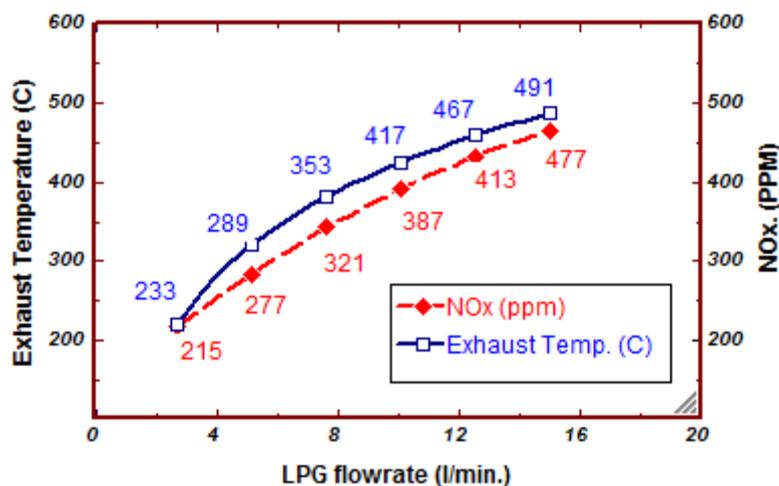
Fig. 2. LPG flowrate VS. NO_x and Exhaust Temperature

4.3 Effect of NOₓ And Exhaust Temperature with Injected Water Directly at Fuel Nozzle Tip

Figure 3 showed that at varying of injected water flowrate related to LPG fuel flowrate at 2.7 l/min. from 0.2 to 0.6 is affecting the exhaust temperature to be reduced from 418 to 173°C that at injected water ratio from 0.2 to 0.4 but at 0.5 and 0.6 injected water ratio, it has been observed that the exhaust temperature is start increasing gradually again to be reached to 187 and 197°C respectively, as a consequence the NO_x has been affected also to be reduced from 302 to 92 ppm at injected water ratio from 0.2 to 0.4 and start increasing gradually again at 0.5 and 0.6 injected water ratio respectively, to be reached up to 135 and 156 ppm. The conclusion here that the effect of injected water into the fuel nozzle tips directly can be observed for NO_x reduction up to 0.4 W/F ratio. After that, with any increase of injected water ratio, there is no obvious effect with the increased water flowrate because there is no enough residence time for the evaporation of the water especially with large size droplets of the water instead of the atomizing shape so there is no efficient heat

transfer that will could help the exhaust temperature to be reduced and as a consequence will not affect to reduce the NO_x emission with the increased water injection over 0.4 W/F ratio.
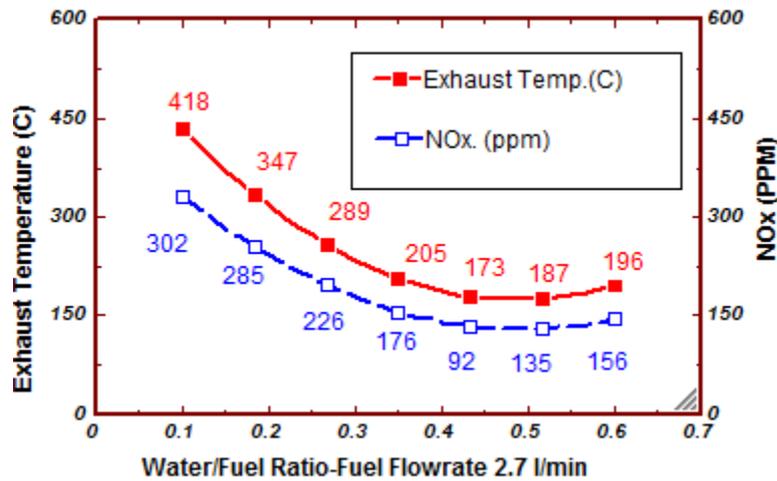
Fig. 3. NO_x and Exhaust Temperature at Different Water Injection at LPG flowrate 2.7 l/min

