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Liquid Fuel Combustion in a Cross-Flow of Multiple Opposing Gaseous Fuel Jets

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Abstract :- An Investigation on the effect of cross flow of multiple opposing gaseous fuel jets on liquid fuel burning was performed that could be retrofit into an existing or future manufactured gas turbine engines to provide an energy solution to problem of growing levels of carbon emissions. The combustion chamber was provided with dual fuel burner, and experimentally burn liquid fuel in a cross flow of gaseous fuel. While the air was co-axially introduced in a double swirl flow field, the combustion efficiency and flame length were recorded in conjunction with varying the number of opposing jets. Results verified that the average temperature of the product gases has been generally improved by 21.8 ~ 52.1 % than the original case of diesel oil burning. Local temperature drop, just after entering cross flow gases, decreased with increasing the number of opposing jets as a result of lower mass flux, which in turn affected the shear rates and mixing between hot gases and cold cross flow gaseous fuel. However, overall fuel to air ratio has been increased with same quantity of air, the cross flow interaction made a clearer exhaust than without this cross flow by visual exhaust observation. The analysis of exhaust emissions indicated using cross flow technique generally, has a positive effect in concentration of Carbon Monoxides (CO) by 6.7~ 68.4 % and Nitrogen Monoxide (NO) by 15.7 ~ 63.1 % and percentage of Hydrocarbons (CxHy) in the product gases by 26.6 ~ 46.6 %.

Keywords: -Combustion, opposing jet, cross flow, diffusion flames

I. INTRODUCTION

In 2017, BP Statistical Review showed that primary energy which are consumed in 2016 all over the world has been raised 1% compared with 0.9% in 2015 and 1% in 2014. Consumption growth significantly decreased compared with 1.8% average increase in the last 10 years [1]. In accordance with global strategy of combustion emissions reduction, alternative energy sources are now widely used and combustion investigations for combustion products improvement. For example, diesel fuel is widely used in engines because of its durability and efficiency, but their emissions are very high like soot and NOx, so the demands of efficient combustion and low emission are more urgent [2]. Experiments on diesel engine test bench showed that the increase of injection pressure reduces both soot and particulate matter (PM) emissions[3][4][5].

Three methods are commonly used regarding NOx emissions reduction from gas turbine power plants [6]. These techniques are premixed combustion, fuel dilution and NOx extraction from combustion exhaust. To optimize flammability limits for hydrocarbon-air mixture, the overall air/fuel ratio in combustion chamber must normally be around 30–40 [7]. In the primary combustion zone, the air/fuel ratio is around 18, but for low nitric oxides (NOx) as a major consideration, the air/fuel ratio is recommended to be around 24.

Experimental data of Mishra and Jejurkar[8] showed that overall equivalence ratio is the main factor and they observed that at leanest flame (global equivalence ratio < 0.3) a lower NOx emissions ranged from 3 to 60 ppm can be achieved, irrespective of the power level for the combustion chamber. And by using of cross flow design, the emission levels significantly reduced. According to flame stability observation, the useful ranges in experiments of the global equivalence ratio: 0.2 – 0.6 and Power level: 5 – 10 kW.

Andrew C. Chambers et al. have studied, using established flow field models, the effects of initial cross flow on heat transfer performance within a racetrack impingement channel which is used in turbine blade cooling[9]. With the potential core striking the target surface, he observed the classic impingement patterns at low mass flux. By increasing the mass flux, the jet potential core cannot to cross the channel and no impingement enhancement. When small quantities of initial cross flow are introduced, a considerably effects on the channel performance due to the near exponential increase in both the impingement hole velocity and the cross flow velocity.

Turbulence has the ability to enhance chemical reactions as combustion with short distance mixing of reactants. Collision of opposing jets is one of high turbulence applications resulting vortex motion, high shear rates and quick mixing in short distance. The effect on mixing of injection of multiple opposing jet with/without offset has been studied by S.J. Wang & A.S. Mujumdar [10]. The study results show that a better mixing can be

achieved by multiple opposing jets compared to single opposing jets. On other hand, as increase number of opposing jets, a deterioration in swirling intensity will occur.

Although the dilution air enters the gas turbine combustion chambers through linear holes at an angle of 60 – 75º with respect to wall, most of previous studies concentrated on normal jets into a crossflow. An investigation has been carried out by Y. R. Chang and K. S. Chen [11] by mixing hot line opposing jets with jet incident angle from 60 – 90º with a cold crossflow in a rectangular shaped duct. The results showed that, after jet openings, zones of circulated fluid had been created in the shear layers adjacent to walls. The jets velocity and thermal routes were enhanced with incident angle and momentum flux ratio. However less uniform temperature profiles occurred using a single jet, an improved thermal mixing properties and higher turbulence levels could be attained compared with multi-jets which have a better uniform profile in short distance. This principle is used widely to shorten and reduce cost of combustion chambers of gas turbines by developing the dilution zone design.

