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Experimental Investigation on the Emission Characteristics of a Dual – Fuel Micro Gas Turbine by Injecting Ethanol into Compressor Inlet Air

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Abstract

Pollutants generation is strongly dependant on the firing temperature and reaction rates of the gaseous reactants in the gas turbine combustion chamber. An experimental study is conducted on a two-shaft T200D micro-gas turbine engine in order to evaluate the impact of injecting ethanol directly into the compressor inlet air on the exhaust emissions. The study is carried out in constant speed and constant load engine tests. Generally, the results showed that when ethanol was added in a concentration of 20% by volume of fuel flow; NO_x emission was reduced by the half, while CO and UHC emissions were almost doubled with respect to their levels when burning conventional LPG fuel alone.

Keywords: *Alcohol gas turbine, Renewable fuels, Exhaust emission control, Inlet cooling.*

1. Introduction

The increasing awareness towards environment protection and peak load response is accredited in the development of gas turbine system. Gas turbines use large amounts of petroleum-based fuel and cause significant air pollution; nevertheless, they play a very important role in minimizing greenhouse gas emissions as they typically burn lower carbon fuels compared to other types of combustion-based power generation and mechanical drive applications [1].

The primary pollutants from gas turbine engines are nitrogen oxides (NO_x), carbon monoxide (CO), and to a lesser extent, volatile organic compounds (VOC). Particulate matter (PM) is also a primary pollutant for gas turbines using liquid fuels. NO_x formation is strongly dependent on the high temperatures developed in the combustor. CO, VOC and PM are primarily the result of incomplete combustion. Ash and metallic additives in the fuel may also contribute to PM in the exhaust. Oxides of sulphur (SO_x) will only appear in a significant quantity if heavy oils are fired in the turbine. Emissions of SO_2, are directly related to the sulphur content of the fuel [2].

Blending of bio-fuels with fossil fuels is a more economic option to provide renewable power. All of the current liquid bio-fuels used exhibit a lower heating value less than petroleum-based fuel; thereby requiring a step increase in fuel flow of 10 to 50% to deliver the same power output. The emission levels with liquid fuel like kerosene or gaseous like natural gas may be reduced by addition of oxygenated fuels like alcohol. Ethanol, hydrous or anhydrous, has already been tested in gas turbines and found to be a more sustainable source of renewable liquid fuel than other bio-fuel crops [3].

Bio-ethanol is distributed in Sweden as a substitute for petrol and goes by the name of E85 (85 % ethanol and 15 % petrol). It can be tricky to store, because of its miscibility with water and the low flash point temperature of 13^{o}C. Ethanol is a volatile, combustible, clear and colourless liquid in room temperature and it has a distinct well known smell and taste. Ethanol is the most widely used liquid bio-fuel which on 2009, accounted for more than 94 % of the global biofuel production [4].

Micro gas turbines can serve as stand-by generators in case of emergency or lack of power production when the National Electricity Grid like that locally utilized fails to support the growing demand on electricity. Micro gas turbines can replace the conventional reciprocating generators those burning the liquid petroleum fuels. The use of the ethanol/LPG fuel mixture in such engines might suppress the pollutants emission and mitigate their environmental impact.

This work unlike the proceedings which add ethanol to the conventional petroleum fuel via blending, but, the liquid ethanol here is directly introduced into the inlet air by a separate injection system. Thus, this technique has the advantage of avoiding the harmful effects of ethanol on seals and gaskets of conventional fuel system if straight blended with the petroleum fuel.

2. Literature Survey

The concept of using water and alcohol/fuel microemulsions for the purpose of reducing smoke emissions from jet engine was studied in a T-63 gas turbine combustor. The base fuels JP-4 and JP-8 with appropriate surfactants were used to prepare several ethanol and methanol microemulsions in concentrations ranged from 20 to 40%. Water microemulsions were also prepared with these base fuels for a range of 15 to 30% water in fuel. These blends increased CO and UHC, while NO_x was reduced when the surfactant did not contain nitrogen. The reduction in smoke correlated with changes in the H/C ratio of the fuel blends. Ethanol/fuel blends were most effective in reducing smoke from the standpoint of cost , operational , and systems effects [5]. A blend of ethanol/Jet A fuel with concentrations ranging from 25 to 100% ethanol by volume was tested for thrust specific emission indices of CO and NO_x over a range of throttle settings. The NO_x emission for the ethanol/Jet A blends was lower than that of pure Jet A due to lower turbine inlet temperature [6].

