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## Article

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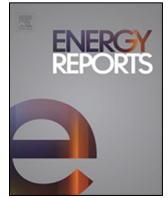
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## Research paper

# Experimental study of spray combustion characteristics of air-blast atomizer

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## ABSTRACT

In the present work, the characteristics of spray combustion an airblast atomizer with an innovative design were experimentally investigated. The flame was stabilized in a water-cooled combustor using air swirler. A test rig was manufactured to investigate the different operating conditions – which include the atomizing Air to Liquid fuel mass Ratio (ALR) of 5, 6, 7 and 8 and the elevated Atomizing Air Temperature (AAT) of 300, 350, 400, and 450 K. The spray combustion characteristics are represented in the form of axial and radial temperatures distributions, temperature gradients, visible flame length, and species concentrations. The axial and radial temperature distributions of flame were measured using the type R thermocouple. The species concentrations were measured by an infrared AO2000 series gas analyzer. The results indicate that the high-temperature combustion region is shifted upstream and outward and the flame length becomes shorter by increasing the value of both ALR and AAT. In addition, the NO concentration reaches its maximum values near the location of the maximum centerline axial temperature. Moreover, it was found that increasing the AAT leads to, on the one hand, decreasing the gas temperature, the O<sub>2</sub> and the CO concentrations at the combustor end, on the other hand, it leads to increasing both the NO and the CO<sub>2</sub> concentrations.

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## 1. Introduction

Combustion of liquid fuels in gas turbines, boilers and industrial furnaces depends on the effective atomization to increase the specific surface area of the fuel, thereby achieving high mixing rates and evaporation. Spray serves as the heart of every type of liquid-fuel combustion system. Ideally, to promote combustion with maximum efficiency and minimum harmful emissions, an injector should deliver a fuel spray that rapidly disperses and evaporates to yield a homogeneous mixture of fuel and air (Lefebvre, 1989). Fuel jets or sheets break up into sprays in various regimes that depend upon the influence and interaction of the liquid's kinetic energy, surface tension, viscosity, and surrounding air. The mechanism, by which the liquid jet breaks up into a spray, is first broached by Rayleigh who analyzed the stability of a low-speed inviscid jet (Lasheras and Hopfinger, 2000).

Some of the atomizer characteristics have been listed for good atomization over a wide range of fuel flow rates and these include the insensitivity to flow instabilities, low power requirements, resistant to blockages, and production of a fine spray. Lin and Reitz (1998) provided a review along with a stability analysis to predict the breakup of liquid jets. Many investigators deal

with fuel sprays optimized for lean combustion (McDonell and Samuelsen, 1991; Razdan, 1998; Mansour, 2005; Nakamura et al., 2006).

The principle of the operation of the airblast atomizer depends on the relative velocity between the air stream and the liquid fuel stream, where the air has relatively high velocity and the liquid fuel has low velocity (Ma et al., 2015; Lefebvre and Dilip, 2010; Pipatpong et al., 2011; Arindam et al., 2013; Sovani et al., 2011; Matouš et al., 2017). The airblast atomizers have many advantages especially in the gas turbine engines. Those advantages include low fuel pressure, finer spray, and creating good mixing between fuels and air which results in low soot formation (Lefebvre, 1980; Min et al., 2016; Hisham, 2012).

The airblast atomizer was found to have significant effects on the spray characteristics. Many researchers investigated experimentally, the effects of the airblast atomizer design on the spray and combustion characteristics. The effects of liquid jet diameter and the internal and external mixing between the atomizing air and liquid fuel in the air blast atomizers were experimentally studied (Baptiste et al., 2016; Gad et al., 2018; Batarseh et al., 2008; Marek, 2016; Hai-Feng et al., 2006; Nguyen and Rhodes, 1998; Jorge et al., 2014).

Increasing fuel viscosity leads to blockage of fuel lines, filters and poor atomization. Jaime et al. (2010) used canola methyl ester (CME) biofuel and petroleum based No. 2 diesel fuel and studied the effects of different parameters, such as air-preheat