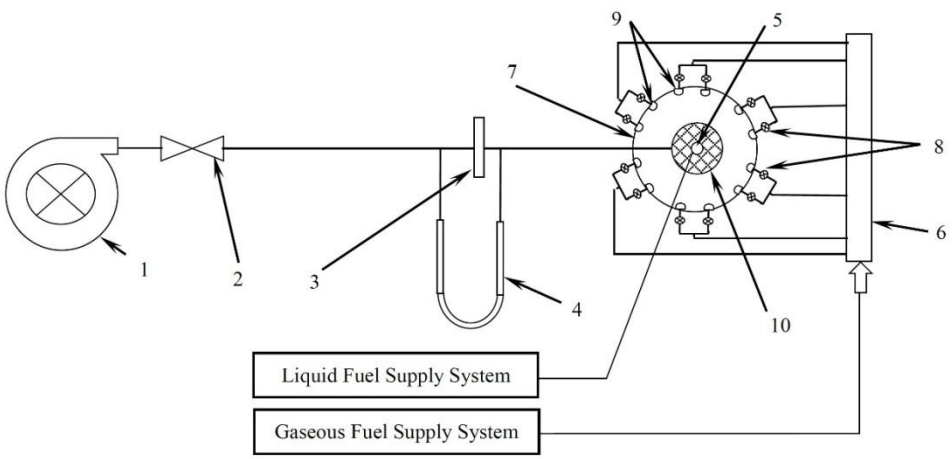
U. Azimov et al. investigated the combustion in engines with dual-fuel of natural gas, syngas and Hydrogen with changing equivalence ratio [12]. They found that heat release in the combustion divided to two phases started with flame propagation of gaseous fuel in the first phase. On the other hand, end-gas mixture auto-ignition zone was in the second phase and by changing the fuel injection timing, equivalence ratio for the gaseous fuel and recirculation rate of the exhaust gases they could control the second phase. By using hydrogen lead to an increase in maximum rise of pressure in the second phase which enhances the mean combustion temperature and efficiency of combustion but also NOx had been raised.

Based on the above researches, the current work is conducting a combination of techniques of air distribution, variation of overall Air/Fuel mixture and using dual fuel burner to burn liquid fuel across flow of gaseous fuel. The opposing gaseous fuel jets number were varied up to twelve jets to investigate this factor in combustion performance; particularly flame length and emissions.

II. TEST RIG

The basic configuration of the test rig allows separating the combustor from test rig for easy changes of liquid fuel nozzle, gaseous fuel nozzles and swirlers. The test rig assembly (*Fig. 1*) consists of combustor and three main systems; Liquid fuel system, Gaseous fuel system and Supply air system.Supply Air System is supplying air for liquid fuel burning where a centrifugal blower (1) is the only air source required for combustion. The air supply reaches a cylindrical combustion chamber (7) that are varied by the butterfly valves (2); while the pressure differences across the orifice plates (3) indicate the flow rates and measured by a set of manometers (4) connected to the tapings. The air is entering the combustion chamber after crossing a double vanned type swirler (10). This swirler splits The combustion air into two streams- Inner Stream which is close to the liquid fuel nozzle, and an Outer Stream which is surrounding the inner stream.

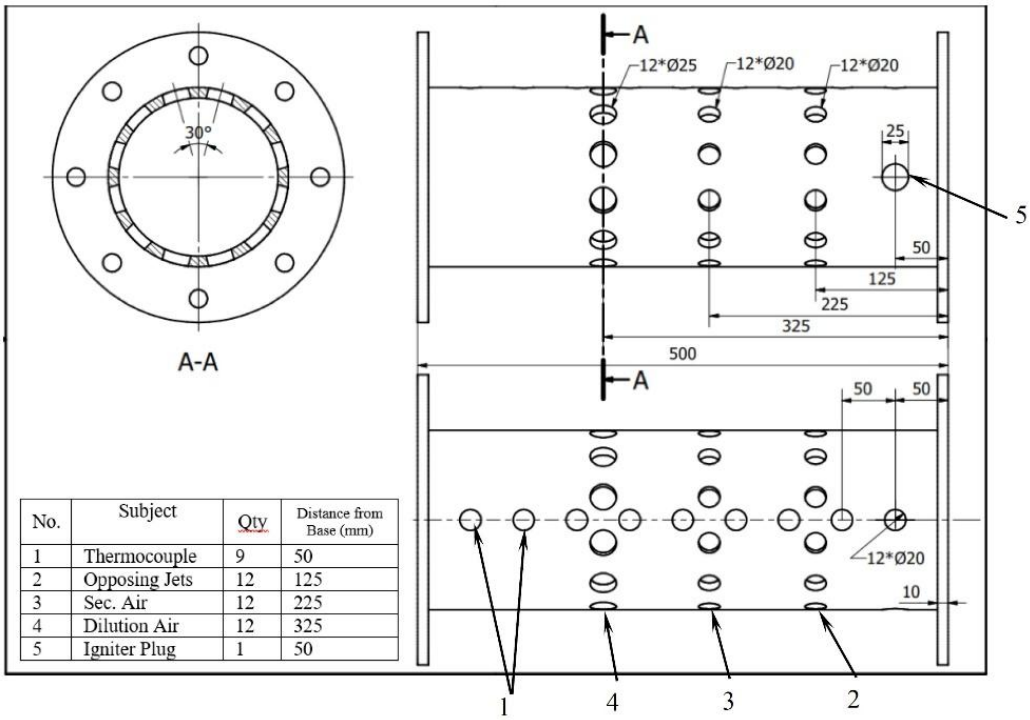
On the liquid fuel side, the fuel is supplied from a liquid fuel reservoir through a fuel filter before entering a gear type SUNTEC AN67C oil pump. The fuel pressure can be adjusted by a built in pressure regulating valve inside the fuel pump and monitored via a pressure gauge. Once the liquid fuel has been regulated, it is directed to a fuel nozzle (5) having a pattern spray cone of 60°. Gaseous fuel supply system, consists of Liquefied Petroleum Gas [LPG] cylinder, where the flow rates are separately regulated and measured via the rotameter flow meter before entering a manifold (6). The gaseous fuel line was split into six lines downstream of premixing chamber, then each line is split into two lines of two opposing jet (9) with shutoff valve (8) for each one producing twelve opposing jets inside the combustion chamber.