Kerosene/ethanol blended fuel has been experimentally investigated on the micro-gas turbine unit Gilkes GT 85/2 with a concentration level up to 25% ethanol [7]. The UHC emission increases with increasing ethanol addition, while the CO emission gives the minimum levels in the equivalence ratio range of 0.1 to 0.2, with 10% of ethanol addition. Thus, it may be concluded that the ethanol addition in the range of 10 to 15% in kerosene fired gas turbine unit will certainly offer reduced emission levels.

General Electric (GE) Energy's Aeroderivative class of gas turbines has tested ethanol among many other biofuels to evaluate its sustainability as fossil fuels substitute, and its environmental impact [3]. Tests indicated a need for 30% increase in fuel flow concerning the combustion chamber and injectors redesign for burning the much lighter fuel. Ethanol produces less NO_x because it burns with a lower flame temperature and it has oxygen available to burn more completely. The study also addressed the hazardous effects of using ethanol which normally contains 2-8% water that may have alkali metals, which are corrosive to the hot gas path of the turbine. GE Co. has been contracted by Petrobras to convert one of the two units at a power plant near Rio de Janiero to burn ethanol [8]. A 43.5 MW, LM6000 gas-fired plant is believed to be the first power plant in the world powered by ethanol. After five months of testing sugarcane ethanol, it was found that NO_x emissions had been greatly reduced, while efficiency and power levels remained the same.

The environmental impact of bio-fuels has been evaluated in an academic study showed that when ethanol was used, the NO_x emissions became half of that with naphtha. But, CO_2 has increased as the fuel consumption was higher. In general, the study stated that the emissions with ethanol are 48 % of that of diesel; the lowest of any fuel. Further, the change to ethanol probably would extend the gas turbines life expectancy with 100 % [4].

It is a common practice to use excess air to control the combustion temperature. But, this excess air can be reduced if methanol vapour reformed by the turbine wasted heat is injected into the combustion gas [9]. This scheme was found superior to control NO_x generation while keeping the inlet turbine temperature at 1100^{o}C. The air, as auxiliary medium was replaced with ethanol-water compound steam that produced with waste heat of a Capstone C33 gas turbine. Ethanol mass flow was increased up to 10% presenting the expected cooling on the inlet temperature. CO and UHC levels were increased by 64 and 59% respectively, while NO_x levels were reduced by 41% [10].

The current work studies the effect of adding ethanol in concentrations of 10% and 20% by volume to the combustion air, on the NO_x, UHC and CO emissions of a micro gas turbine engine. Introducing ethanol prior to the compressor gives enough time for liquid ethanol to vaporize and mix with the compressed air such that ethanol / air mixture is well prepared to react soon after entering the combustor. This technique will certainly reflected on the pollutants emission from the engine.

