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Effect of Atomizing Air Swirl Angle on Combustion and Emission Characteristics of Spray Flame

A. K. Khodir, Gaber M. Asar, Samy M. El-Behery andW. A. El-Askary
Mechanical Power Engineering Department. Faculty of Engineering, Menoufia University, Shebin El-Kom, Egypt
Corresponding Author:Samy M. El-Behery

Abstract:*In the present paper, the effect of atomizing air swirl intensity on the combustion and emissions of liquid fuel is investigated experimentally.An external mixing air assist atomizer is used in order to qualitatively analyze the flame structure in a small scale water cooled laboratory furnace. The atomizer design allows changing the atomizing air swirl angle. Three cases of swirl angles (15, 30 and 45^o) in addition to no swirl case are studied. In each case, the exhaust emissions, axial and radial inflame temperature profiles; exhaust gas temperature, flame length and the heat transfer distributions for the water jacket are measured. Experimental results indicated that the inflame temperature increased and the flame length decreased with increasing the atomizing air swirl angle. Decreasing the atomizing air swirl angle leads to an increase in the overall heat transferred to the cooling water jacket. In addition, increasing the air swirl angle decreases the CO and NOx emission level.*

Keywords:A*ir assist atomizer, Spray combustion, Emissions, Swirl intensity, Inflame temperature, Flame length.*

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I. Introduction

Currently, spray combustion of liquid fuels provides a considerable part of the world energy resources. Considerable percentages of fuels are in a liquid phase such as diesel, vegetable oils and biodiesel. Unfortunately, global warming and climate change have been increased remarkably, due to emissions from the combustion applications. Industrialized countries are forced to pay attention to the issue of emission reduction in spite of their increasing demand of energy. For this reasons, it is important to burn liquid fuels with high combustion efficiency and low pollutant emissions. The spray combustion of liquid fuels is of significant practical importance and currently accounts for a considerable share of the world energy use [1]. Air-assisted atomizer spray flames, as commonly used in industrial furnaces, boilers, and gas turbine combustors. The purpose of swirling air is to enhance the atomization characteristics and mixing of reactants at low fuel injection pressures, and to control the spray cone angle. The swirling motion introduced into the fuel and air flows for the control of flame stability, flame length, combustion intensity and efficiency, causes the structure of air-assist atomizer spray flames to be different from that of turbulent gas diffusion flames [2]. Structure of igniting ethanol and n-heptane spray flames with and without swirl was studied by Letty et al. [3]. They found that swirl induces a wider and shorter flame, precession, and multiple reaction zones, while the non-swirling flames had a simpler structure. Marrero-Santiago et al. [4] investigated experimentally the aeronautical ignition in a swirled confined jet-spray burner. They concluded that the outer recirculation zone is the best region for placing the spark. Yilmaz and Yilmaz [5] studied experimentally the combustion and emission characteristics of premixed flame in a combustor with a geometric swirl number varied between 0.2 and 1.6. They found that the widest stable combustion range was achieved at a swirl number of 1.4. The characterization of atomization and combustion of turbulent spray flames produced by an external mixing air assist atomizer was presented by Kourmatzis et al. [6, 7]. They reported that the sprays with significant atomization at the exit plane of the burner are of intermediate complexity between dilute and fully dense sprays.

