Experimental Investigation of Dual-Fuel Combustion Characteristics inside a Gas Turbine Combustor

Ibrahim, I. A., Shabaan, M. M., Shehata, M. A., and Farag, T. M

***Abstract*—** This paper represents an experimental study to improve the spray combustion by using dual fuel (diesel and N.G. fuels) combustion. A burner head is designed to be suitable for burning dual fuel together. The burner head was fitted coaxially with a water–cooled combustor of 0.2 m inner diameter and 1 m in length. The flame characteristics of dual fuel (diesel and N.G.) in which the natural gas, with and without swirl, is added into the combustion chamber with different thermal heat percentages of 5, 10, 15, and 20 % of the total thermal load. The experimental results show that, increasing the natural gas thermal heat percentage when the N.G. used with and without swirl, leads to increase high temperatures region size while to decrease the flame length. The NOx and CO2 concentrations increase but CO and O2 concentrations decrease at the same operating conditions. The effect of using N.G. with swirl has stronger effect than that of without one. The flame size in its diameter and length is larger for N.G. with swirl than that of without one.

***Keywords*—** Swirl number, Gas turbine combustor, Dual Fuel Combustion, Species concentrations.

I. Introduction

THE firing of liquid fuel gives a good heat transfer to the combustor walls while gives high pollution emissions. Inserting small percentages of light gaseous fuel like natural gas to the burner probably enhance the combustion and decrease the pollution emissions. Relying on only one fuel for the operation of thermal power plants could pose problems in the times of fuel market instabilities [1-3].

A dual fuel single can combustor for the Niigata Gas Turbine was developed by Koyama and Fujiwara [4]. Combustion and fluid flow characteristics of coflowing LPG and kerosene have been investigated experimentally by Abdel-Latif [5]. The possibility of dual fuels applications in existent thermopower plants in order to enable their pollutant emissions to conform to the ecological norms, which limit their values were analyzed by Mircea and Malvina [6]. The effects of nitrogen injection into the near-nozzle region of a liquid (kerosene) spray flame produced from a twin-fluid atomizer was experimentally studied by Gollahalli and Puri [7]. Dual firing capabilities of retrofitted power plant have been analyzed by Schneider and Bogdan [8]. The combustion characteristics of Kerosene diffusion flame using different gaseous fuel such as N.G. and LPG in combustion air studied experimentally by Gad [9]. Experimental study were performed to investigate directly the local flame properties of turbulent propagating flames at the same weak turbulence condition in order to clarify basically the influence of the addition of hydrogen to lean and rich methane or propane mixtures on its local burning velocity by Nakahara et al [10].

An investigation into the effects of introducing additional diluents into the primary air stream of pressure-jet and air-blast atomizers on their flame characteristics was conducted by Gollahalli [11]. The effect on smoke point of diluting the flame with nitrogen, argon, helium, carbon dioxide and water vapour over a wide range of diluent concentrations was investigated by Mclintock [12]. A premixed spray burner for the observation of stable turbulent flames propagating in a droplet cloud suspended in a stream of air or for a gaseous fuel-air mixture was designed carefully by Kazuyoshi et al [13]. The burning velocity of open inverted-cone shaped kerosene-air sprays at constant air-fuel ratio and for several degrees of atomization of the spray was measured by Polymeropoulos and Das [14].

Some of the previous investigators concerned with studying the combustion characteristics of dual fuel in gas turbine combustor but as additives to combustion air [4-9, 15], none of them concerned with studying the combustion characteristics of dual fuel in gas turbine combustor with both fuels (gas and liquid) introduced into the combustion chamber coaxially as diffusion flame, in addition to swirling and none swirling gaseous fuel (the task of the present study). Therefore, the present work perhaps gives effort to use the dual fuel technique in gas turbine combustor to enhance the evaporation rate of liquid fuel. Inserting small percentages of light gaseous fuel like natural gas to the burner enhance the combustion and decrease the pollution emissions.

II. Experimental Test Rig

The schematic drawing of the test rig is shown in Fig. 1. The dimensions and assembly of the combustion chamber are shown in Fig. 2. The test section is water-cooled, horizontal, cylindrical steel tube of 200 mm inner diameter and 1000 mm long. A double concentric jet burner is fitted axially at the up-stream end of the test section in which different air swirlers could be mounted co-axially at its outlet. The burner arrangement as shown in Fig. 3 consists of; a pressure swirl-type atomizer is fitted co-axially with the air swirler. The

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atomizer exit is placed at the combustor inlet and its center line coincides with the center line of the combustor chamber. The gaseous fuel exit between the atomizer hub and the air swirler hub. The liquid fuel is fed to the pressure swirl atomizer which is a hollow cone spray with spin chamber angle equal 45º.The fuels used in the present work are commercial diesel, that is available at petrol fueling stations, and the compressed natural gas, that is available at natural gas fueling stations, with reasonable price.