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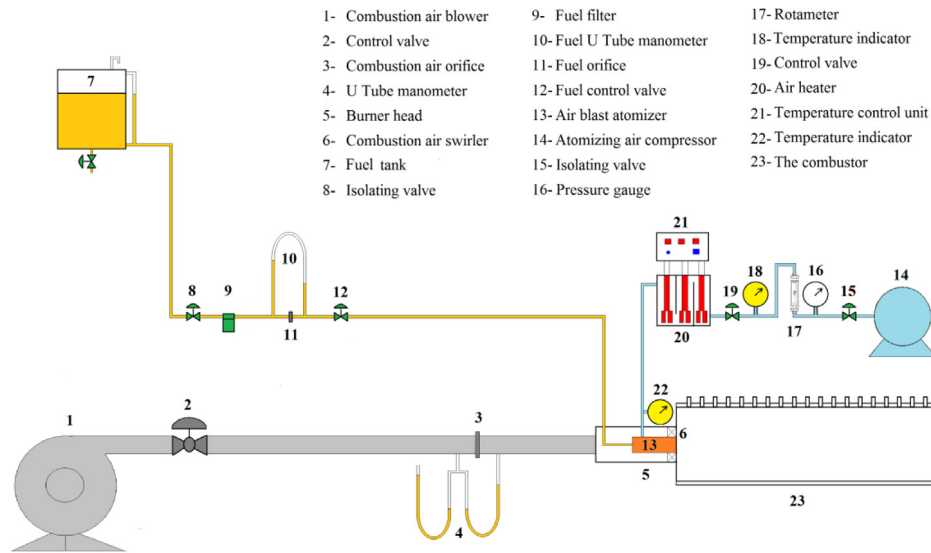


Fig. 1. Schematic diagram of the testing rig.

### Nomenclature

ALR	Atomizing air to Liquid fuel mass Ratio
AAT	Atomizing Air Temperature
$\dot{m}_f$	Fuel mass flow rate, g/s
$\dot{m}_{a,a}$	Atomizing air mass flow rate, g/s
$L$	Combustor length, cm
$L_f$	Flame length, cm
$r$	Local radius, cm
$R$	Combustor radius, cm
$X$	Local length, cm
$S_n$	Swirl number

Table 1

The properties of the commercial diesel fuel.

Fuel property		Units
Kinematic viscosity at 40 °C	1.3–4.1	mm <sup>2</sup> /s
Density	850	kg/m <sup>3</sup>
Carbon	87	wt. %
Hydrogen	13	wt. %
Cetane number	40–55	
Heating value	45	kJ/kg

temperature, global equivalence ratio. Gas temperature, species concentrations (i.e. NO, CO, CO<sub>2</sub> and O<sub>2</sub>), spray droplet size and mean droplet axial/radial velocities.

The effects of preheated air temperature on diffusion flame was studied experimentally by Amer et al. (2015). The combustion air was heated, electrically before entering the combustor, up to a temperature of 500 K. They found that, as the preheated air temperature increases, the volume of the high-temperature region increases and the flame length decreases.

In the present study, the design of the atomizer and its operating conditions selected based on the experimental study carried out by Gad et al. (2018). The main objective of the present work is to investigate, experimentally, the combustion characteristics of the commercial diesel fuel in a continuous combustion system. The effect of changing the Atomizing air to Liquid fuel mass Ratio (ALR) are investigated. Four values of ALR, i.e. 5, 6, 7 and 8. Also, the effects of the Atomizing Air Temperature (AAT). Also, four different values of AAT, i.e. 300, 350, 400, and 450 K, are investigated. The properties of the commercial diesel fuel are shown in Table 1.

## 2. The test rig

In order to investigate the effects of changing the values of the ALR and the values of the AAT on the combustion characteristics of an air blast atomizer with an innovative design, a testing rig was designed and constructed. This testing rig consists of a combustion air line, an atomizing air line, an atomizing air heating

unit, a fuel line, a burner head and a combustor. The layout of the testing rig is shown in Fig. 1. In the heating unit of the atomizing air, the steel box is divided into four sections by steel baffles to force the atomizing air to pass through all electrical heaters. The desired temperature is monitored on a temperature indicator and is controlled manually by changing the electric power of the heaters. The heating unit of the atomizing air is, schematically, shown in Fig. 2. The fuel flows by gravity from the upper fuel tank which is located at about 6 m above the fuel orifice. The combustion air swirler with swirl number 0.87 is used as a flame stabilizer.

The fuel enters the air blast atomizer which has an atomizing air swirler. This air swirler gives the atomizing air a swirling motion before exiting the orifice. The air blast atomizer is coaxial with the combustion air swirler. The dimensions and the construction of the used airblast atomizer are taken from Gad et al. (2018) and are shown in Fig. 3. The fuel nozzle diameter ( $D$ ) and the Atomizing Air Swirler Angle (AASA) are taken constants as 1.0 mm and 45°, respectively. A water-cooled horizontal combustor tube was manufactured with inner diameter and length of 20 cm and 100 cm, respectively. The combustor has nineteen measuring tapings distributed along its length as shown in Fig. 4.