3. Experimental Setup

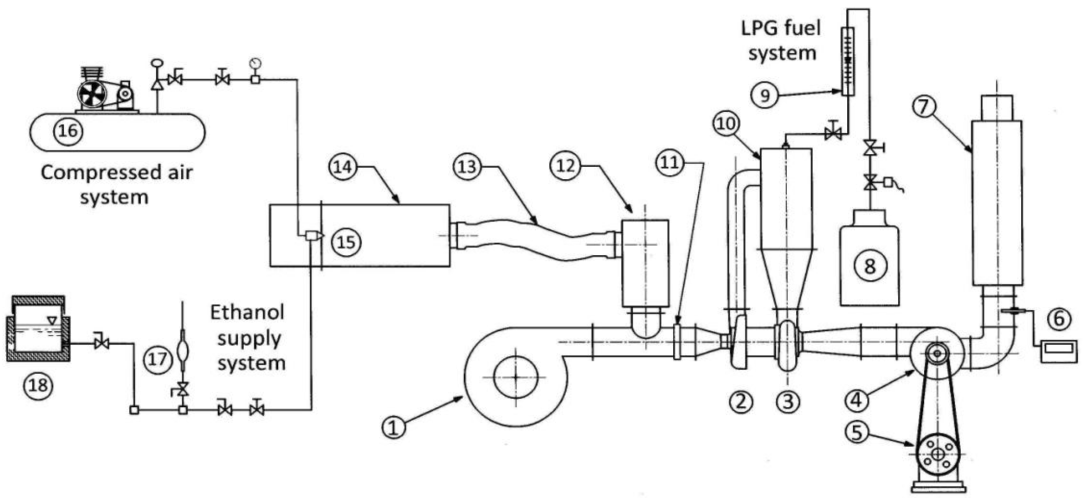
3.1. Test Rig

A rig has been constructed specially to introduce ethanol in the way of the incoming inlet air such that to reduce its temperature in the sense of controlling exhaust gas emissions. The experimental rig shown in Figure (1) is mainly a duct that inducing the ambient air inside to pass across the sprayed ethanol source and driving the treated air down to the gas turbine inlet. At the end of the spray chamber, an air atomiser was installed to create a mist of fine ethanol droplets travelling downstream along with the air draught. The ethanol atomiser has an orifice diameter of (1.2 mm), and it is working at a safe pressure of (4 bar).

The gas turbine used in this study is a Two-Shaft T200D micro-gas turbine unit fabricated by *Didacta Italia* which specifications are given in the Appendix. The combustion chamber burns the *LPG* gaseous fuel that ignited by a spark plug. Ethanol needs to be introduced in such a way that no disturbance is created within the air flow into the unit components. The above task can be satisfied by means of inlet injection as ethanol easily mix and penetrate the bulk flow of air. The attachment of the gas turbine unit with the spraying system is done by adding the "Admission Box" which encloses the machine inlet matrix to decelerate and separate the non-evaporated droplets escaping out of the treatment duct before entering the unit.

The exhaust emissions of the unit have been measured by extracting samples out of the gases leaving the power turbine. The gas analyser used is manufactured by *HEPHZIBAH* Co., model AIRREX HG-540 with measuring range up to 10000 ppm and a resolution of 1 ppm. The analyser equipped with a sampling probe that installed between the power turbine exit and the exhaust silencer. The samples are directed to the processing unit of the analyser which displaying digitally the level of each pollutant on LCD screen.

The study comprises the performing of experiments on the micro-gas turbine unit supplied with ethanol/LPG dual fuel at concentrations of 10 % and 20% ethanol by volume. The purpose is to track the changes in NO_x, UHC and CO emission levels as ethanol being sprayed in the intake air of the unit.



1	Starting blower	7	Exhaust silencer	13	Flexible conduit
2	Gas generator compressor	8	LPG fuel vessel	14	Treatment duct
3	Gas generator turbine	9	LPG fuel flow meter	15	Ethanol atomiser
4	Power turbine	10	Combustion chamber	16	Compressed air plant
5	Dynamometer	11	Orifice air flow meter	17	Ethanol bulb flow meter
6	Exhaust gas analyser	12	Admission box	18	Ethanol reservoir

Fig. 1. Experimental Set-Up Showing the Spraying System Attached To the Gas Turbine.

3.2. Testing Procedure

The tests are initiated with running the machine on the conventional LPG fuel in the sequence described in reference [11]. Each test is targeted to evaluate the engine exhaust emissions under the intended operating condition. Switching to dual fuel run needs firstly to reduce the LPG flow rate in accordance to the prescribed volume ratio. Secondly, the ethanol fuel is to be supplied into the inlet air in the required volume ratio and brought the ethanol vapour into the combustion chamber. Nevertheless, this process is very difficult since the two fuels are come from separate streams such that the combustion chamber acts as a mixing box for them. A good approximation is to deliver the two fuels in amounts determined on basis of the heating value to compensate the reduction in the heat liberated due to lower ethanol heating value. However, practically this is not enough because of the unexpected losses accompany the real engine run. Slight changes in both fuels flow rates must be done very slowly to keep the volume mixing ratio while attaining the intended condition with the adequate total mass flow of the dual fuel.

Due to this prolonged complicated process, some deviations from the nominated volume ratios are to be accepted, although, these deviations were actually marginal. The maximum deviation recorded in the worst cases was on the lower limit of nominal 10% ethanol which gave a ratio of 9.74% representing a deviation of – 2.6%. On the other hand, the upper limit of nominal 20% ethanol in dual fuel gave a ratio of 21.2% representing a deviation of + 6.1%. However, all other tests were accomplishing volume ratios with deviation never exceeded $\pm$ 1.5%.

4. Results and Discussion

Experiments were first conducted to estimate the variation in exhaust emissions with the power turbine speed. These tests were carried out under a constant load of 65% of the engine full load.