Figure 4 showed that with increased LPG fuel flowrate to be 5.5 l/min. as the exhaust temperature is rapidly decreased from 508 to 292°C with injected water ratio from 0.2 to 0.4 then after that with W/F ratio 0.5 and 0.6 the Exhaust Temperature is start increasing gradually again to be 317 and 336 ppm accordingly the NO_x is rapidly decreased as well from 482 to 215 ppm at injected water ratio 0.2 to 0.4 then it tends to increase gradually again at 0.5 and 0.6 W/F ratio to be 284 and 326 ppm. The results in Figure 2 and Figure 3 are in agreement practically with Farokhipour *et al.,* [15].
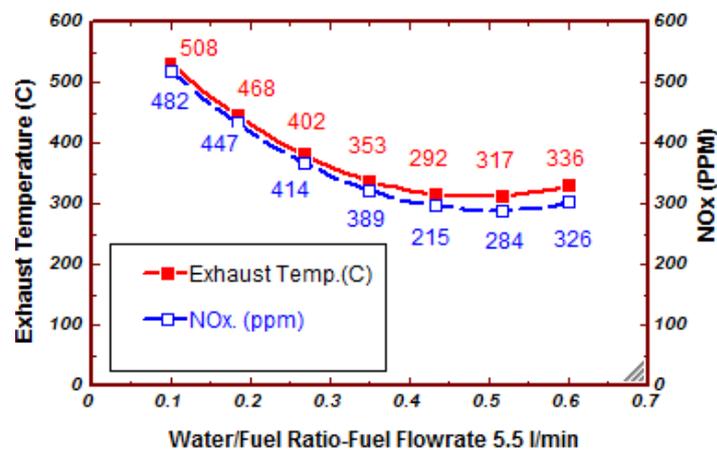
Fig. 4. NO_x and Exhaust Temperature at Different Water Injection at LPG flowrate 5.5 l/min

4.4 Effect of NO_x And Exhaust Gas Temperature with Diff Injected Water at Different LPG Fuel Flowrates at The Primary Combustion Air with Different Inclination Angles

Figure 5 to Figure 10 showed that the best injection location is to be at the primary combustion air instead of directly to the fuel nozzle tips as the initial stage of reaction had proceeded to completion accordingly the reduction in Exhaust Temperature will be more effective and lower the NO_x will be as a consequence of Exhaust Temperature Also having the water injection in the combustion primary air will help to increase the water droplets residence time inside the combustor

and perform a vortex that will lead to reduce the exhaust gas temperature and NO_x emission respectively. On the other hand, the best injection location as explained and inclination angle will be at the primary air zone and water injected angle degree around 45°. The reason that at 45° as the better water droplets distribution will be approximately at this degree. Also, the larger magnitude of the gas droplet relative velocity will be around 45° as well that will lead to a better evaporation rate and a real intense breakup of the NO_x components to reduce finally the NO_x emissions.