## 3. Experimental results and discussion

The flame characteristics of the combustion of the commercial diesel fuel using air blast atomizer are studied. Combustion air to fuel mass ratio, air swirl number and thermal load are chosen and kept constant at 30, 0.87 and 45 kW, respectively. The effects of changing values of the ALR and values of the AAT are studied.

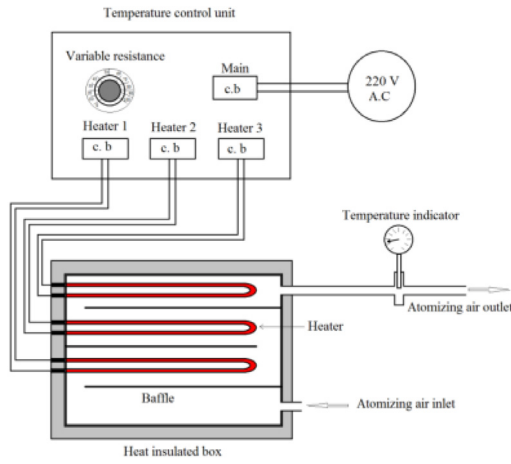


Fig. 2. Heating unit of the atomizing air.

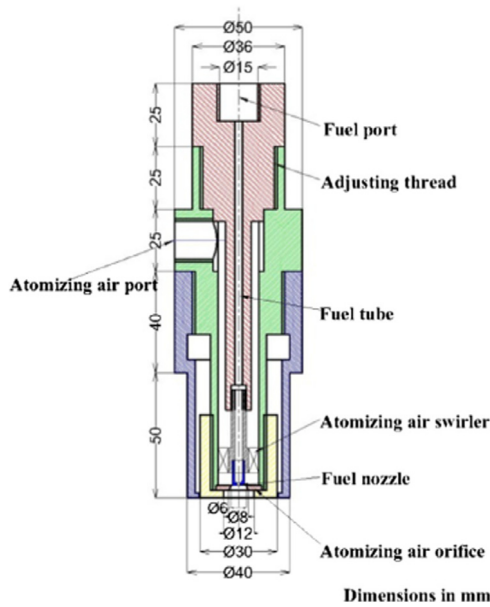


Fig. 3. Schematic of the airblast atomizer assembly.

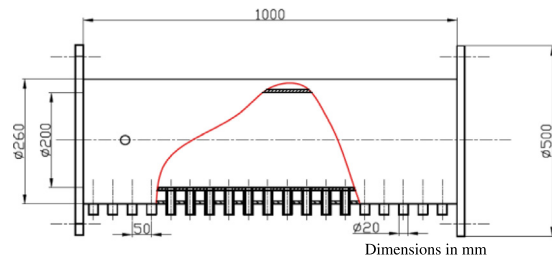


Fig. 4. Combustor tube dimensions.

### 3.1. Effect of changing the ALR

The values of the ALR were taken as 5, 6, 7 and 8. The values of the ALR was varied by changing the atomizing air mass flow rate while keeping the fuel mass flow rate constant at 1 g/s. The effects of changing the values of the ALR on temperature distribution, temperature gradient, the visible flame length and the species concentrations are studied.

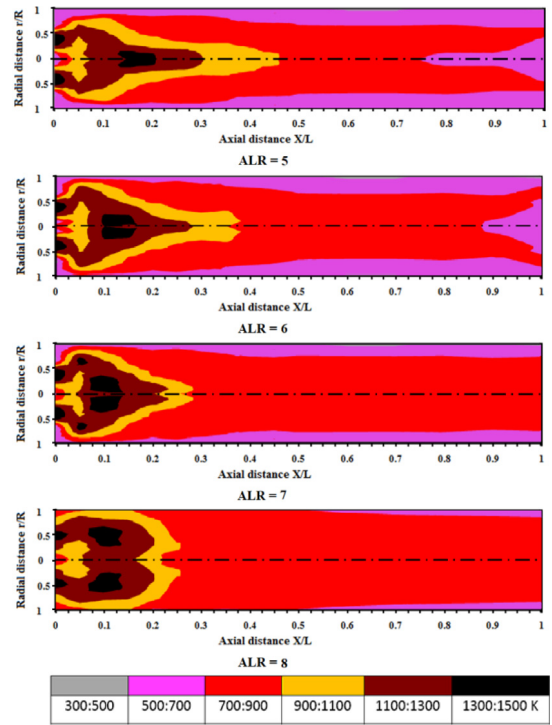


Fig. 5. The effects of changing values of the ALR on the gas temperature distribution.