Pollutant emission of gaseous and liquid aqueous bioethanol combustion in swirl burners was studied. Hydrous ethanol was produced to the largest extent among all renewable liquid fuels. The utilization of aqueous ethanol, however, seems to be a more economical solution due to considerable savings on the production costs while the combustion performance is affected slightly [8]. Combustion and exhaust emission characteristics of low swirl injector were studied by Deng et al. [9]. They found that the NOx and CO emission levels depended mainly on the gas composition and thermal load. Abu-Qudais [10] studied experimentally the performance and emissions characteristics of a cylindrical water cooled furnace using non-petroleum (shale oil) fuel. It was found that the rate of heat transfer to the water jacket of the water cooled furnace is improved in the case of shale oil compared to diesel fuel when they are tested under the same conditions. Combustion and emission characteristics of kerosene/bio-oil were studied experimentally by Yang et al. [11]. It was found that increasing the spray angle reduces the droplet size distribution. In addition, they also found that the increasing the turbulence intensity enhances the mixing of the vaporized droplets and the oxidizer and in turn hastening and intensifying the combustion and shortening the flame length. The addition of CO_2 to the oxidizer is normally used in oxy-fuel combustion to prevent too high flame temperatures. Oxygen-enriched combustion using recirculated flue gases, rich in CO_2, is an effective way of controlling furnace temperature and reduces the fuel consumption [12]. In addition, the heat transferred by radiation increases due to the higher CO_2 concentration and soot volume fraction in the flame [13]. Nitrogen, Argon, and CO were used as the atomizing gas in an air-assist fuel nozzle to determine the effect of these gases on droplet size, number density, and velocity distribution in kerosene spray [14]. The introduction of swirl to the combustion air modifies the droplet/air velocity field in addition to the spatial distribution of droplet size and number density [15]. Abu-Qudais and Gassan [16] reported an extensive experimental study for the atomization and direct combustion of a liquid fuel olive-cake (OC) slurry. The liquid fuel is atomized using a twin fluid atomizer. Three angles of swirl (0, 30 and 45^o) have been used for the atomizing air and the fuel was fed from an overhead tank by gravity.

According to the previous background, further investigations are necessary in order to improve the existing knowledge of the effect of atomizing air swirl angle on the combustion and emission characteristics. This paper introduces an extensive experimental study for four cases of atomizing air swirl angles (0, 15, 30 and 45^o). An external mixing air assist atomizer is used and installed in a burner tube. The tests are performed using a small scale water-cooled laboratory combustor. Specifically, this work intends to examine the impact of atomizing air swirl angle on the flame structure, spatial distributions of temperature, heat flux and emissions.

II. Experimental Setup

An experimental setup was designed and constructed to provide an experimental data of spray flame combustion. The test rig shown schematically in Fig. 1 consists of a horizontal small-scale cylindrical furnace (1) equipped with an external mixing air assist atomizer (2) which installed through the burner (3). The combustion air is supplied to the burner by a centrifugal blower (4). The combustion air flow rate is regulated through a globe valve (5) and measured using calibrated orifice meter (6). The atomizing air is supplied from a large tank (7) of volume 7 m^3 and charged with screw compressor (8). The atomizing air pressure is regulated through a pressure regulator (9) and its flow rate is measured using calibrated orifice meter (10). The liquid fuel is supplied from a tank (11) pressurized by a compressed air. The pressure of compressed air in the fuel tank is regulated using a pressure regulator (12). The fuel is filtered through a filter (13) to prevent the atomizer blockage, hence keep a constant fuel flow rate. A pressure relief valve (14) is used as a safety valve and helps in keeping constant air pressure above the liquid fuel surface. The combustor is an insulated horizontal cylindrical water cooled flame tube of 480 mm inner diameter and 1500 mm length manufactured of thick steel sheet of 5 mm thickness. The cylindrical flame tube is cooled by a water circular jacket of 600 mm external diameter and is segmented to a 10 unequal segments. At the middle of each segment a radially aligned tap of 15 mm diameter is provided to allow the insertion of the different temperature measuring probes. A 50 mm diameter main cooling water header is used for the distribution of the cooling water to each segment via an 18.5 mm diameter inlet pipe (15) at the bottom of each segment. Gate valves (16) are located at the entrance of each segment for the purpose of controlling the water flow rates. The volume flow rate of cooling water is measured using a calibrated orifice meter at the inlet of each segment. The hot water leaves each segment at the top side (17) and its temperature is measured using thermocouple (18) before drained to the sink. The exhaust temperature is measured at exhaust port (19). The emissions are measured using gas analyzer (20) at port (21). Figure 2 illustrates a schematic diagram of an external mixing air assist atomizer. The fuel nozzle has a diameter of 1mm. The atomizer is installed through a burner tube as shown in Fig. 3a while figure 3b presents a photograph of the air swiler.