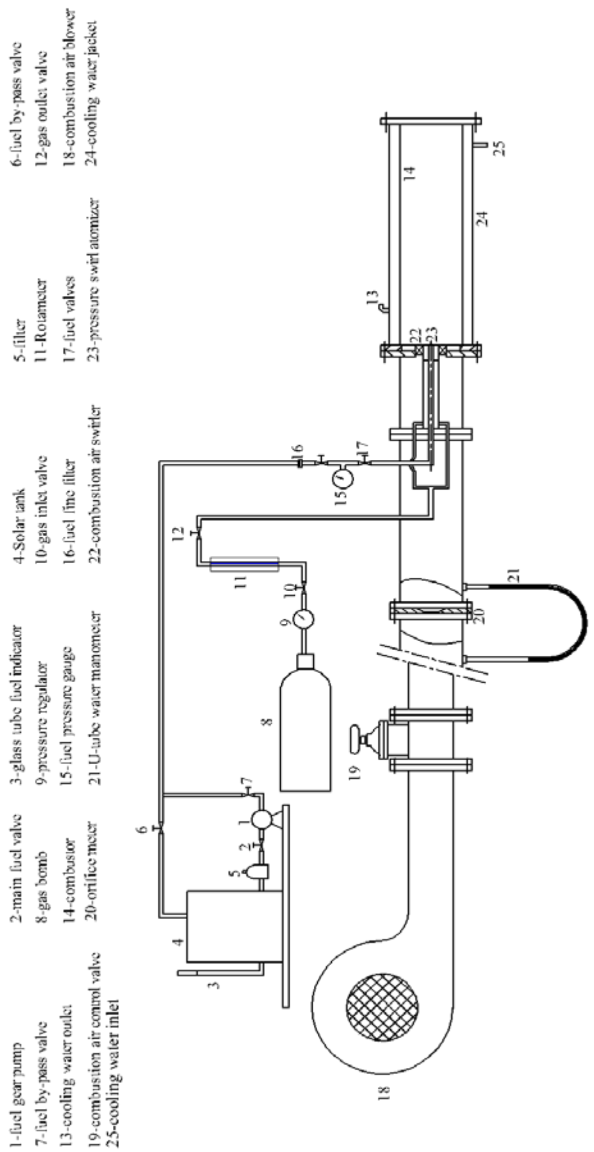

Fig. 1 schematic of experimental test rig

III. Experimental Results and Discussion

The flame characteristics were studied with the combustion of the dual fuel of diesel fuel and natural gas (N. G.) with different natural gas thermal energy percentages. The air to fuel mass ratio and the thermal load were chosen and kept constant for all operating conditions and they are 30 and 110 kW, respectively. The air to fuel mass ratio is the ratio between the combustion air mass flow rate to the total fuel mass flow rate (N. G. and Diesel fuels), while two swirl

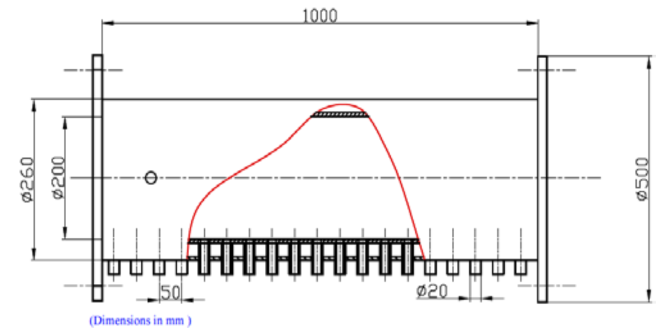

Fig. 2 Combustor dimensions

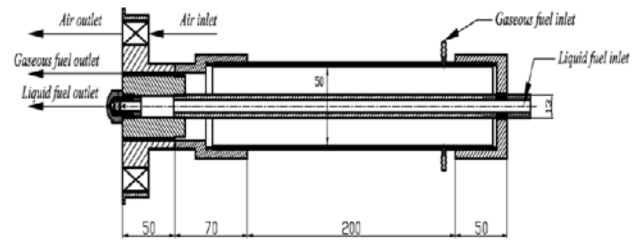

Fig.3 Assembly of the burner head

numbers of 0.5 and 0.87 are used. The natural gas enters the combustor with and without swirl.The swirl number of natural gas used is equal to 0.0 and 0.5. The effect of the thermal energy percentage of natural gas fuel flow rate to the total thermal energy from the natural gas fuel and the diesel fuel is studied. These percentages are 5, 10, 15 and 20 %. The above parameters were discussed in detail in the following sections.