#### (i) Temperatures distributions

The effects of changing the values of the ALR from 5 to 8 on temperature patterns (temperature maps, radial and axial temperature distributions) and temperature gradient are shown in Figs. 5–8. The axial and radial temperature distributions of the flame were measured using the type R (Pt–Pt Rh 13%) thermocouple with correction factor of 1.03. Data acquisition was used; the data was corrected for radiation and convection errors. The temperature maps for different ALR values are shown in Fig. 5, while the radial temperature distributions are shown in Fig. 6. From the observations of these figures, it is clearly seen that increasing the values of the ALR leads to an increase in the size of the high-temperature region. This can be attributed to the increase of the spray cone angle, which results in enhancement of the spray quality, i.e. smaller droplet size, higher evaporation rate and higher mixing rate of diesel fuel. Moreover, it can be seen that the flame length is decreased while the flame diameter is increased. In addition, a high reaction region can be distinguished with high-temperature values around the flame centerline.

The centerline axial temperature profiles for flames at different values of the ALR are shown in Fig. 7. It is observed that the maximum centerline axial temperature is located upstream before the flame end, i.e. inside the formed reaction zone. Then the temperatures have lower values at further downstream sections. The decrease in the temperatures at downstream sections indicates that the chemical reaction is almost completed. This decrease in temperature is mainly due to the heat transfer from the combustion products to the water-cooled combustor wall. By increasing the values of the ALR, the centerline axial peak temperature location shifts further upstream because the flame becomes shorter due to the improvement of the spray quality and mixing rate.

The gas temperature gradients along the flame axis were obtained from the temperature distribution for the flames at different ALR values, see Fig. 8. It is shown that, at an ALR value of

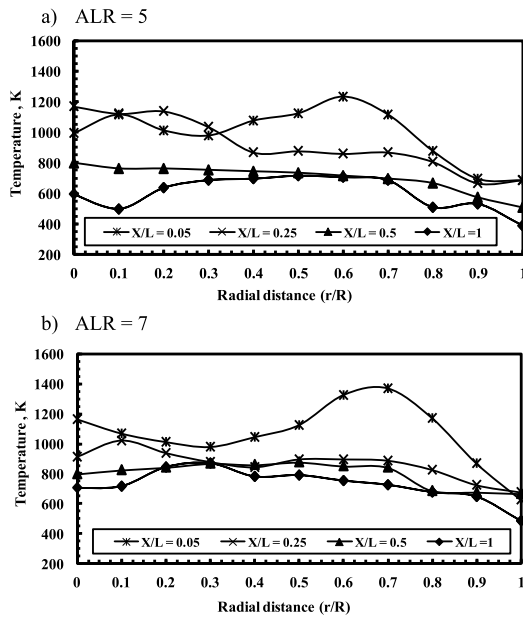


Fig. 6. The effects of changing the values of the ALR on the radial temperature distribution.

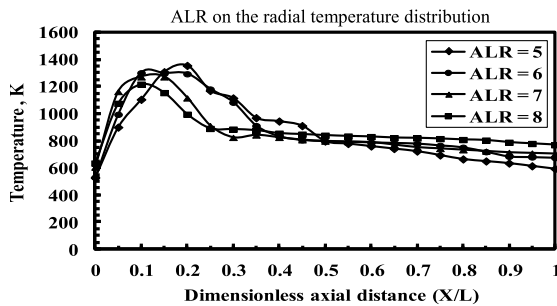


Fig. 7. The effects of changing the values of the ALR on the centerline axial temperature distribution.

5, the temperature gradient curve has more than one peak, and the temperature gradient reaches a steady state value at about 55% of the combustor length. For the value of the ALR of 8, the temperature gradient curve has just one peak at about 5% of the combustor length, then it starts to be convergent with small values from about 30% of the combustor length to the end of the combustor.

The small values of the temperature gradient, almost about zero, after 30% and 55% of the combustor tube length for ALR of 5 and 8, respectively, indicate that the chemical reaction is nearly completed upstream from these axial locations.

### (ii) visible flame length

The effects of changing ALR values on the visible flame length is shown in Fig. 9. It can be seen that, as the ALR increases from 5 to 8, the visible flame length is decreased by about 22%. The reduction of the visible flame length is due to the increase in the atomizing air flow rate which corresponds to higher atomizing air velocity. Therefore, the spray quality is improved and this led to decrease the time needed to complete the evaporation of the spray droplets. This means that the spray droplets will move shorter distances inside the combustor to be evaporated and burned, consequently this causes a reduction in the visible flame length.