Also, we can observe in the experiment results from Figure 4 to Figure 9 that the direct water injection angle at right side 90° is less effective than at 135° as the water droplets velocity is not larger enough and accordingly the evaporation rate will be less in addition to the water droplets size will be larger at this case and doesn't have a chance to be atomized for more distribution so the water droplets will be stagnant and fall inside a combustor with no effect due to the gravity by the water weight at this case.
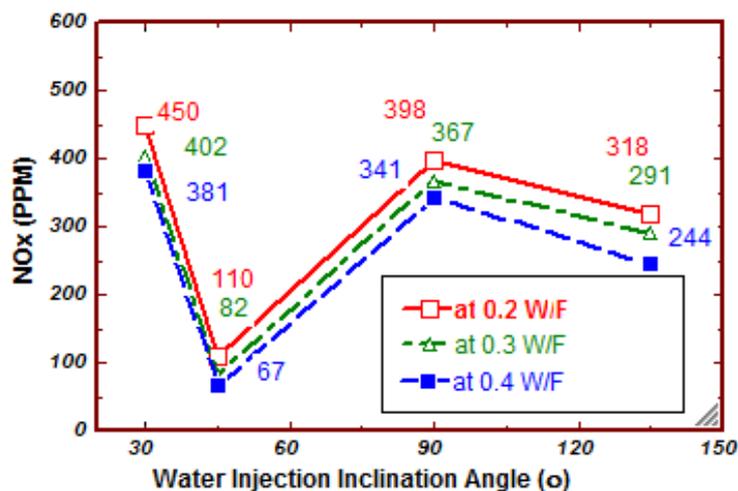
Fig. 5. NO_x at Different WI Inclination angles at LPG 2.7 l/min
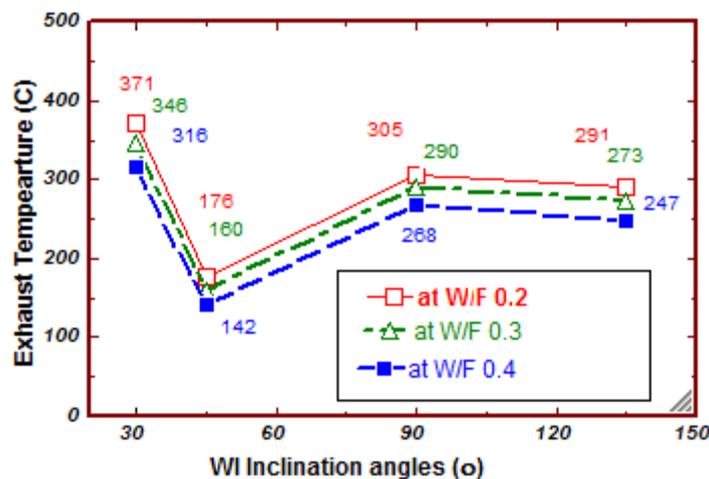
Fig. 6. Exhaust Temperature at Different WI Inclination angles at LPG 2.7 l/min
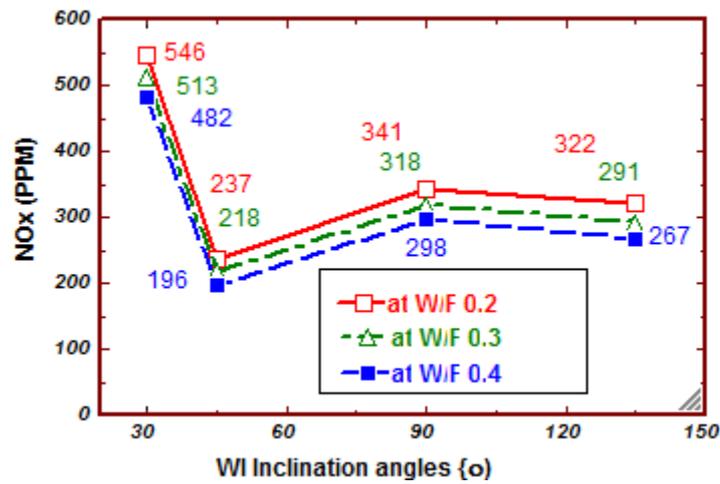
Fig. 7. NO$_x$ at Different WI Inclination angles at LPG 5.5 l/min
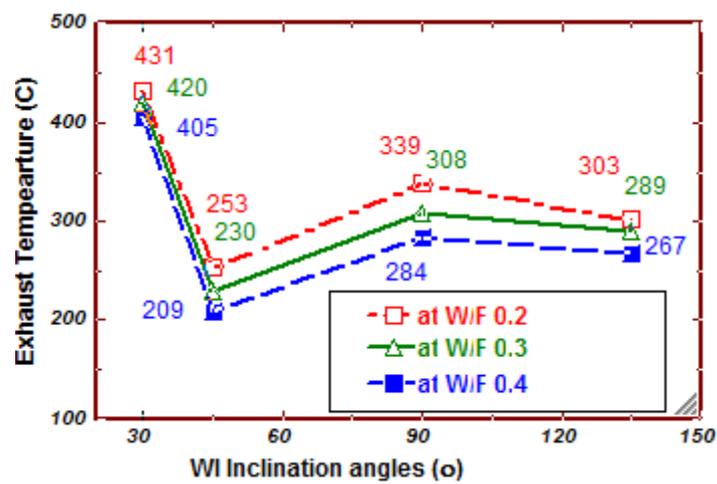
Fig. 8. Exhaust Temperature at Different WI Inclination angles at LPG 5.5 l/min
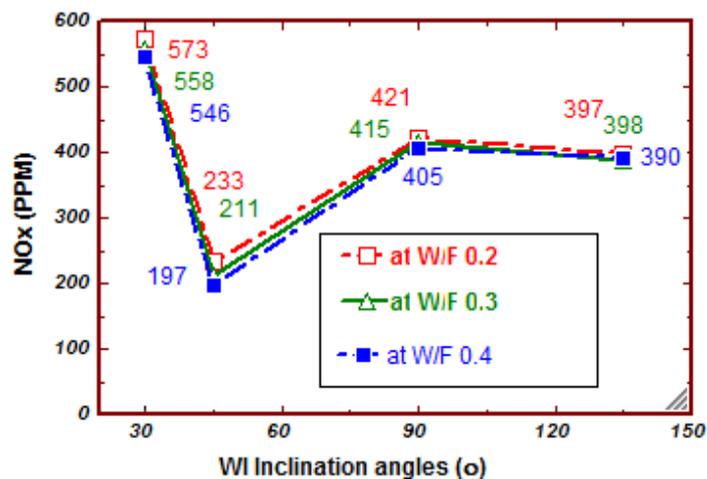
Fig. 9. NO$_x$ at Different WI Inclination angles at LPG 8.0 l/min
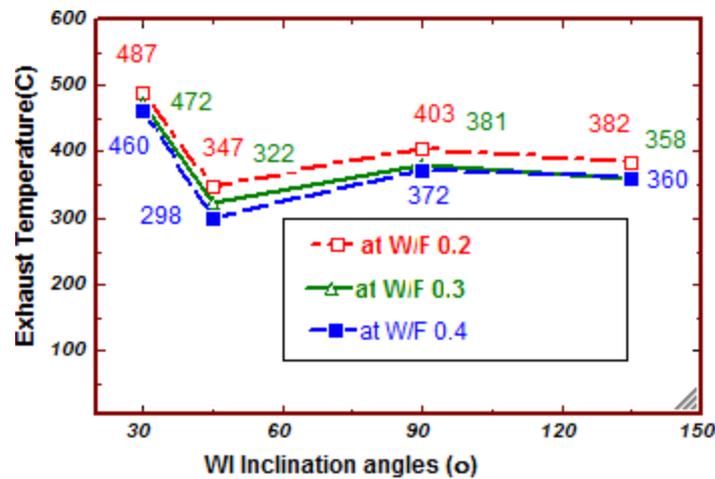
Fig. 10. Exhaust Temperature at Different WI Inclination angles at LPG 8.0 l/min