1- Primary Blower. 2- Butterfly Valve. 3- Orifice Meter. 4- Manometer. 5-Liquid Fuel Nozzle 6- Gaseous Fuel Manifold. 7- Combustion Chamber. 8- Shutoff Valve (12). 9- Opposing Jet Nozzle (12). 10– Swirler.

Fig. 1 *Air Supplying System Schematic*

Combustor, *Fig. 2*, is a cylindrical type with 500 mm Length and 147 mm in diameter. To ensure efficient combustion a part of the air flow can be admitted into the 12 secondary and 12 dilution ports (3) and (4) so as to be delivered symmetrically into the combustor thus providing an overall excess air. Also 12 ports (2) have been provided to deliver the gaseous fuel jets into the combustor by 12 removable 3 mm hole nozzles, *Fig. 3*.



No.	Subject	Qty	Distance from Base (mm)
1	Thermocouple	9	50
2	Opposing Jets	12	125
3	Sec. Air	12	225
4	Dilution Air	12	325
5	Igniter Plug	1	50

Fig. 2 *Combustion Chamber ports distribution*

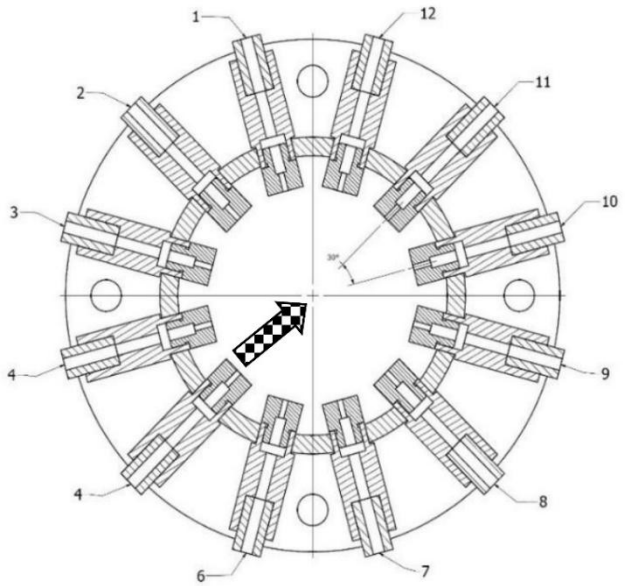


Fig. 3 *Gaseous Fuel Opposing Jets section in the Combustion Chamber (Air Flow Inside View)*

Measurements

Measurement of Air supply flow rates, used in combustion purposes, has been carried out using orifice plate between blower exit and combustion chamber. The Orifice Plate was designed and manufactured in

according with British Standard[13]. Diesel Oil flow rate is obtained by counting the time of consuming a specific quantity of liquid fuel volume from the scaled reservoir's sight glass and gaseous fuel volume flow rate was measured by a ball type float rotameter.

The local flame temperature is measured by an unshielded, 1mm bead diameter and30 cm probe length of thermocouple type S (90% Platinum/10% Radium–Platinum, by weight), which was used to measure temperatures up to 1600 °C. The thermocouple is directly connected to SHEMADEN SR3 series digital controller which is designed for controlling temperature/humidity and other physical quantities of general industrial equipment.This thermocouple was used to measure a local temperature of as a mesh of 56 points distributed inside the combustion chamber along nine axial stations with eight radial points. The Eight Radial points are in equal distance of 1 cm from its center axis to the upper boundary layer of hot gases that touches the wall. The Nine Axial stations are in equal distance of 5 cm starting from just downstream of liquid fuel nozzle and air inlet at station no. 1 to combustion chamber exit at station no. 9 to cover the combustion stages and know the effect after and before presence of gaseous opposing jets.

Concentrations of Carbon Monoxide (CO), Nitrogen Monoxide (NO) and Hydrocarbons (C_xH_y) were measured radially at last station in the combustion chamber by a portable gas analyzer LANCOM III.

Setup and Constraints

Each time the test has been performed, the test rig is ensured to be adjusted in fixed values of flow rates and pressures to make constraints to ensure that results is only because of changing the number of opposing gaseous fuel jets. Also, the parameters were adjusted to make sure the desired intensified, minimum sooty flame occurs for study purposes. Regarding Liquid fuel, a constant pressure was obtained at 15 bar and flow rate was calculated and fixed to 1.116 $*10^{-3}$ Kg/s. Gaseous LPG Fuel had a constant flow rate of 3.87 * 10^{-4} Kg/s. Air supply required for combustion was set its value of mass flow rate to 0.0355 Kg/s. Overall A/F (Air to Fuel) Ratio was considered as 31.76 for diesel oil burning only and 23.58 for overall diesel oil burning with all opposing gaseous fuel jets cases.

III. RESULTS AND DISCUSSION

First, a Diesel Oil burning was carried out to establish a base of diesel oil burning characteristics and the performance of the combustion chamber in terms of temperature distribution along axial and radial directions, also to know a correct image of emissions of product gases.

Fig. 4 showed a 60° cone of diffusion flame of diesel oil that resulted from atomization in the liquid fuel nozzle. The process of atomization is mostly consisting of two separate processes primary and secondary atomization. The primary atomization process intends to break up the fuel stream into strips and ligaments, and secondary atomization process, in which the large drops and globules produced in primary atomization are fragmented into smaller droplets[7][14]. Also the swirling effect on the flame was clear as shown in *Fig. 5*, where the tangential momentum has been risen due to swirl angle [15]. Also, double swirler led to higher shear stresses between the counter rotating air streams and diesel oil spray which led to a remarkable shorter flame length of 13 cm.