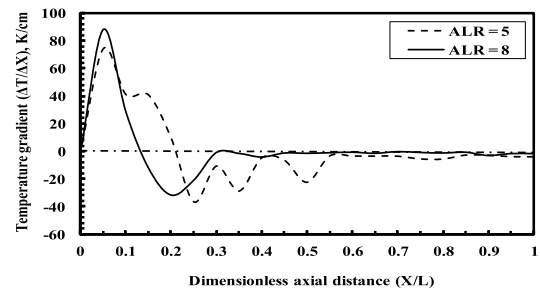


Fig. 8. The effects of changing the values of the ALR on the axial temperature gradient.

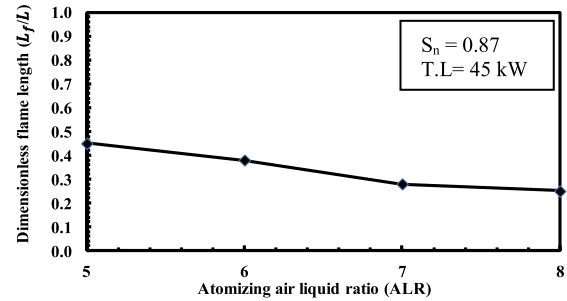


Fig. 9. The effects of changing the values of the ALR on visible flame length.

### (iii) species concentration

The species concentrations are measured by Advanced Optima Uras 26 for CO<sub>2</sub>, CO and NO measurements and by Magnos 206 for O<sub>2</sub> measurement the maximum uncertainties are 0.48%, 0.65%, 0.01 ppm and 0.03 ppm for O<sub>2</sub>, CO<sub>2</sub>, CO and NO respectively. The species concentrations are measured along the axis of the combustor tube. The effects of changing the values of the ALR on the species concentrations along the axis are presented in Fig. 10, while Fig. 11 shows the effects of changing the values of the ALR on the species concentrations at the end of the combustor tube. It is found that, by moving axially downstream of the combustor tube, the concentrations of CO and O<sub>2</sub> are decreased while the concentration of NO is increased. Also, the concentration of NO is increased to reach its maximum values close to the high-temperature zone then the concentration of NO is decreased gradually to the end of the combustor.

By increasing the values of the ALR, the atomization process is improved which leads to an enhancement in the mixing process between air and fuel. This leads to an increase of fuel oxidation which means that some of the CO will be converted to CO<sub>2</sub> accompanied with more release of heat energy from the combustion process. Increasing the heat released from the combustion process raises the temperatures of the flame which leads to an increase of the NO formation. It could be concluded that increasing the ALR leads to an increase of NO and CO<sub>2</sub> concentrations, but a decrease of CO and O<sub>2</sub> concentrations.

The axial NO concentration and temperature profiles along the combustor tube centerline for the values of the ALR of 5 and 8 are shown in Fig. 12. It can be seen that both of them have the same trend, as shown in Fig. 11. The peak values of NO are happened to occur at the same position where the maximum temperature takes place. This means that the reaction rates depend on reactant temperatures.

### 3.2. The effects of changing AAT

A set of experiments were carried out to quantify the effect of changing the AAT from 300 K to 450 K, on temperature distributions, temperature gradient, visible flame length, and species

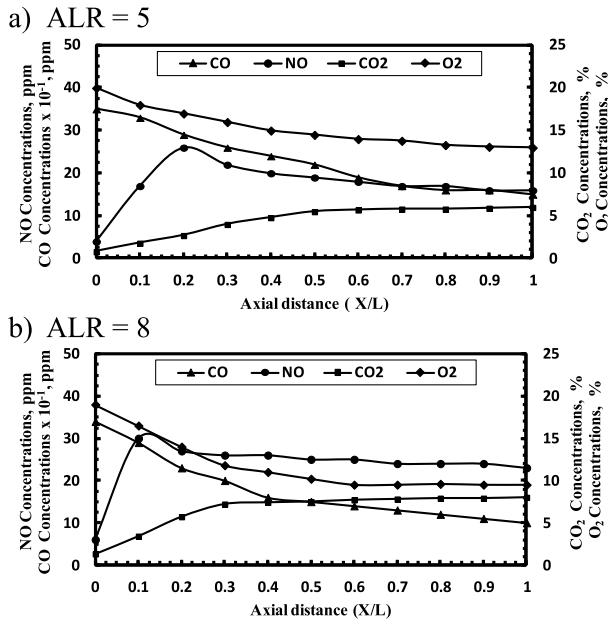


Fig. 10. The effects of changing the values of the ALR on the axial species concentrations.