Another observation that the NO$_x$ reduction value will be larger with more water injection rate up to 0.4 W/F ratio at fixed LPG fuel flowrate as the result of the Exhaust Temperature Effect that will be gradually increased with more water injection W/F ratio. As the water injection distribution will be less and the water droplets will be stagnated in the combustor with less evaporation rate that will lead to an inverse effect on the NO$_x$ emission. The results are in agreement practically with Pavri and Moore [8].

4.5 Effect of NO$_x$ With Different LPG Fuel Flowrates at Fixed W/F Ratio in Line with Different Water Injection Inclination Angles

In Figure 11 to Figure 13, it could be observed that NO$_x$ emission is getting more with increasing LPG fuel flowrate at fixed water injection flowrate, at LPG flowrate from 2.7 to 8.0 l/min. with W/F 0.2 at different injected water inclination angles. The NO$_x$ values varying from 110 to 450 ppm at fuel flowrate 2.7 l/min. and from 237 to 546 ppm at fuel flowrate 5.5 l/min. and from 233 to 573 ppm at fuel flowrate 8.0 l/min. and also the same behavior at W/F ratio 0.3 as the NO$_x$ at fuel flowrate 2.7 l/min. is varying from 67 to 381 ppm, at 5.5 l/min. the NO$_x$ is changing from 298 to 482 ppm and at 8.8 l/min. the NO$_x$ is varying from 211 to 558 ppm. Finally, at W/F ratio 0.4 the NO$_x$ is between 67 to 381 ppm at Fuel 2.7 l/min at Fuel 5.5 l/min. the NO$_x$ is varying from 196 to 482 ppm and at the end at fuel 8.0 l/min. Then, NO$_x$ value is between 197 to 546 ppm. The reason the Exhaust Temperature is rapidly increased with more fuel flow rate. Also note that all of these values considering that the best NO$_x$ reduction value at the three conditions W/F ratio 0.2, 0.3 and 0.4 is at injected water inclination angle 45° due to the explained reason before. The results are in agreement practically with Ayed *et al.,* [16] and Luo *et al.,* [17].
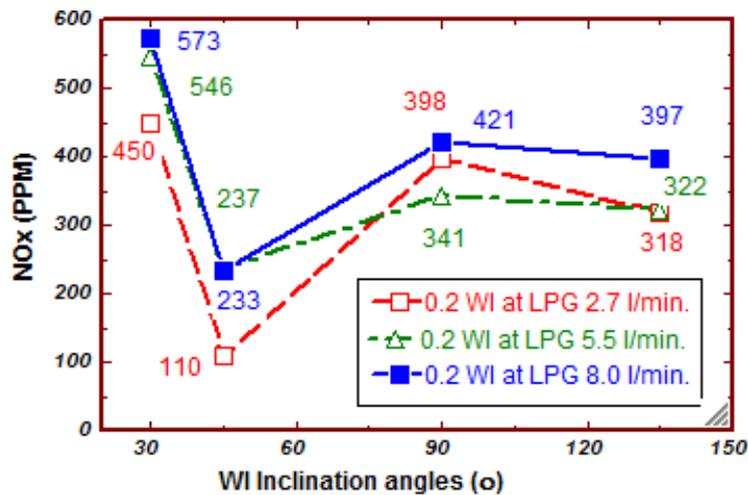
Fig. 11. NO$_x$ at Different WI angles & LPG flowrates at W/F 0.2
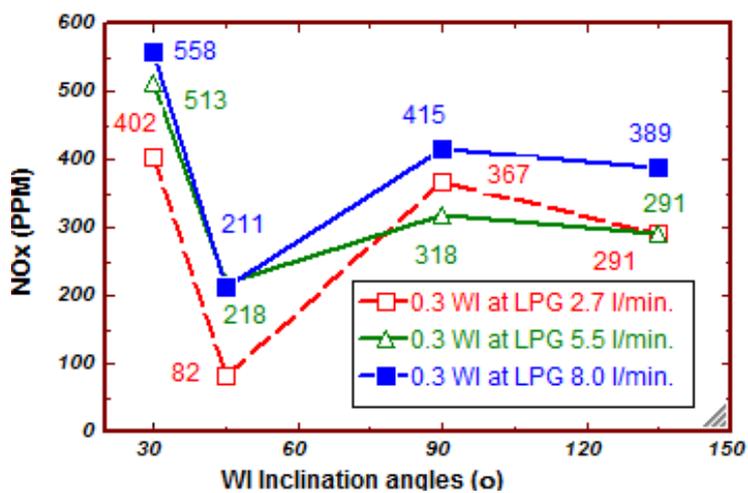
Fig. 12. NO$_x$ at Different WI angles & LPG flowrates at W/F 0.3
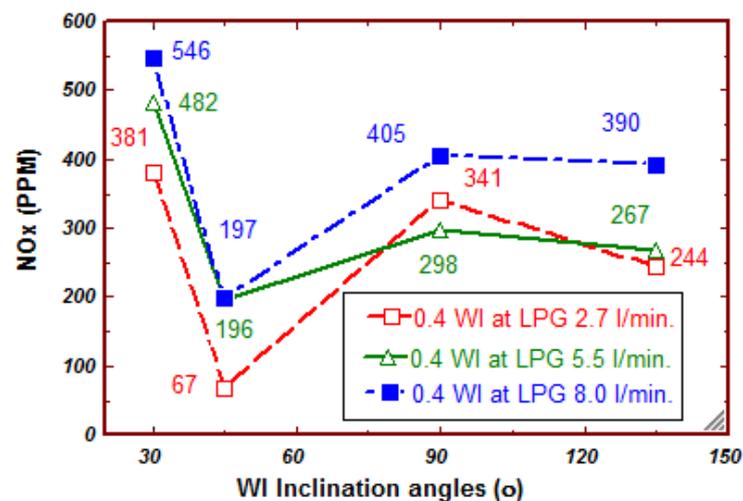
Fig. 13. NO$_x$ at Different WI angles & LPG flowrates at W/F 0.4