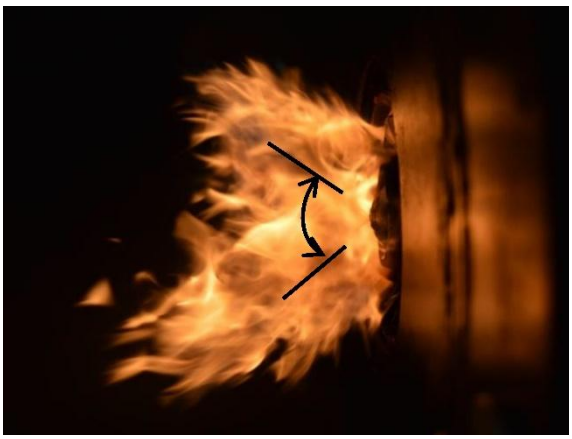


Fig. 4 *Liquid fuel atomization and 60°cone of diesel oil*

Fig. 5 *Swirler Effect on Burning of Diesel Oil*

Local temperature distribution inside the combustion chamber (*Fig. 6)* showed 8 layers, from center axis to boundary layer just adjacent to combustor's wall at 7 cm from center axis. Local temperature increased in the first and second station just after liquid fuel nozzle till reached its highest value, about 1140 °C in station 3 at 1 cm away from center axis. Then a gradually decrease of temperature in a convergent manner between air flow layers that leads to about 533 °C of Average exit temperature.

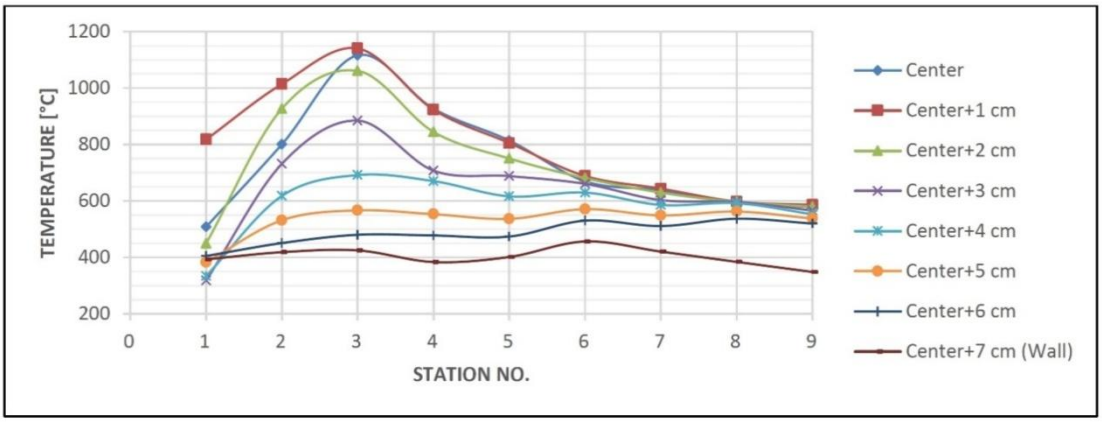


Fig. 6 *Temperature Distribution for Burning of Diesel Oil only (Overall A/F = 31.76)*

Liquid Fuel Burning in addition of Gaseous opposing jets

The combustion chamber was equipped with 12 ports evenly distributed, and each port had a gaseous nozzle of 3 mm and a shut off valve to control the number of opposing jets to enter the combustion chamber. *Fig. 7* showed LPG fuel burning and the opposing-jet diffusion flame. Observation revealed location of the stagnation point, which compared well with that of a typical opposing-jet diffusion flame[16].

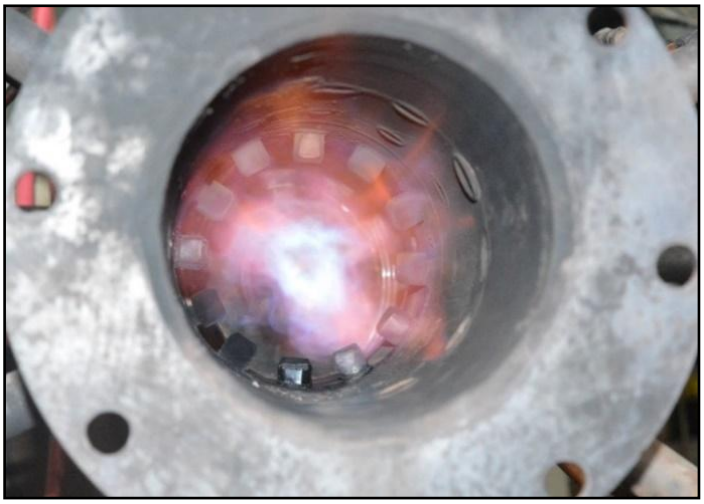


Fig. 7 *Burning of opposing Gaseous Fuel (LPG) jets only*

As experiment arrangement, a matrix of opposing jets was set for each configuration. Experiments was initiated with 2 opposing gaseous fuel jets then increased to four, six, eight and twelve opposing jets evenly distributed around the combustion chamber. Also, overall air to fuel ratio was decreased to 23.58, when using gaseous fuel added to liquid fuel, instead of 31.76 for diesel oil burning only.

For first configuration, 2-set of gaseous opposing jets, the cross flow and impingement properties of opposing gaseous fuel jets was acting as a coolant to the burned gases which produced from diesel oil burning [9]. It was seen that at high mass flux of the jets, a significant insight into the impingement were observed with the potential core striking the burned air/fuel flow stream. After initial jets between stations two and three, Fig.*8*, an abrupt drop in local temperature of flow streams existed in station three due to quick mixing in short distance to hot gasses and high shear rates. Then gradually increase of temperature took a place due to a starting of LPG burning but less in convergent manner of temperature decrease between air flow layers to the exit station than diesel oil burning in *Fig. 6*. Results of this combustion are helpful to increase the flame temperature and complete the diesel oil burning.