3.1 Effect of different natural gas thermal energy percentage

3.1.1 Effect of N.G thermal energy percentage on temperature map

The effect of natural gas thermal energy percentage of 5, 10, 15 and 20 %, N.G. without swirl, on temperature patterns at air swirl numbers of 0.5 and 0.87, air to fuel mass ratio of 30 and thermal load of 110 kW are shown in Figs. 4-5, from these figures, it is clear that, the high temperatures regions are increased with the increase in natural gas thermal energy percentage. Increasing the natural gas mass flow rate, leading to increase the gas velocity and this causes shifting the high temperature region downstream and increasing of flame length. A relatively low temperature region appears at upstream section around the flame centerline. The volume of this zone decreases by increasing natural gas mass flow rate. By increasing natural gas thermal energy percentage, the evaporation rate of Diesel fuel, the mixing rate and the high temperature region size increase.

The same behavior of the effect of the natural gas thermal energy percentage on the flame temperature distribution is also found when using different air swirl numbers. By increasing the air swirl number, the high temperature region shifting upstream. The flame decreased in length and increased in diameter. For air swirl number of 0.5, the high temperatures regions are found at $0.25 \le X/D \le 1.5$, $0.25 \le X/D \le 1.6$, $0.75 \le X/D \le 2.75$ and at $0.3 \le X/D \le 2.25$ for natural gas thermal energy percentage of 5, 10, 15 and 20 respectively. For air swirl number of 0.87, the high temperatures regions are found at 0.25≤X/D≤1.1, 0.25≤X/D≤1.4, 0.3≤X/D≤1.9 and at 0.25≤X/D≤1.85 for natural gas thermal energy percentages of 5, 10, 15 and 20 %, respectively. The flame length increased due to increase of the velocity of gaseous fuel and so the momentum flux increased.

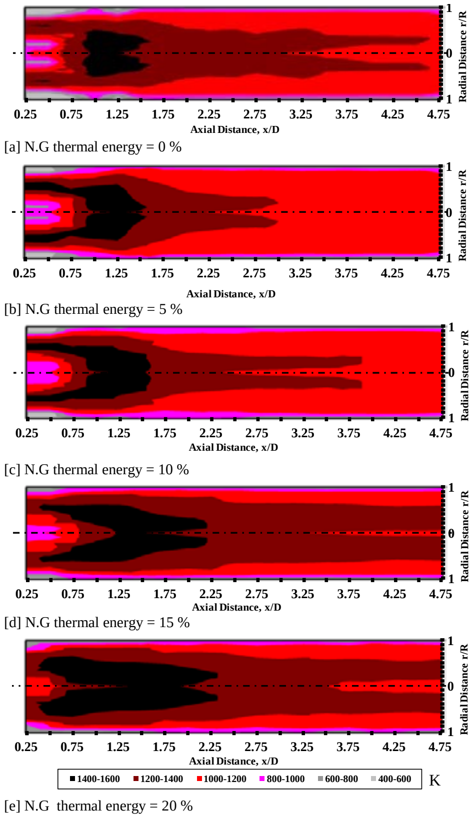

Fig. 4 Effect of N.G thermal energy percentages on temperatures maps [S =0.5, Sg = 0.0, AFR =30 and T.L. = 110 kW]

The effect of natural gas thermal energy percentage of 5, 10, 15 and 20 %, N.G. with swirl, air swirl numbers of 0.5 and 0.87, air to fuel mass ratio of 30 and thermal load of 110 kW on temperature patterns are shown in Figs.6-7, from these figures, when the natural gas fuel, N.G. with swirl, entering the combustor, the gas axial velocity increases leads to increasing in flame length. The size of high temperatures regions are increased with the increase in natural gas thermal energy percentage. Increasing the natural gas mass flow rate enhanced the rate of evaporation of diesel fuel. Therefore the rate of mixing increase and this leads to the increasing of the flame width and the flame length.

The same behavior of the effect of the natural gas thermal energy percentage on the flame temperature distribution is also found when using different air swirl numbers. Increasing air swirl number, the flame width increased and the high temperature region increased. For air swirl number of 0.5, the high temperatures regions are found at 0.8≤X/D≤2.4, 0.25≤X/D≤2.0, 0.25≤X/D≤2.1 and 0.25≤X/D≤2.3 for natural gas thermal energy percentage of 5, 10, 15 and 20 respectively. For air swirl number of 0.87, the high temperatures regions are found at 0.25≤X/D≤1.5, 0.25≤X/D≤2.0, 0.25≤X/D≤2.1 and at 0.25≤X/D≤2.5 for natural gas thermal energy percentages of 5, 10, 15 and 20 %, respectively.