5. Conclusion

Direct water injection effect on NO_x reduction from the gas fuel is investigated experimentally. It can be concluded that

i. Adiabatic flame temperature which is directly related to exhaust gas temperature experimentally and LPG fuel flowrate are the major effective parameters on NO_x formation.

ii. Injection location has a major effect on the NO_x reduction as the best injected location is the primary air zone compared with the direct fuel nozzle tip due to the increase of the water droplets residence time inside the combustor and perform a vortex that will affect the reduction of exhaust gas temperature and NO_x emission respectively.

iii. The best water injection Inclination angle is at 45° due to the better water droplets distribution at this degree. Also, the larger magnitude of the gas droplet relative velocity will be around 45° as well that will lead to a better evaporation rate and a real intense breakup of the NO_x components to reduce finally the NO_x emissions.

iv. The direct Water injection angle at right side 90° is less effective than at 135° to reduce the NO_x emission as the water droplets velocity is not larger enough and less evaporation rate in addition to the water droplets size will be larger at this case. There is no chance to be atomized for more distribution so the water droplets will be stagnant and fall inside a combustor with no effect due to the gravity by the water weight.

v. NO_x reduction value will be larger with more water injection rate up to 0.4 W/F ratio at fixed LPG fuel flowrate as the result of the Exhaust Temperature effect that will be gradually increased with more water injection W/F ratio. As the water injection distribution will be less and the water droplets will be stagnated in the combustor with less evaporation rate that will lead to an inverse effect on the NO_x emission.

Based on the above conclusion, it can be concluded that WI (Water Injection) is an effective method to reduce the NO_x emission from gaseous fuel flames used for gas turbines considering the injection area, location and the inclination water injected angle.

For the experimental study, the measurements of experimental air flowrate were done using the same model of fuel flowmeter after recalibration considering the air temperature and density. So, the variation results with the theoretical chemical reaction was about 3%.

The other compositions of the real LPG gas bottle composition were neglected except the C_3H_8 propane used gas that was adopted in the chemical reaction calculation as it's all considered about 7 to 9% from the whole chemical compositions.

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