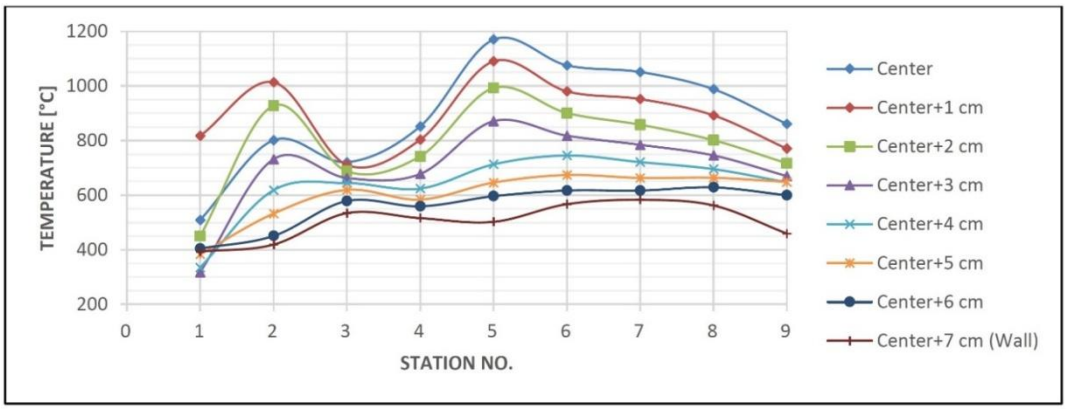


Fig. 8 *Temperature Distribution for Burning of Diesel Oil with 2 Opposing LPG Fuel Jets*

By increasing the number of opposing gaseous fuel (LPG) jets, the mass flux decreased to reduce the shear rates and impingement regions areas, *Figures 9, 10, 11 and 12*. Therefore, local temperature drop in core layers decreased leading to a wider temperature gradient between layers in station 3, the most affected station by crossflow cold streams,similarly in the previous case of 2 opposing gaseous fuel jets, a less in convergent manner of local temperature decrease between air flow layers to the exit station than diesel oil combustion's case. Multi-jets, having a better uniform profile in short distance, had the shortest flame length and get the combustion chambers of gas turbines by developing the dilution zone design.

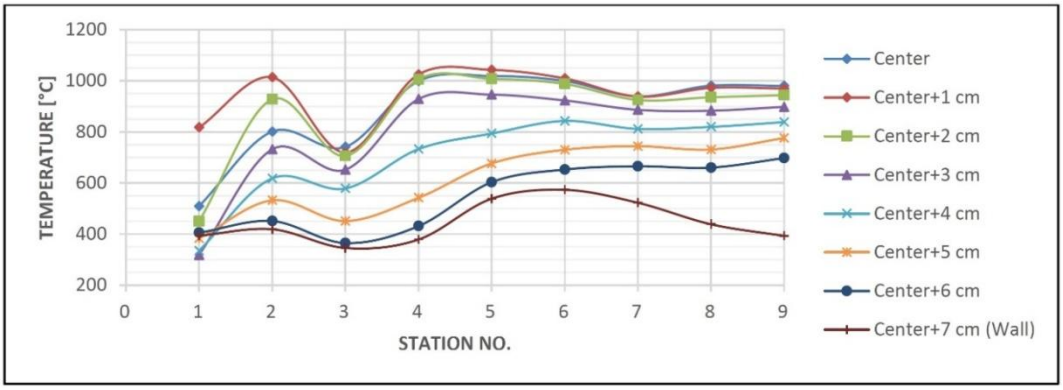


Fig. 9 *Temperature Distribution for Burning of Diesel Oil with 4 Opposing LPG Fuel Jets*

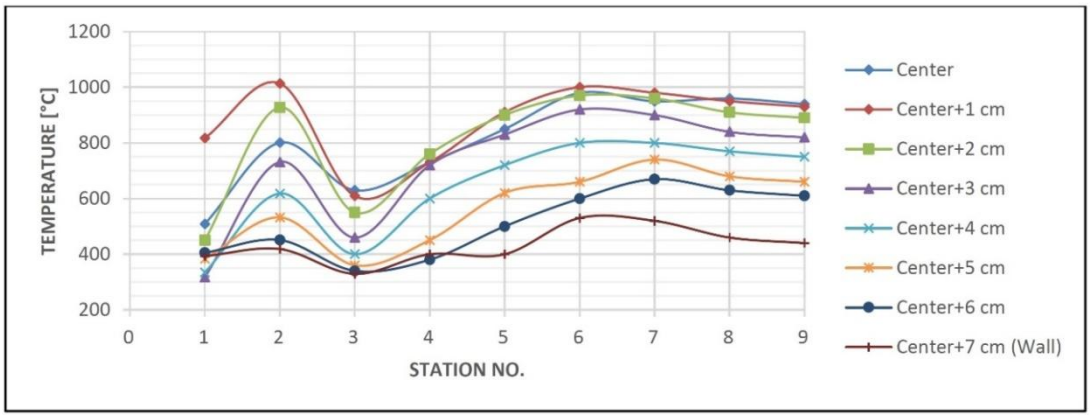


Fig. 10 *Temperature Distribution for Burning of Diesel Oil with 6 Opposing LPG Fuel Jets*