Figure (2) shows the reduction in NO_x emission with increasing power turbine speed due to the decrease in residence time and better air utilization in combustion chamber. Ethanol presence in the air delivered to the combustion chamber will lower the firing temperature such that suppresses the NO_x formation. The reduction ranked a value of 40.7% for ethanol to liquefied petroleum gas ratio (Eth/LPG) of 10%, while for the ratio of 20% the reduction reached 49.7% compared to the pure LPG run.

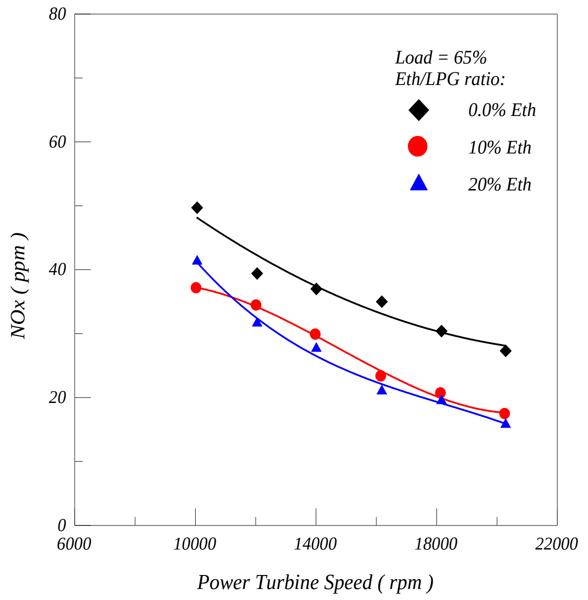


Fig. 2. Effect of Power Turbine Speed on No_x Emission.

The opportunity of completing the combustion is less probable when raising the turbine speed due to shorter residence time, and therefore, higher CO levels are expected as shown in Figure (3). Ethanol addition results in lower firing temperature, and hence, lowering the reaction rates which in turn further increases the CO emission. For Eth/LPG ratio of 10% the average increase in CO level was 98.9%, but with a ratio of 20% this increase reached 127.2% over that with normal LPG run.

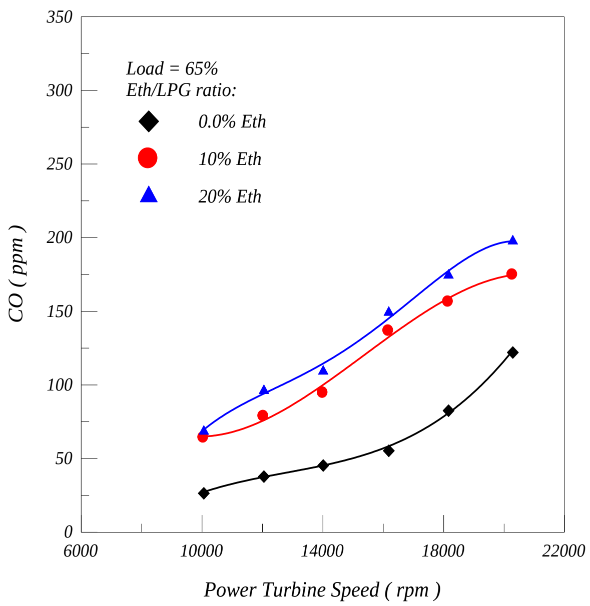


Fig. 3. Effect of Power Turbine Speed on CO Emission.

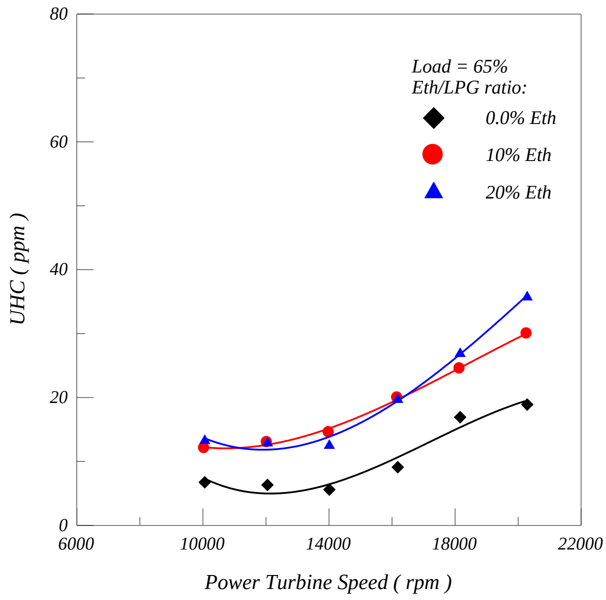


Fig. 4. Effect of Power Turbine Speed on UHC Emission.