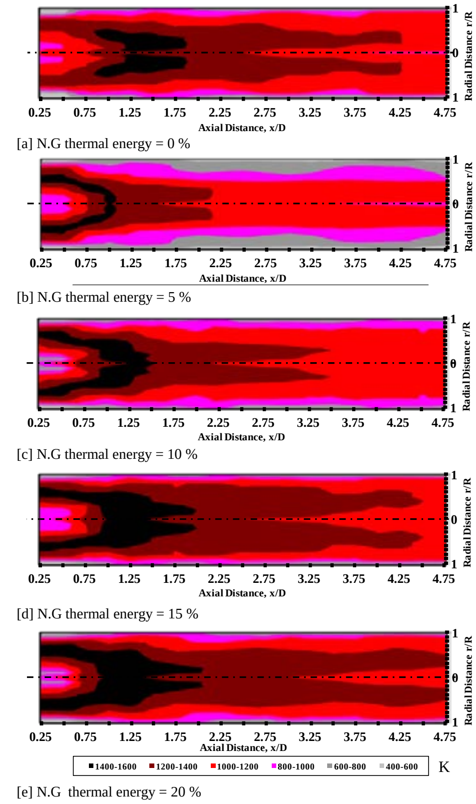

Fig. 5 Effect of N.G thermal energy percentages on temperatures maps [S =0.87, Sg = 0.0, AFR =30 and T.L. = 110 kW]

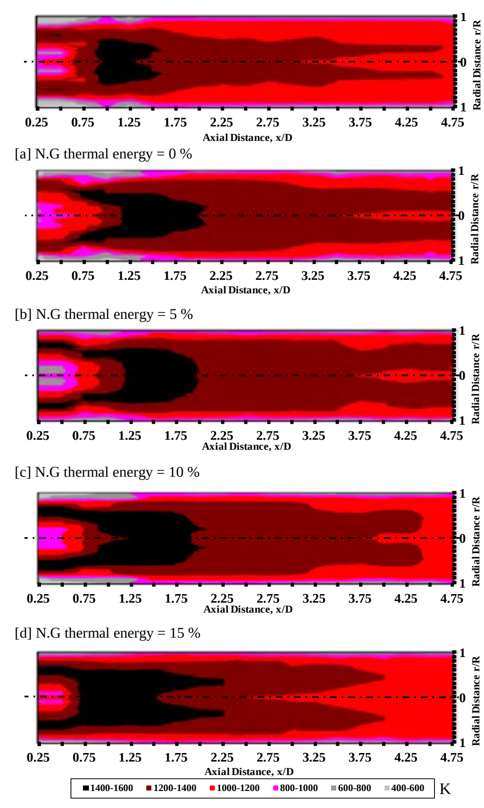

Fig. 6 Effect of N.G thermal energy percentages on temperatures maps [S =0.5, Sg = 0.5, AFR =30 and T.L. = 110 kW]

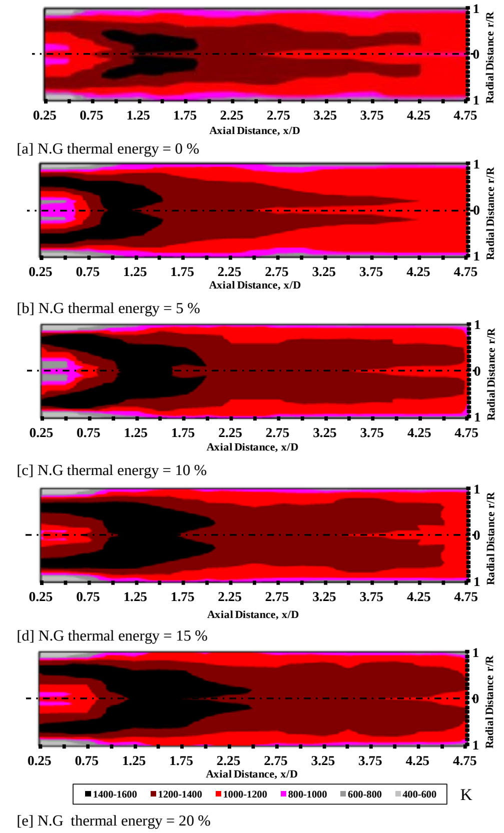

Fig. 7 Effect of N.G thermal energy percentages on temperatures maps [S =0.87, Sg = 0.5, AFR =30 and T.L. = 110 kW]

3.1.2 Effect of N.G thermal energy percentage on visible flame length

The effect of the natural gas thermal energy percentages, without gas swirl, on the flame length at air swirl numbers 0.5 and 0.87, air to fuel mass ratio of 30 and thermal load of 110 kW is shown in Fig. 8-a. It is shown that, the flame length is increased when increasing the percentage of the natural gas fuel thermal heat. When increasing natural gas thermal energy percentage, the heat released from natural gas burning increased which leads to the increase in the rate of evaporation of diesel fuel, but the N.G. velocity (i.e. momentum flux) increased resulting an observed increase in the flame length. For air swirl numbers of 0.50 and 0.87 when increasing the percentage of the natural gas fuel thermal energy from 5 to 20 %, the flame length increased by 38 % and 40 % for air swirl numbers of 0.50 and 0.87, respectively. Increasing the natural gas thermal energy percentage, the rate of increasing of flame length was increased.