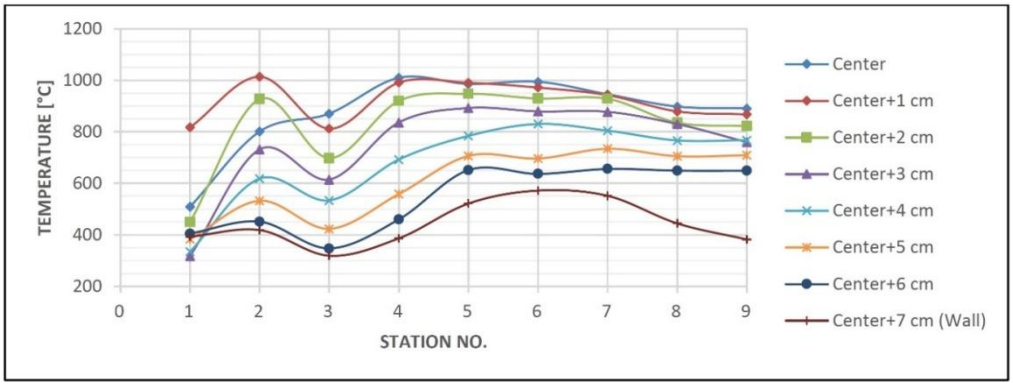


Fig. 11 *Temperature Distribution for Burning of Diesel Oil with 8 Opposing LPG Fuel Jets*

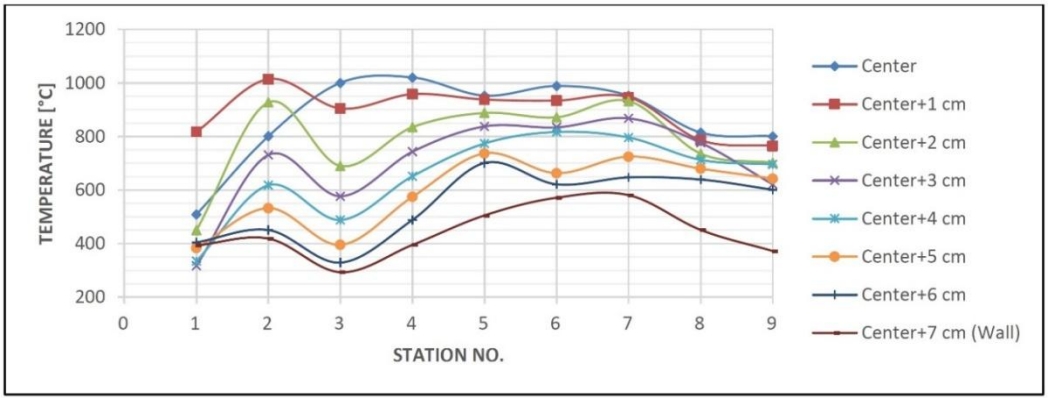


Fig. 12 *Temperature Distribution for Burning of Diesel Oil with 12 Opposing LPG Fuel Jets*

After gaseous injection between stations two and three, local temperature distribution, discussed previously, showed that an abrupt drop in local temperature of flow streams existed in station three due to cold gaseous fuel injection, of quick mixing in short distance to hot gasses and high shear rates took place for the quick mixing. Data at station no. 3, just downstream air flow after gaseous injection, was analyzed to clarify the effect of cold cross flow. Ratio of ΔT_{Jets} / ΔT_{Diesel} was calculated and placed in a graph to clarify the drop in temperatures of air flow layers; Where ΔT_{Jets} and ΔT_{Diesel} is temperature difference between minimum and maximum temperatures at station no. 3 during diesel oil burning with and without opposing gaseous LPG jets respectively. *Fig. 13* shows that the drop due to crossflow cold streams decreased with increase of number of opposing jets because of a lower mass flux which in turn reduced shear rates and mixing between gases because opposing jets flow had a less kinetic energy to reach and mix with core layers. The maximum drop was recorded when using two jets with a value of 0.74 due to higher mass flux, while the minimum drop was recorded also at the twelve jets case with a value of 0.012, and it was too near to burning of diesel oil only case.

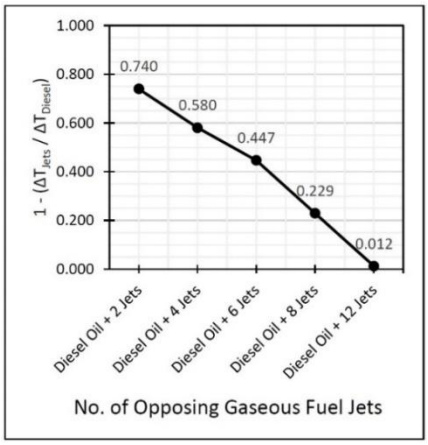


Fig.13 *Cross-Flow Local Temperature Drop on Air Flow Temperature at Station no. 3 (Overall A/F was 31.76 for burning of Diesel oil Only and 23.58 for dual fuel burning)*

The exit temperature profile was important to know improvement in exhaust gases. *Fig. 14* showed minimum and maximum temperature at last station, station no. 9, of the combustion chamber and average temperature. However, the average temperature of the product gases was higher, temperature range was at minimum in the original case of diesel oil burning which means that a better uniform and constant temperature at exit station. Using opposing fuel jets made a higher average product temperature by 21.8 ~ 52.1 % but a wider range in layers' temperatures up to 587 °C, with 6 Jets Case, between minimum and maximum compared with 237 °C for Diesel Oil burning Case.