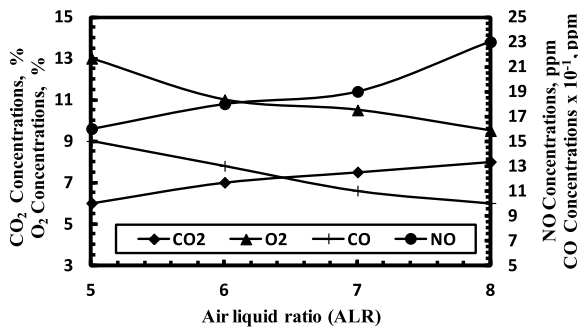


Fig. 11. The effects of changing the values of the ALR on the species concentrations at combustor end.

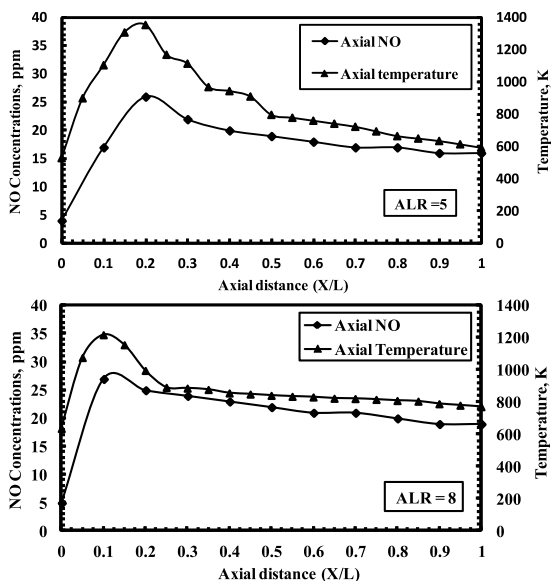


Fig. 12. The NO axial concentration and gas temperature profiles for ALR = 5 and 8.

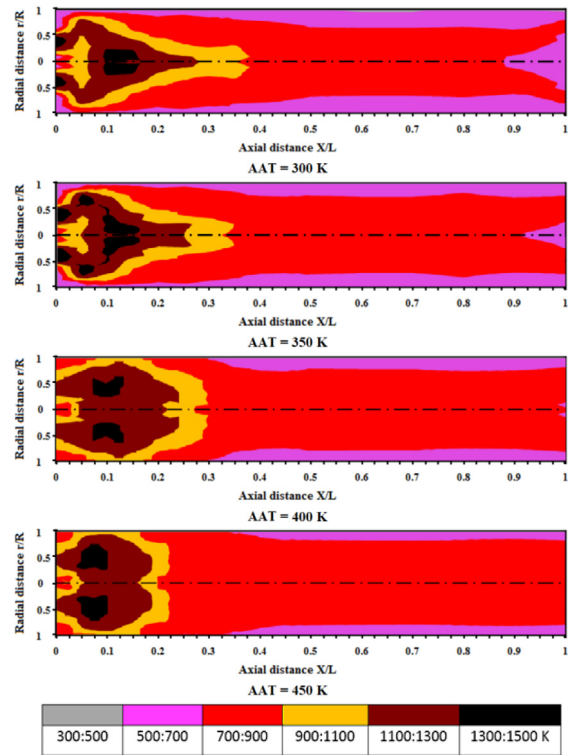


Fig. 13. The effects of changing the values of the AAT on temperature distribution.

concentrations at values of ALR, air swirl number and thermal load of 6, 0.87 and 45 kW, respectively.

(i) temperature distributions

The effects of changing the values of the AAT, from 300 K to 450 K in steps of 50 K on gas temperature patterns (temperature maps, radial and axial temperature distributions) and temperature gradient are shown in Figs. 13–16. The temperature maps for different AAT values are shown in Fig. 13 and the radial temperature distributions are shown in Fig. 14. From these figures, it can be seen that by increasing the AAT values, the high-temperature region is shifted upstream close to the burner, the flame diameter is increased by increasing the values of the AAT. This can be attributed to the increase in the evaporation rate of the commercial diesel fuel.

The centerline axial temperature profiles for flames at different values of the AAT are shown in Fig. 15. It is noted that, by increasing the AAT, the temperature of the fuel spray droplets increased, during the atomization process. The evaporation rate increased too, and the flame became wider and shorter, and the high-temperature region is shifted upstream, the atomization process and the combustion are improved by increasing the values of the AAT. This leads to increasing the heat energy released from the combustion which leads to the decrease in the centerline axial temperatures at the combustor exit.