III. Measuring Instruments

This section describes the different measuring devices that are used to measure inflame temperature distribution, exhaust temperature, water temperature, air flow rate, emissions, heat flux and fuel flow rate. The inflame temperature and exhaust gas temperature measurements system consists of thermocouple and position guide. The thermocouple employed in the present study is made of platinum/ (platinum 10% rhodium) wires of 190 µm diameter. The thermocouple wires are supported in a twin-bore ceramic tube having an external diameter of 4 mm. The ceramic tube is placed inside a stainless steel tube of 6 mm external diameter. The temperature of the hot water at the exit of each furnace segment is measured using calibrated T-type thermocouple located at the exit of each segment. The fuel flow rate, combustion air and atomizing air flow rate are measured using calibrated orifice meter for each. The exhaust gases' concentrations are measured using calibrated E-instrument gas analyzer.

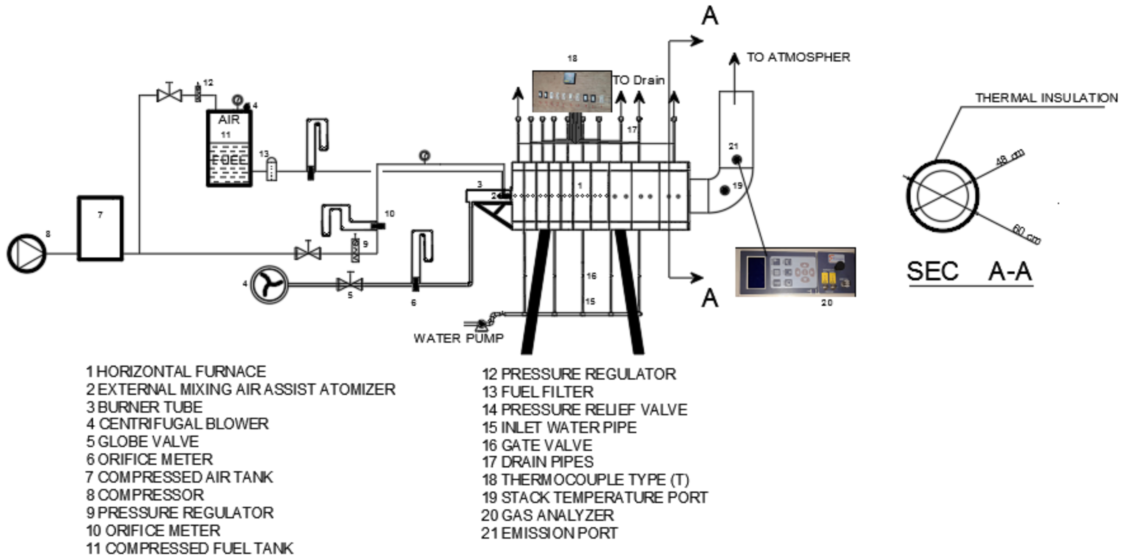
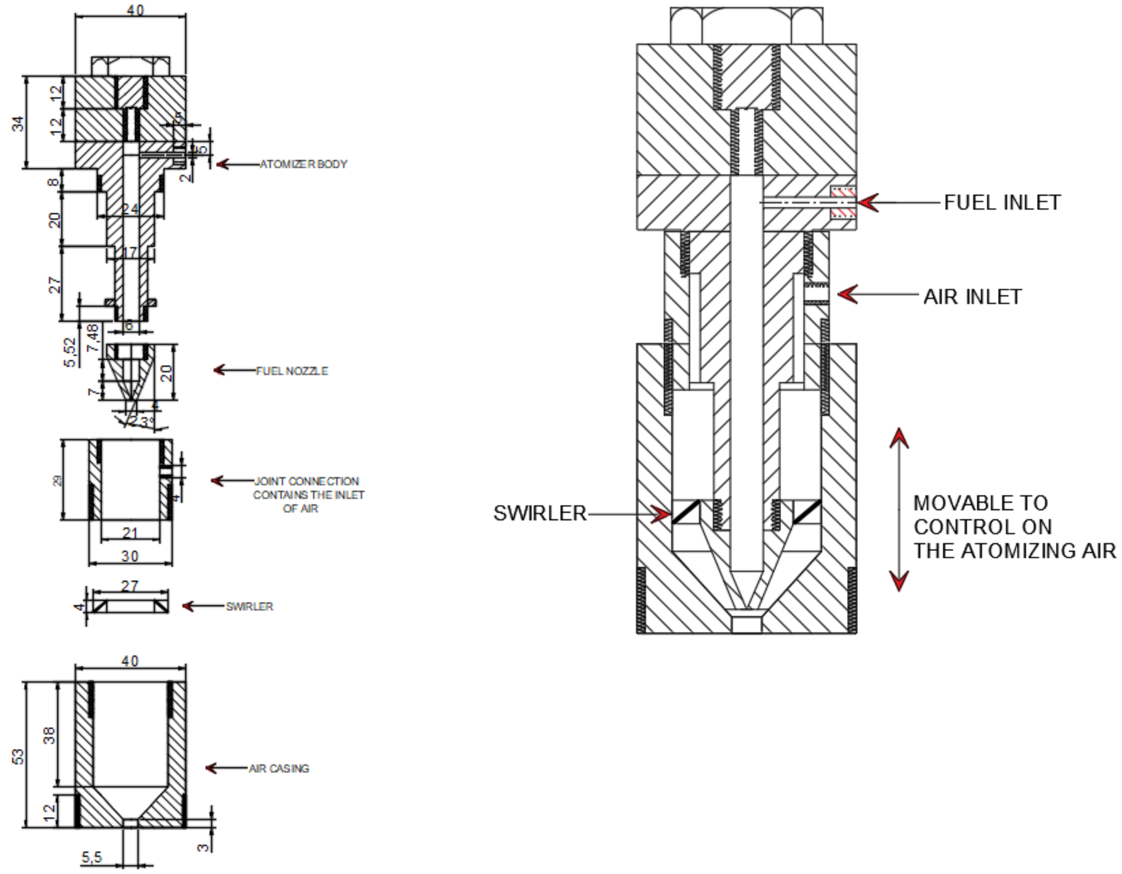