The effect of the natural gas thermal energy percentages, with gas swirl, on the flame length at air swirl numbers 0.5 and 0.87, air to fuel mass ratio of 30 and thermal load of 110 kW is shown in Fig. 8-b. It is shown that, the flame length is slightly increased when increasing the percentage of the natural gas fuel. By increasing natural gas thermal energy percentage, the recirculation zone became stronger and the mixing rate increased results in larger flame size, i.e., longer in flame length and wider flame diameter. Enhance in the mixing rate and evaporation of diesel fuel, resulting in an observed increase in the flame length. For air swirl numbers of 0.50 and 0.87 when increasing the percentage of the natural gas fuel thermal energy from 5 to 20 %, the flame length increased by about 20% and 17 % for air swirl numbers of 0.50 and 0.87,

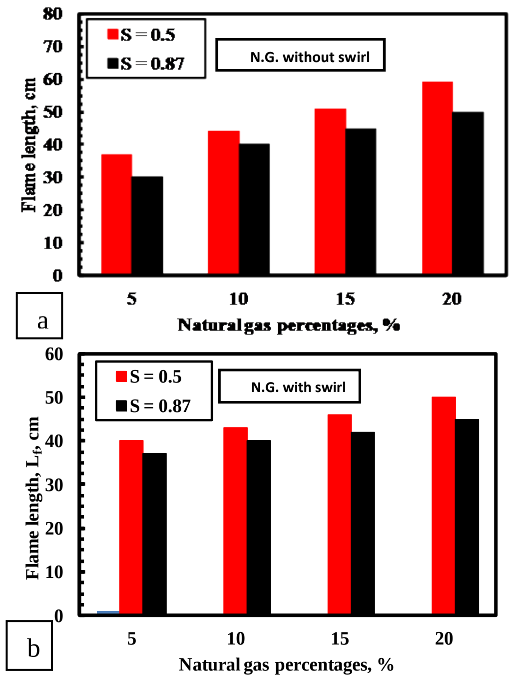

Fig. 8 Effect of natural gas thermal energy percentages on flame length [AFR =30 and T.L. = 110 kW]

3.1.3 Exhaust Species Concentrations

The effect of natural gas thermal energy percentages on species concentrations at air swirl numbers of 0.5 and 0.87, N.G. without swirl and thermal load of 110 kW is shown in Fig. 9. It is shown that, increasing the natural gas thermal energy percentages from 5 to 20%, NOx, and CO2 concentrations increased, but CO and O2 concentrations decreased. At air swirl number of 0.5, when the natural gas percentages increased from 5 to 20%, NOx and CO2 concentrations increased by about 32% and 40 % respectively, but CO and O2 concentrations decreased by about 44 % and 60 % respectively . At air swirl number of 0.87, when the natural gas thermal energy percentages increased from 5 to 20%, NOx and CO2 concentrations continuous increased by about 55% and 44 %, respectively but CO and O2 concentrations continuous decreased by about 39% and 32 %, respectively. Increasing the natural gas thermal energy percentages, the high temperatures region size and the flame length increased due to increase the velocity of natural gas fuel i.e. the momentum flux of gas resulting longer flames. The effect of natural gas percentages on species concentrations at air swirl numbers of 0.5 and 0.87, N.G. with swirl, and thermal load of 110 kW is shown in Fig. 10. It is shown that, increasing the natural gas thermal energy percentages, NOx and CO_2 concentrations increased, but CO and O_2 decreased. At air swirl number of 0.5, when the natural gas thermal energy percentages increased from 5 to 20%, NOx and CO_2 concentrations increased by about 22% and 27% respectively, but CO and O_2 concentrations decreased by about 37 % and

52% respectively. At air swirl number of 0.87, when the natural gas thermal energy percentages increased from 5 to 20%, NOx and CO_2 concentrations continuous increased by about 25% and 29% respectively, but CO and O_2 concentrations continuous decreased by about 33 % and 48% respectively. Increasing the natural gas thermal energy percentages, the high temperatures region size increased and the flame size increased in its length and diameter.