The temperature gradients along the axis of the combustor tube at the values of the AAT of 300 and 450 K are shown in Fig. 16. It is inferred that each temperature gradient curve has only one peak and the temperature gradient starts to be convergent with small values from about 50% of the combustor length for AAT = 300 K, while at AAT of 450 K the temperature gradient convergent with small values from about 33% of the combustor length. This means that increasing the AAT enhances the spray quality, i.e. smaller droplets and higher surface area of

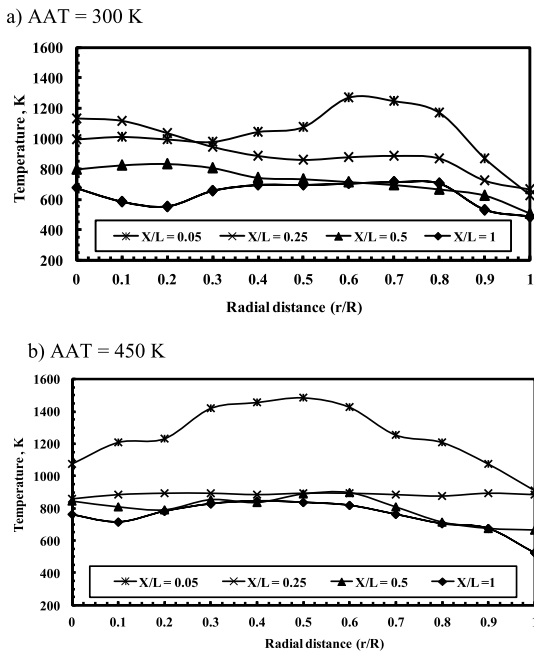


Fig. 14. The effects of changing the values of the AAT on the radial temperature distribution.

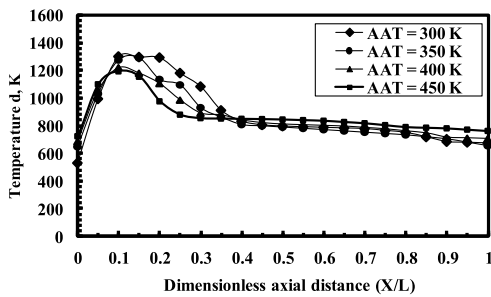


Fig. 15. Effect of changing AAT on the centerline axial temperature distribution.

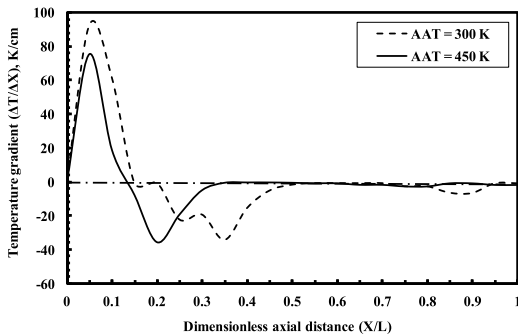


Fig. 16. The effects of changing the values of the AAT on the temperature gradient at the combustor centerline.

fuel and mixing rate, and hence the chemical reaction between fuel and air is enhanced.

**(ii) visible flame length**

The effects of changing the values of the AAT on visible flame length are shown in Fig. 17. It can be seen that, the lower the values of the AAT, the longer flame length by increasing; the AAT from 300 to 450 K, the visible flame length is decreased by about

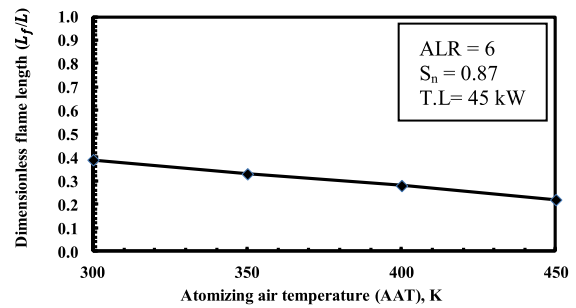


Fig. 17. The effects of changing the values of the AAT on the visible flame length.

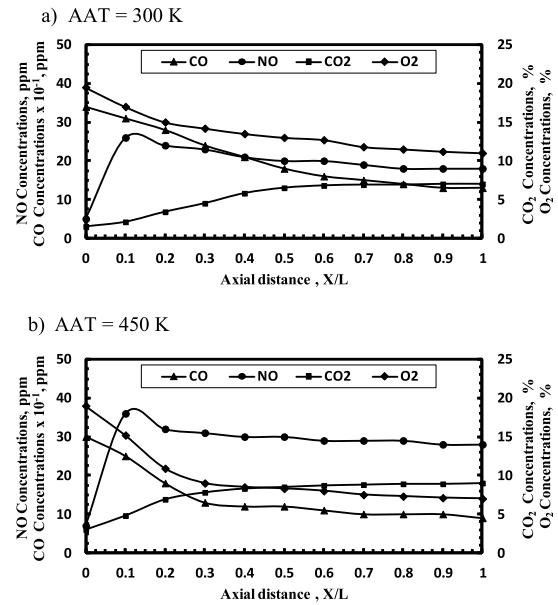


Fig. 18. The effects of changing the values of AAT on the axial species concentrations.