Fig. 1. Schematic diagram of an experimental test rig.



a. Detailed drawing(dimensions in mm). b. Assembly drawing

Fig. 2. An external mixing air assist atomizer.

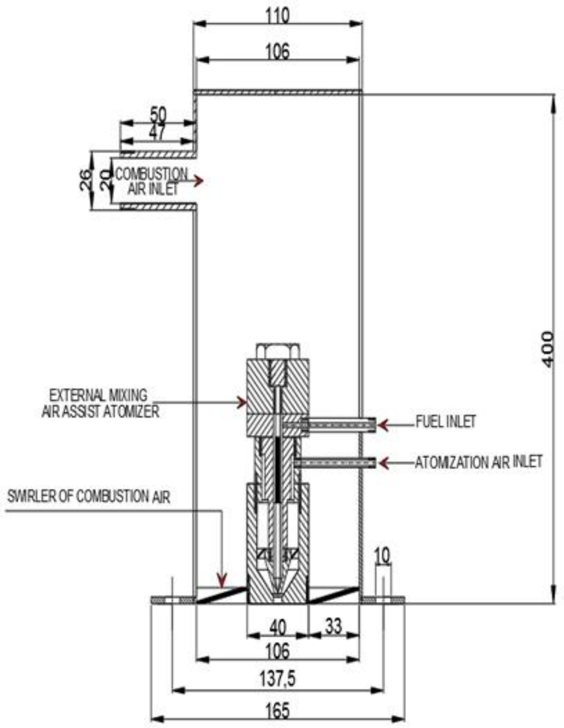


Fig. 3a. Burner assembly (dimensions in mm).

Fig. 3b. Atomizing air swirl generators with different angles

IV. Methodology

The atomizing air is swirled using swirl generator (swirler) that manufactured with different angles (15, 30 and 45 ^{o}). The effect of atomizing air swirl angle is studied at the same atomizing air pressure 1.5 bar, combustion air swirl angle 45^o and air to fuel ratio 20 kg_{air}/kg_{fuel}. The inflame temperature, emissions, heat flux and exhaust temperature of an external mixing air assist atomizer flame are measured. The physical properties of an Egyptian diesel fuel are given in Table (1) which obtained from Misr Petroleum Company. The chemical composition of the fuel is analyzed at micro analytical center in Cairo University and listed in Table (2). The flame characteristics is obtained at different values of atomizing air swirl angles (0, 15, 30 and 45^o) at constant air to fuel ratio and the same atomizing air pressure. The emissions (CO and NOx), combustor efficiency, axial and radial inflame temperature profiles and the heat transfer distribution for the water jacket are obtained in each case. A direct picture of the free flame is taken using a full frame Nikon D600 Camera with specifications given in Table (3).