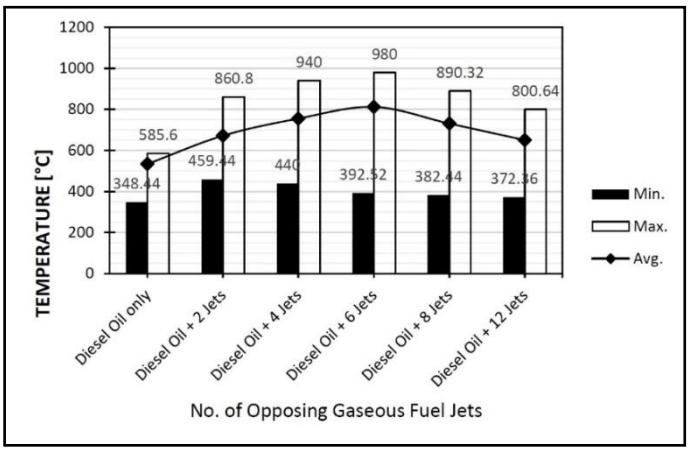


Fig. 14 *Temperature profile at Station no. 9*

Flame Length

The visible flame length was measured and clarified that the flame length became increasingly shortened with the increase of the opposing gaseous fuel jets, *Fig. 15*, the configuration of twelve sets of jets recorded the shortest flame length, 22 cm, with an increase of 69% in the flame length than diesel oil burning only and that coincides with investigation carried out and resulted that with multi-jets have a better uniform profile in short distance[11]. Also, maximum flame length, 57 cm, was recorded at the case of 2 sets of opposing jets with an increase of 338% in the flame length than diesel oil burning.

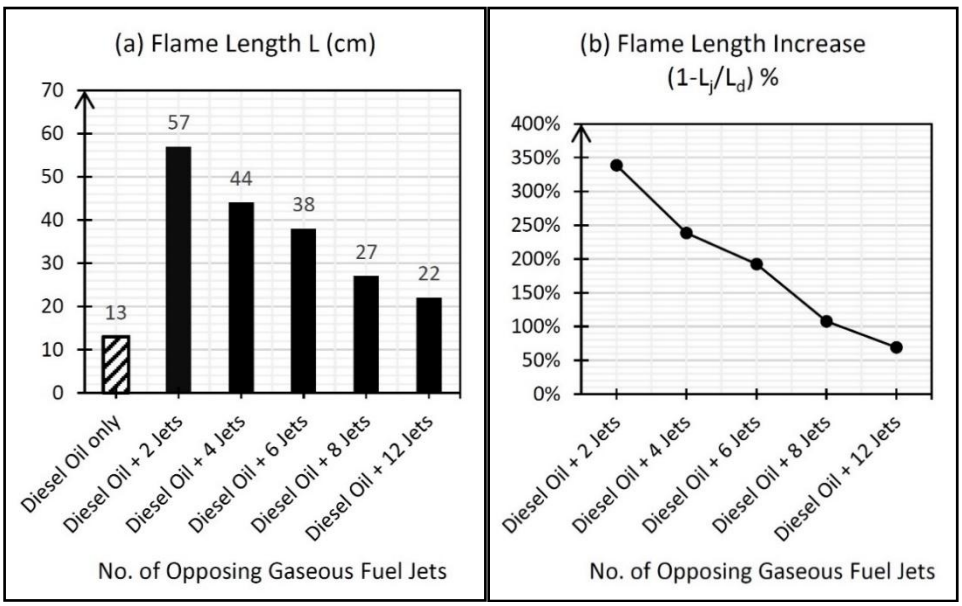


Fig. 15 *(a) The recorded flame length for visible flame. (b) flame length increase when using opposing gaseous fuel (LPG) jets.*
(Overall A/F was 31.76 for burning of Diesel oil Only and 23.58 for dual fuel burning)

Product Gas Analysis

CO levels in ppm was measured and plotted in *Fig. 16*which had the diesel oil burning case and the effect of opposing gaseous fuel jets. Using cross flow technique generally had a positive effect in CO

concentration in the product gases by 6.7 ~ 68.4 % and significant improvement in CO concentration with increase the number of jets specially for twelve jets case which had minimum value of 968 ppm compared with 3065 ppm for diesel oil burning only due to lower shear rates effect and enhanced uniform mixing between distributed gaseous fuel and hot air in the combustion chamber. Also highest rate was recorded at two jets case with a value of 2857 ppm.

On the other hand, Nitrogen Oxide (NO) is one of the most important factor to measure the quality of product gases. This factor was measured and could be found in *Fig. 17*that clarified a general decrease in NO emissions by 15.7 ~ 63.1 % was observed with using cross flow of LPG fuel as opposing jets. The 2 jets case had a value of 16 ppm compared with 19 ppm for diesel oil combustion. So increasing number of opposing jets leaded to decrease in the NO concentration till reaching a value of 7 ppm at 12 jets case.

Fig. 18 showed the hydrocarbons concentration's improvement by 26.6 ~ 46.6 % due to using opposing gaseous fuel jets which verified that percentage is dropped to 0.11% for 2 jets case compared to 0.15% for diesel oil burning only. This percentage was decreased by using more jets to reach 0.08 for 12 jets case.