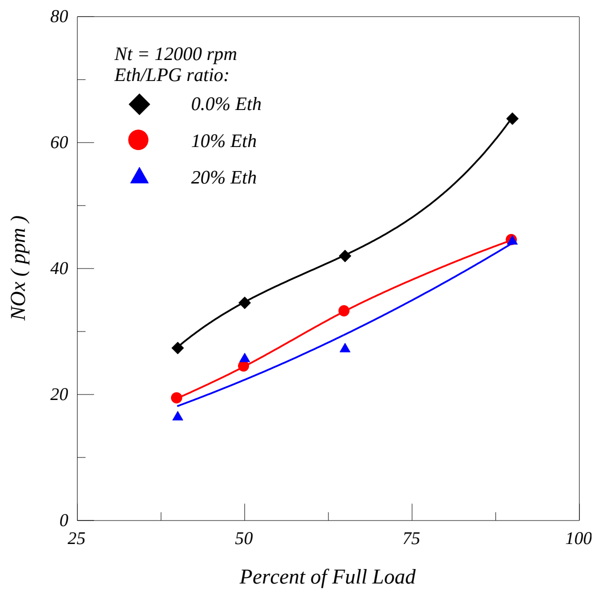


Fig. 5. Effect of Engine Loading on No_x Emission.

For the same reasons as CO, the UHC emission is also increases with turbine speed. Nevertheless, an additional source of UHC in the exhaust gases comes from the breakdown of evaporated ethanol which fails to be oxidized. The UHC emissions for both the Eth/LPG ratios are almost the same for whole turbine speed range. However, at higher speed, the higher the ethanol in fuel mixture, the higher UHC emission was recorded due to excess supply of fuel mixture. Figure (4) shows an average increase in UHC of 88.3% for both Eth/LPG ratios , but when goes beyond 16000 rpm, 20% ethanol reached a level of 19.3% higher than that with 10% ethanol ratio.

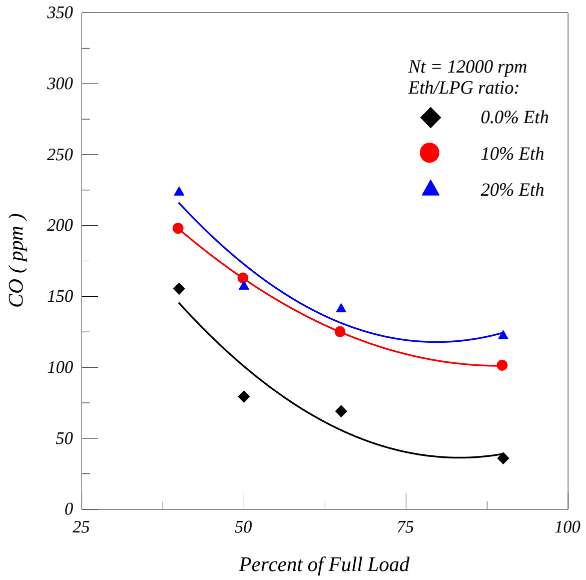


Fig. 6. Effect of Engine Loading on CO Emission.

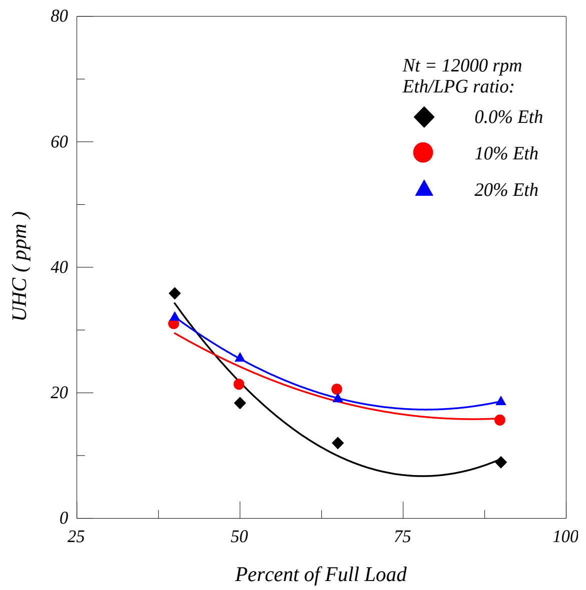


Fig. 7. Effect of Engine Loading on UHC Emission.