Table (1) Physical properties of diesel fuel.

Test	Unit	Test method	Results	
Relative Density @60/60oF		ASTM D-1298 ESS-80	(MIN) (MAX)	0.82 0.87
Flash Point (P.M.C)	^{o}C	ASTM D-93 ESS-177	(MIN)	55
Viscosity Kinematic @40^{o}C	CST	ASTM D-445 ESS-1390	(MIN) (MAX)	1.6 7
Gross Calorific Value	MJ/kg	ASTM D-4868 ESS-420	(MIN)	44.3
Total Sulphur	%wt	ASTM D-2622 ESS-178	(MAX)	1
Conradson carbon	%wt	ASTM D-189 ESS-83	(MAX)	0.1
Ash content	%wt	ASTM D-482 ESS-81	(MAX)	0.01

Table (2) Chemical composition of diesel fuel.

Element	Value
C %	86.73
H %	10.8
S %	2.36
N %	0.13

Table (3) Specifications of the digital camera.

Type	**DSLR (Nikon D600)**
Resolution	24.3 Mega pixels
HD-movie	1920x1080 Mp at 30 fps
	1080x720 Mp at 60 fps
Max shatter speed	1/4000 s.
Frame rate	5.5 fps (at full resolution)
Sensor size	35.9x24 mm (full frame)

V. Results and discussions

In this section the effect of atomizing air swirl angle on temperature distribution, heat transfer to the cooling water and emission will be discussed in detail.

5.1 Axial inflame temperature

Figure 4 shows the inflame temperature distribution along the axis of the flame for different values of atomizing air swirl angles at Pa = 1.5 bar and A/F=20 Kg_{air}/Kg_{fuel}. It is found that the maximum temperature of the flame is at 270 mm from the atomizer tip, at which the mixing of air and fuel was nearly completed. As the atomizing air swirl angle increases, the flame temperature increases in the flame region near to atomizer tip because of good mixing. At low swirl angle, the trailing edge flame temperature is higher than those of big swirl angle. This behavior can be interpreted as increasing atomizing air swirl angle increasing the cone angle and reducing penetration length.

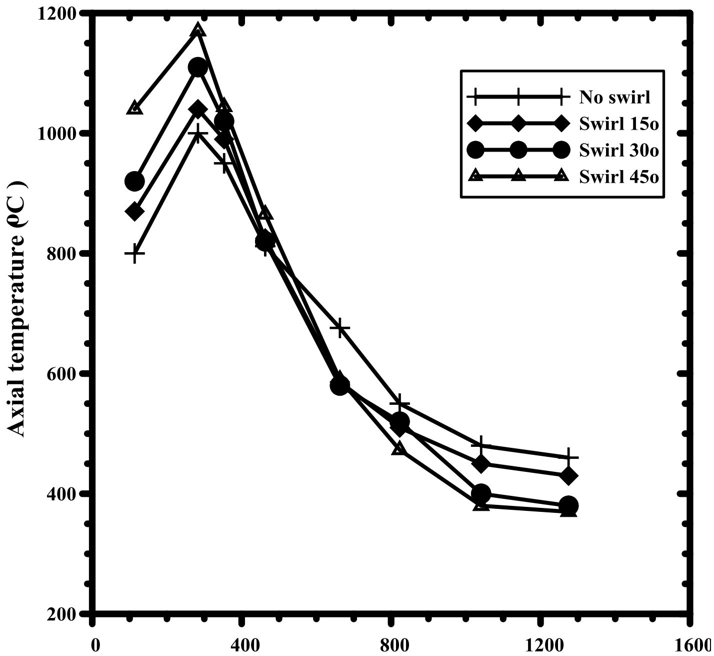


Fig. 4. Axial temperature at different values of atomizing air swirl angle

5.2 Radial inflame temperature

The radial temperature profiles at different axial sections from atomizer tip along the combustor are shown in Figs. 5 to 8 at different atomizing air swirl angle (0, 15, 30 and 45^o) and air to fuel ratio 20 kg_{air}/kg_{fuel}. The profile at x = 113.5 mm, shows a high temperature at the center and then a very low temperature at the other points farther than the center because of the flame diameter is small. The peak temperature monitored where intense mixing among fuel, atomizing and combustion air streams. A uniform temperature region almost occurs in the outer recirculation zone and the temperature declines near the wall of the furnace. This temperature profile starts to flatten with increasing axial distance. The profiles at x = 1275 mm, shows a nearly flat temperature profiles and low temperature as this measuring points lies outside the flame zone.