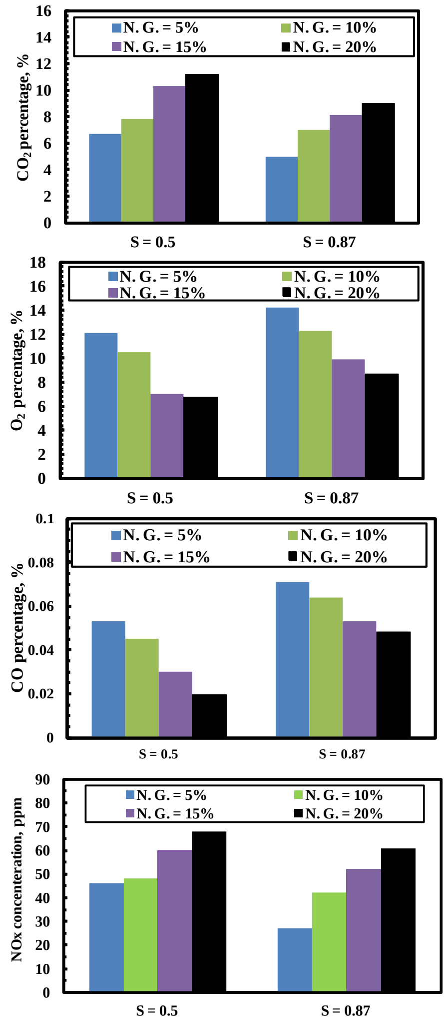

Fig. 9 Effect of the air swirl number on species concentrations at different natural gas percentages [T.L. = 110kW and Sg = 0.0]

3.1.4 Comparison between the diesel fuel and dual fuel flames

The temperatures maps of diesel fuel and dual fuel with natural gas thermal energy percentages of 5, 10, 15 and 20 % is shown in Fig. 11 and Fig.12 when the natural gas without and with swirl, respectively. It is shown that, for diesel fuel flame; a relatively low temperature zone appears at upstream section around the flame centerline due to the existence of dense of fuel vapour. The high temperatures region formed downstream and is found at $0.8 \leq x/D \leq 1.8$. When using the N.G. without swirl as shown in Fig. 11, and for the N.G. thermal energy percentages, the high temperature region formed very close to the burner due to the increase in the evaporation rate of the diesel fuel droplets and hence the chemical reaction increased resulting in high temperature.

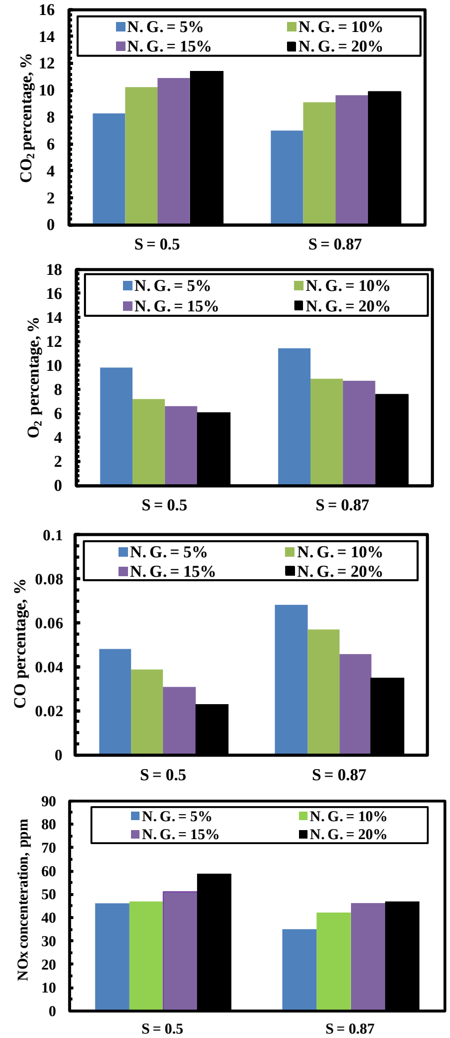

Fig. 10 Effect of the air swirl number on species concentrations at different natural gas percentages [T.L. = 110kW and Sg = 0.5]

The size of this high temperature region increases remarkably by increasing the N.G. thermal energy percentages up to 20 % and formed further downstream and found at axial distance, x/D about 2.1 longer than that of Diesel fuel combustion only. Increasing the N.G. thermal energy percentage up to 10 % the high temperature region size is formed from the burner exit and ended at downstream axial distance, $x/D \leq 1.5$ and still smaller than that of diesel fuel only used of its high temperature region ended at about $x/D \leq 1.8$. While increasing the N.G. thermal energy percentage more than 10 % up to 20 %, the high temperature region size increase remarkably and ended at about axial distance, $x/D \leq 2.1$ which is longer than that of diesel fuel only at about $x/D \leq 1.8$. It can be explained that, increasing the N.G. thermal energy percentage, the amount of N.G. fuel flow rate also increased in time the N.G. fuel velocity increased and also its momentum increased resulting in longer flame length. When using the N.G. with swirl, as shown in Fig. 12. The effect of using N.G. with swirl has stronger effect than that of using N.G. without swirl.