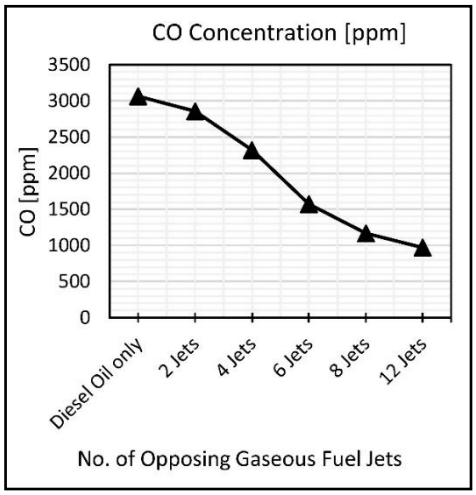


Fig. 16 *CO Concentration [ppm]*

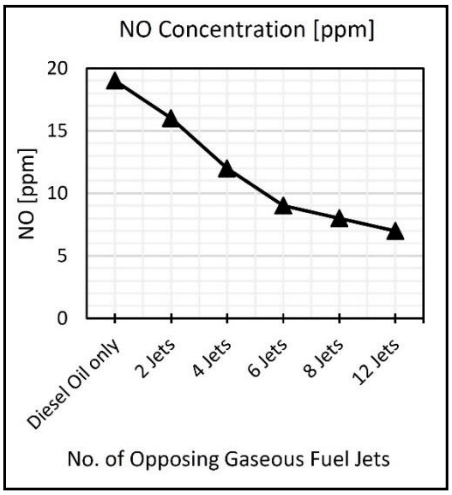


Fig. 17 *NO Concentration [ppm]*

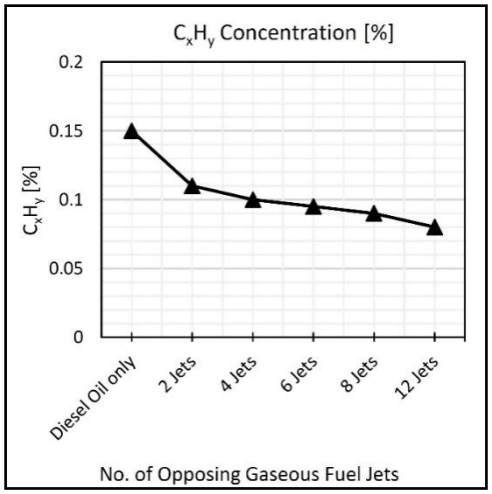


Fig. 18 *CxHy Concentration Percentage*

* Overall A/F was 31.76 for burning of Diesel Oil Only and 23.58 for dual fuel burning

IV. CONCLUSION

This work investigated the effect of a cross-flow gaseous fuel opposing jets on the combustion performance of liquid fuel combustion and flame qualitative features. A Test rig was designed and built for this investigation. Station no. 3 is the most important station because it is first stage after the cross flow of opposing jets and provides valuable information for cross flow effect. After performing experiments on burning of constant quantity of diesel oil with cross flow of constant quantity of LPG opposing jets up to twelve jets at constant air flow rate, the following has been concluded from experimental works:

- Local Temperature Drop effect, especially in station no. 3 decreased with the increase of number of opposing jets because of a lower mass flux which in turn reduced shear rates and mixing between gases. The maximum drop was recorded when using two jets with a value of 0.74 due to higher mass flux, while the minimum drop was recorded at the twelve jets case with a value of 0.012, and it was too near to burning of diesel oil only case.
- Regarding exit temperatures, the average temperature of the product gases was generally improved by 21.8 ~ 52.1 % than the original case of diesel oil combustion and maximum average temperature was recorded at 6 jets case with value of 811°C compared with 533 °C for burning of diesel oil only.
- However, the average temperature of the product gases was improved, temperature range was at minimum in the original case of diesel oil combustion which means that a better uniform and constant temperature at exit station. Using opposing fuel jets made a higher average product temperature but a wider range in layers' temperatures up to 587 °C, with 6 Jets case, between minimum and maximum compared with 237 °C for diesel oil burning case.
- The shortest flame length, 22 cm, was recorded at the configuration of twelve jets with an increase of 69% in the flame length than diesel oil burning. Also, maximum flame length, 57 cm, was recorded at the case of 2 jets with an increase of 338% in the flame length.
- Twelve jets case had the best uniform profile in short distance and the shortest flame length so a shorter combustion chambers could be achieved by developing the dilution zone design.
- By analysis for exhaust emissions, using cross flow technique generally, had a positive effect in CO concentration in the product gases and significant improvement in CO concentration by 6.7 ~ 68.4 % with decrease the number of jets specially for twelve jets case which had minimum value of 968 ppm compared with 3065 ppm for diesel oil burning only. Also highest rate was recorded at two jets case with a value of 2857 ppm which still less than diesel oil only burning.
- A general decrease in NO emissions by 15.7 ~ 63.1 % was observed with using cross flow of LPG fuel as opposing jets especially at 12 jets case with a value of 7 ppm compared with 19 ppm for diesel oil burning. So, decreasing number of opposing jets led to increase the NO concentration till reaching a value of 16 ppm at 2 jets case.
- Hydrocarbons (C_xH_y) concentration's percentage was recorded with an improvement of 26.6 ~ 46.6 %. Concentration percentage was dropped to 0.11% for 2 jets case compared to 0.15% for diesel oil burning only. This percentage was decreased by using more jets to reach 0.08 for 12 jets case. This indicated an improvement due to using opposing gaseous fuel jets.

From the above points, this study of using cross flow of opposing gaseous fuel jets resulted in a general improvement in combustion performance and emissions' products. A higher temperature of exit gases was achieved with an overall air to fuel ratio of 23.58 compared with 31.76 for burning of diesel oil only (25% less overall air to fuel ratio) and that means more fuel with same quantity of air with better emissions.

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A. Mounir "Liquid Fuel Combustion in a Cross-Flow of Multiple Opposing Gaseous Fuel Jets." IOSR Journal of Engineering (IOSRJEN), vol. 07, no. 12, 2017, pp. 74-84.