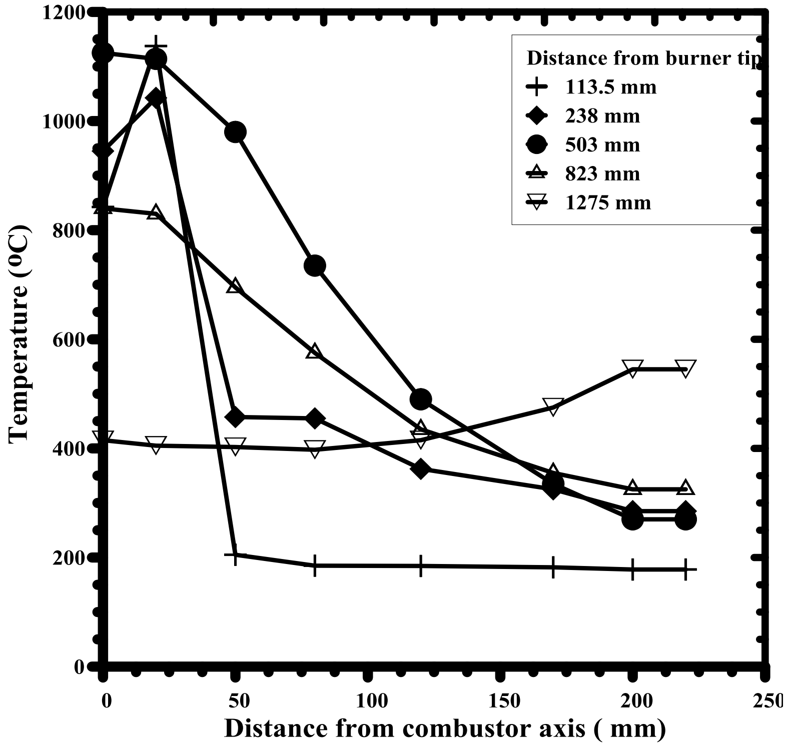


Fig. 5 Radial inflame temperature profiles at different locations along the axis of the combustor at θs= 0^o, Pa=1.5 bar and A/F=20 Kgair/Kgfuel