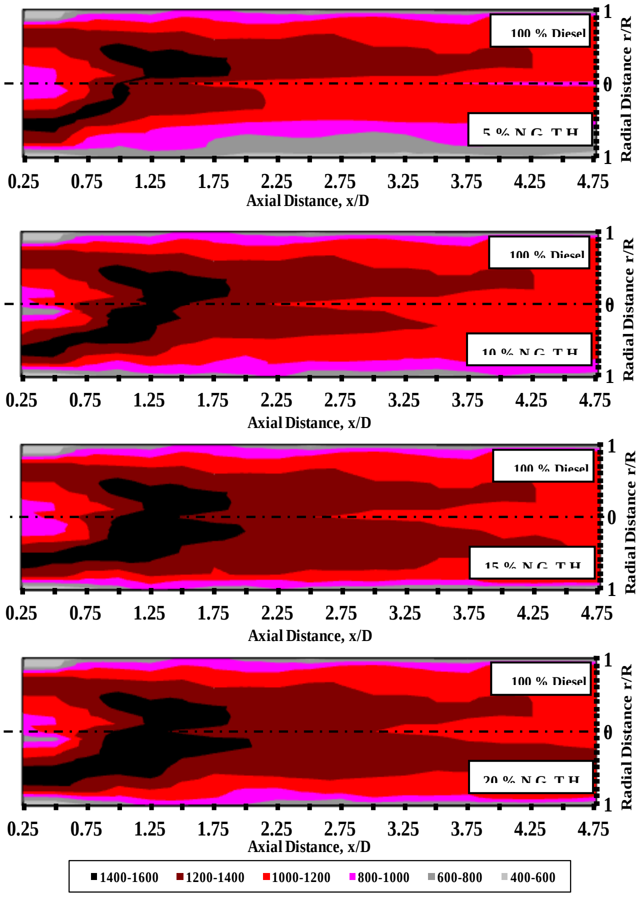

Fig. 11 Comparison of temperature maps for diesel and dual fuels flames [S = 0.87, Sg = 0.0, AFR =30 and T.L. = 110 kW]

The size of flame in its diameter and high temperature region is larger for N.G. with swirl than that of without swirl. For dual fuel flames, N.G. without swirl, the O2 concentrations are higher than that of diesel fuel flame by 5.4, 3.5 and 1.1% for N.G. thermal energy percentages of 5, 10 and 15 %, respectively. These concentrations at N.G. thermal energy percentages of 20 % are 0.1 lower than that for diesel fuel flame. The CO2 concentrations are lower than that of diesel fuel flame only by 3.9, 1.9 and 0.8% for N.G. thermal energy percentages of 5, 10 and 15 %, respectively. These concentrations at N.G. thermal energy percentages of 20 % are 0.1 higher than that for diesel fuel flame, as shown in Fig. 13. When using the N.G. without swirl, The NOx concentrations of the dual fuel flame is lower for N.G. thermal energy up to 10 % of than that of diesel fuel flame. While increasing the N.G. thermal energy percentage more than10 %, the flame length increased and the average exhaust gases temperature became higher than that of Diesel fuel flame only. When using the N.G. without swirl, the CO concentrations of the dual fuel flame is higher for N.G. thermal energy up to 10 % of than that of diesel fuel flame. While further increasing the N.G. thermal energy percentage, the CO concentrations of the dual fuel flame became lower than that of diesel fuel flame. For dual fuel flames, the N.G. with swirl, the O2 concentrations are higher than that of diesel fuel flame by 2.8 and 0.2% for N.G. thermal energy percentages of 5 and 10 %, respectively. But these concentrations at N.G. thermal energy percentages of 15 and 20 % are lower than that of diesel fuel flame by 0.1 and 0.7%, respectively. The CO2 concentrations are lower than that of diesel flame only by 3%, for N.G. thermal energy percentages of 5. However these concentrations at N.G. thermal energy percentages of 15 and 20 % are 0.2 and 0.6 % respectively, are higher than that for diesel fuel flame.