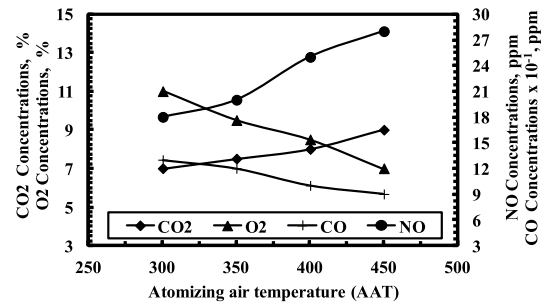
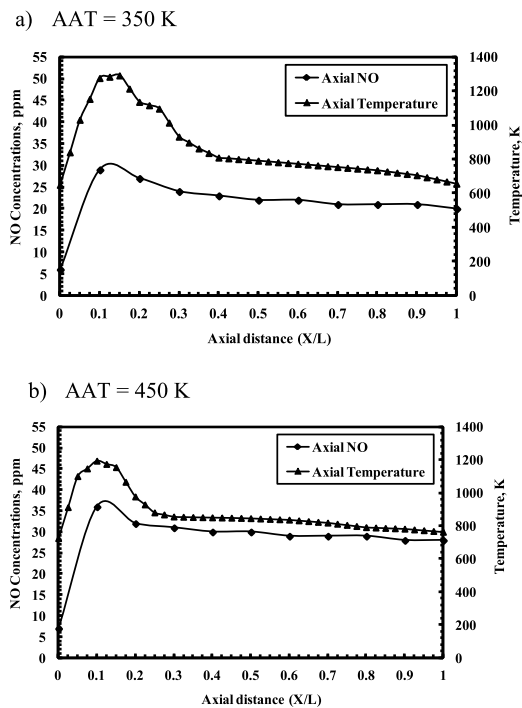


Fig. 19. The effects of changing the values of AAT on the species concentrations at combustor tube end.

25%. By increasing the values of the AAT, the time needed to complete evaporation of the spray droplets is decreased. Therefore, the spray droplets burned early, i.e. at a shorter distance from the atomizer/swirler, and thus causing a reduction in the visible flame length.

**(iii) Species concentration**

The effect of changing the values of the AAT on the centerline species concentrations are shown in Fig. 18. The species concentrations at the combustor tube end are shown in Fig. 19. Furthermore, the chemical reaction is nearly completed and hence the carbon dioxide increases to reach its maximum at the flame



**Fig. 20.** The NO concentration and the gas temperature profiles along the centerline of the combustor tube.

front. Consequently, carbon monoxide and oxygen concentrations decreases.

The nitrogen oxide concentration increased to its peak values which matched with the peak temperatures. Then, it decreased, likewise the flame temperatures to the combustor end. Increasing the AAT improved the atomization process which leads to enhancement in the combustion process. Consequently, the gas temperatures increases which matched with NO concentrations according to Zeldovich mechanism. By increasing the values of the AAT, the NO and CO<sub>2</sub> concentrations increased while the CO and O<sub>2</sub> concentrations decreased at the end of the combustor tube as shown in Fig. 19.

The gas temperature profiles are found to have the same trend of NO profiles. Both of the centerline NO concentration and the centerline gas temperature are shown in Fig. 20.

#### 4. Conclusions

From the experimental results of spray combustion using air blast atomizer by changing: 1- the values of the ALR to be 5, 6, 7 and 8. 2- the AAT to be 300, 350, 400 and 450 K, the following conclusions are obtained.

- By increasing the values of both the ALR and the AAT, the high temperature regions are shifted upstream towards the burner head and also are shifted outward far away from the combustor. In addition the flame length becomes shorter and its diameter is increased by increasing the ALR and AAT.
- The visible flame length is decreased by about 22% by increasing the values of the ALR from 5 to 8 while it is decreased by about 25% by increasing the values of the AAT from 300 to 450 K.
- By increasing the values of the ALR from 5 to 8, the O<sub>2</sub> and the CO concentrations are decreased, however, the NO and the CO<sub>2</sub> concentrations are increased, at the combustor end.

- By increasing the values of the AAT from 300 and 450 K, the O<sub>2</sub> and the CO concentrations are decreased while the NO and the CO<sub>2</sub> concentrations are increased, at the combustor end.
- The NO concentration and the gas temperature profiles are found to have the same trend.
- Under the current setup, the flame characteristics could be enhanced by increasing the values of both the ALR and the AAT. However, this leads to an increase in the NO concentration. The ALR has significant effect higher than the AAT.

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