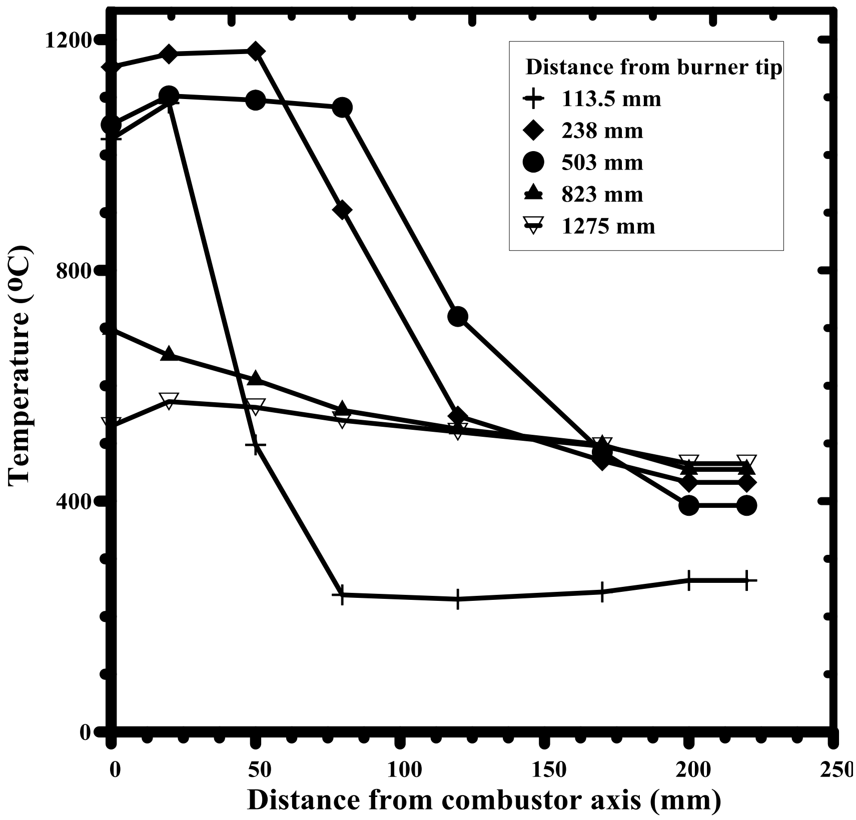


Fig. 6 Radial inflame temperature profiles at different locations along the axis of the combustor at θs= 15^o, Pa=1.5 bar and A/F=20 Kgair/Kgfuel

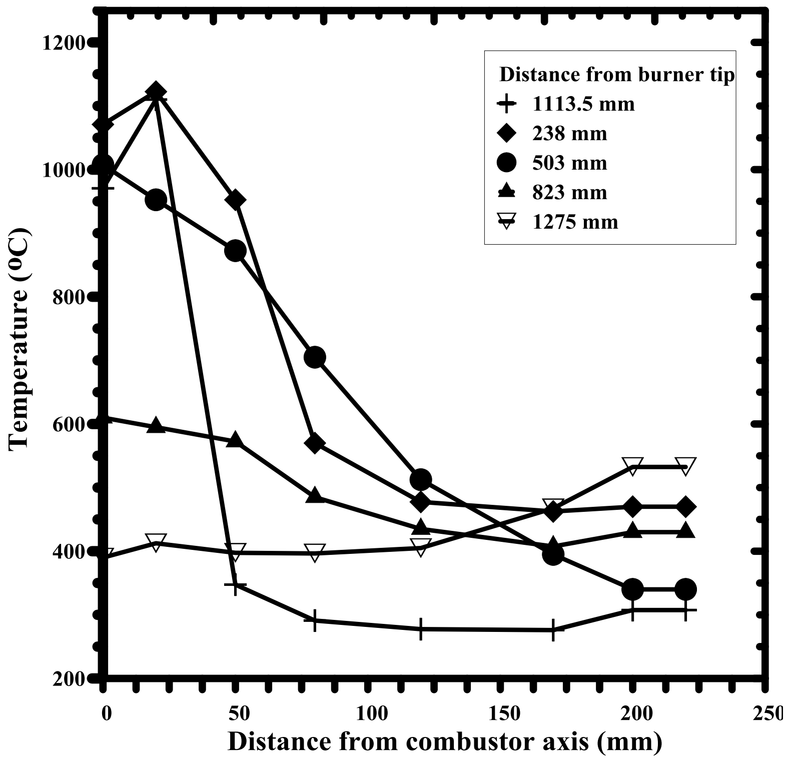


Fig. 7 Radial inflame temperature profiles at different locations along the axis of the combustor at θ_s = 30^o, Pa=1.5 bar and A/F=20 Kg_{air}/Kg_{fuel}.