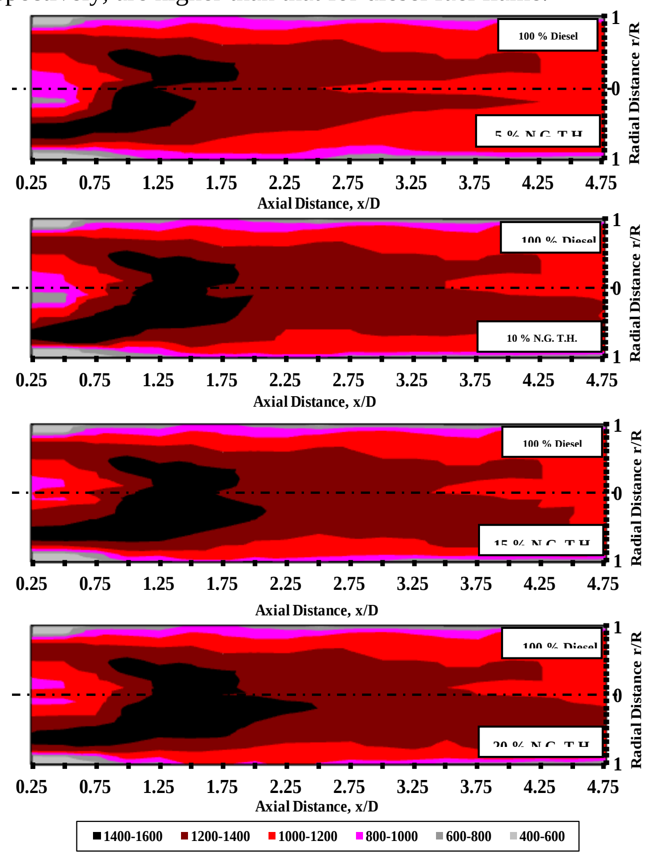

Fig. 12 Comparison of temperature maps for diesel and dual fuels flames [S = 0.87, Sg = 0.5, AFR =30 and T.L. = 110 kW]

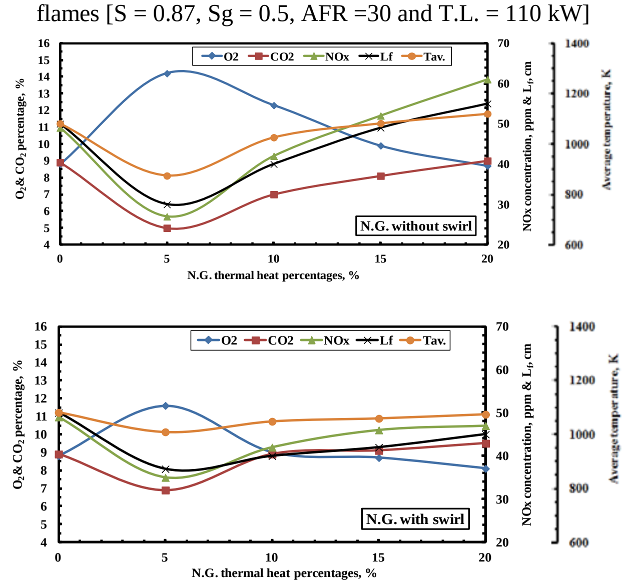

Fig. 13 Effect of N.G. thermal energy percentage on species concentrations, flame length and average exhaust gases temperature [S = 0.87, AFR = 30 and T.L. = 110 kW]

When using the N.G. with swirl, the NOx level of the dual fuel flame up to 20 % of N.G. thermal energy is lower than that of diesel fuel flame. This is because by increasing the N.G. thermal energy percentages up to 20 %, the flame length slightly increased but its length in all N.G. thermal energy percentages shorter than that of diesel fuel flame only resulting in the average exhaust gases temperature became less than that of diesel fuel flame only.

IV. Conclusions

In the present study, the flame combustion characteristics of the dual fuel were studied experimentally. The duel fuel consists of diesel and natural gas fuels. The experiments were carried out when using the diesel or the natural gas fuels alone and besides using the two fuels at same time but with different natural gas thermal energy percentages. The flame combustion of dual fuel (diesel and N.G.) in which the natural gas, with and without swirl, is added into the combustion chamber with different thermal heat percentages of 5, 10, 15, and 20 % of the total thermal.

From the experimental results of the present work, the following conclusions can be summarized:

1. Increasing the natural gas thermal heat percentage, N.G. without swirl, the high temperatures region size and the flame length increase by about 40 %. The NOx and CO2 concentrations increase by about 55% and 44 %, respectively at air to fuel mass ratio, air swirl number and thermal load of 30, 0.87 and 110 kW, while the CO and O2 concentrations decrease by about 32% and 39 %, respectively.

2. Increasing the natural gas thermal heat percentage, N.G. with swirl, the high temperatures region size increases and the flame length slightly increases by about 17%. The NOx and CO2 concentrations increase by about 25% and 29% respectively, while CO and O2 concentrations decrease by about 48 % and 33% respectively at the same operating conditions.

3. When using the N.G. without swirl, The NOx concentrations of the dual fuel flame is lower for N.G. thermal heat up to 10 % than that of diesel fuel flame. While further increasing the N.G. thermal heat percentage, the NOx concentrations of the dual fuel flame became higher than that of diesel fuel flame. While increasing the N.G. thermal heat percentage more than10 %, the flame length increases and the average exhaust gases temperature becomes higher than that of diesel fuel flame only.

4. When using the N.G. with swirl and with thermal heat up to 20%, the NOx level of the dual fuel flame is lower than that of solar fuel flame only.

5. The effect of using N.G. with swirl has stronger effect than that of using N.G. without one. The flame size (diameter and length) is larger for N.G. with swirl than that of without one.

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