Understanding the impact of engine loading on the dual-fuel gas turbine, requires tests to be conducted at four steps of loading namely, 40, 50, 65 and 90% of the engine full load. Those tests were executed to maintain a constant power turbine speed of 12000 rpm.

Figure (5) shows the variation of NO_x emission with engine loading. More fuel must be supplied to support the load exerted which in turn leads to rise the firing temperature, as well as, increasing the NO_x emission. The depreciation in heating value due to LPG substitution with ethanol brings more fuel to be supplied and hence, the firing temperature to be decreased causing the NO_x emission to reduce. The reduction in NO_x emissions was 36.8 and 48.6% for Eth/LPG ratios of 10 and 20% respectively, both compared to the pure LPG run.

Increased firing temperature with higher engine loading will promote the reaction rates and less CO levels were observed along the loading range. Nevertheless, adding ethanol will lower these rates and cause the oxidation process to regress resulting in higher CO emissions. Figure (6) indicates an average increase in CO levels of 95.6 and 138.3% at Eth/LPG ratios of 10 and 20% respectively.

Almost same trends of UHC emission were observed for both Eth/LPG ratios when dual fuel was supplied. The average increase in UHC levels over that of pure LPG was 62.7 and 78.5% for 10 and 20% Eth/LPG ratio respectively as shown in Figure (7).

5. Conclusions

- When increasing the power turbine speed up to 20300 rpm, NO_x has reduced by 49.7% for Eth/LPG ratio of 20% by volume. But when rising the engine loading from 40 to 90%, the average NO_x emission was reduced by 48.6% for that ethanol concentration compared to normal LPG run.
- CO emission was increased by an average of 127.2% when increasing the turbine speed up to 20300 rpm at 20% Eth/LPG ratio. However, the load exerted on the engine when elevated to 90% limit gave a rise of 138.3% at the respective Eth/LPG ratio over pure LPG run.
- UHC emissions where almost the same for both Eth/LPG ratios as increasing the ethanol content in fuel resulted in an average increase of 88.3% with respect to LPG normal run along the low and medium speed range. Increasing the level of load exerted led to an average of 78.5% increase at 20% ethanol in fuel flow with respect to LPG engine run.

Abbreviations

CO	Carbon monoxide
Eth	Ethanol
GE	General Electric Co.
H / C	Hydrogen to Carbon ratio
LCD	Liquid crystal display

LPG	Liquefied petroleum gas
NO_x	Nitrogen oxides
PM	Particulate matters
SO_x	Sulphur oxides
UHC	Unburnt hydrocarbons
VOC	Volatile organic compounds

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Appendix

Specifications of T200D Twin-Shaft Gas Turbine Unit [11]

Compressor	:	Centrifugal
Turbines	:	Radial inflow
Power output	:	1.5 kW @ N_g/N_t : (55000/21000) rpm
Compressor Speed	:	60000 rpm max.
Free turbine Speed	:	23000 rpm max.
Overall Pressure ratio	:	1.3 / 1 max.
Firing Temperature	:	700 – 750^{o}C max.
Fuel	:	LPG, 3 g/s max. @ 2 bar max.

دراسة تجريبية لخصائص أنبعاث الملوثات من وحدة توربين غازي مصغرة تعمل بوقود ثنائي بحقن الأيثانول في الهواء الداخل للضاغطة

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الخلاصة

يعتمد تكون الملوثات بشكل كبير على درجة حرارة الأحتراق ومعدلات التفاعل للمكونات المتفاعلة في غرف إحتراق التوربينات الغازية. تم إجراء دراسة تجريبية على وحدة توربين غازي مصغرة T200D ثنائي المحورلتقييم أثر حقن الأيثانول مباشرة في الهواء الداخل للضاغطة على إنبعاث الملوثات. أجريت الدراسة وفقاً لأختبارات ثبوت السرعة وثبوت الحمل للماكنة. بصورة عامة ؛ أظهرت النتائج أن إضافة الأيثانول بتركيز 20% حجماً في الوقود يؤدي الى خفض إنبعاث NO_x الى النصف ، بينما أرتفع إنبعاث كل من CO و UHC الى الضعف تقريباً مقارنة بمستوياتها المنبعثة عن إحتراق وقود LPG الغازي التقليدي للماكنة.