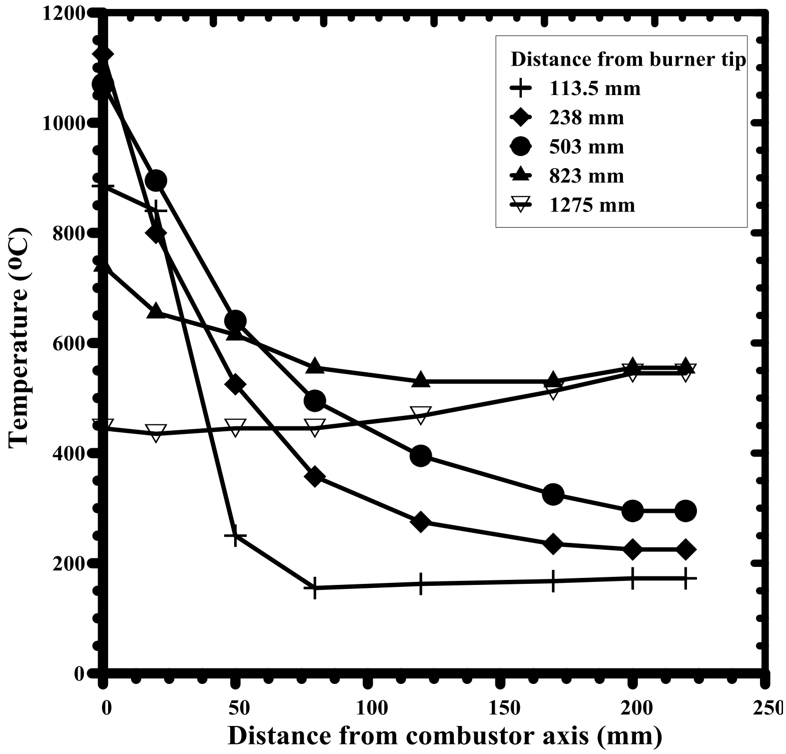


Fig. 8 Radial inflame temperature profiles at different locations along the axis of the combustor at θs= 45^o, Pa=1.5 bar and A/F=20 Kg_{air}/Kg_{fuel}.

5.3 Free and confined flame length

At various values of atomizing air swirl angle the flame length is recorded in average value. Figure 9 presents the flame length in the combustor at various values of atomizing air swirl angle. It is noticed that the flame length decreases (by 36.1 % relative to the length at no swirl with increasing atomizing air swirl angle up to θ_s = 45^o at the same air to fuel ratio. This indicates that increasing atomizing air swirl angle decreases the penetration of fuel droplet and helps in burning the fuel droplet in a short distance near the burner tip. The flame length effect is compatible with the axial temperature measurements shown in Fig. 4.

Figure 10 shows the free visualization of the flame at various values of atomizing air swirl angle. It is clear that increasing of atomizing air swirl angle with the same air to fuel ratio leads to short, stable flame.

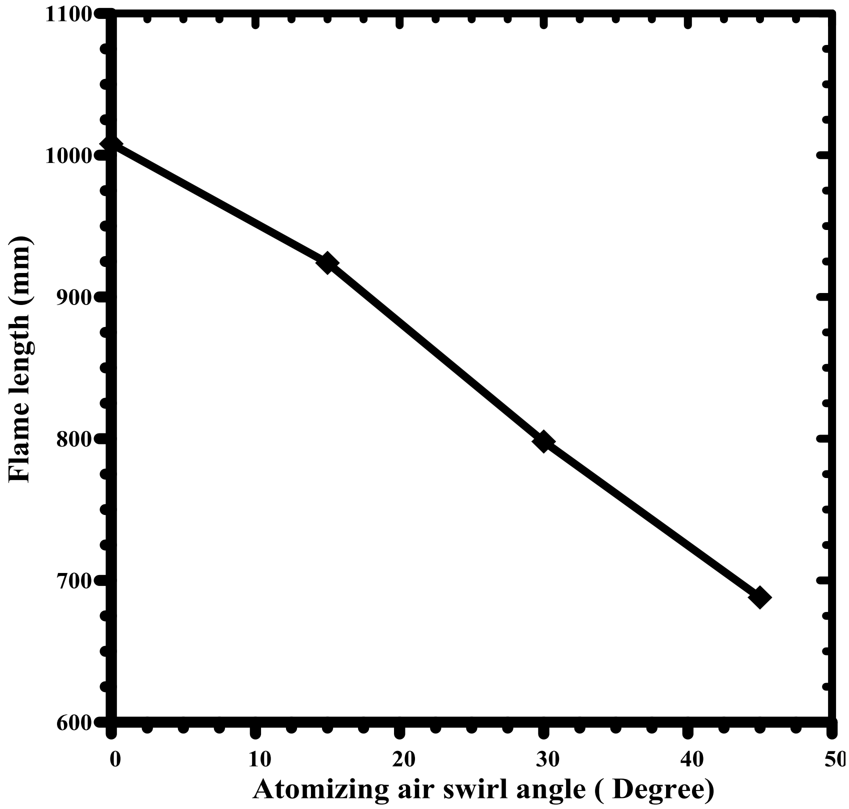


Fig. 9. Flame length at different atomizing air swirl angle and (A/F=20 Kg_{air}/Kg_{fuel}).

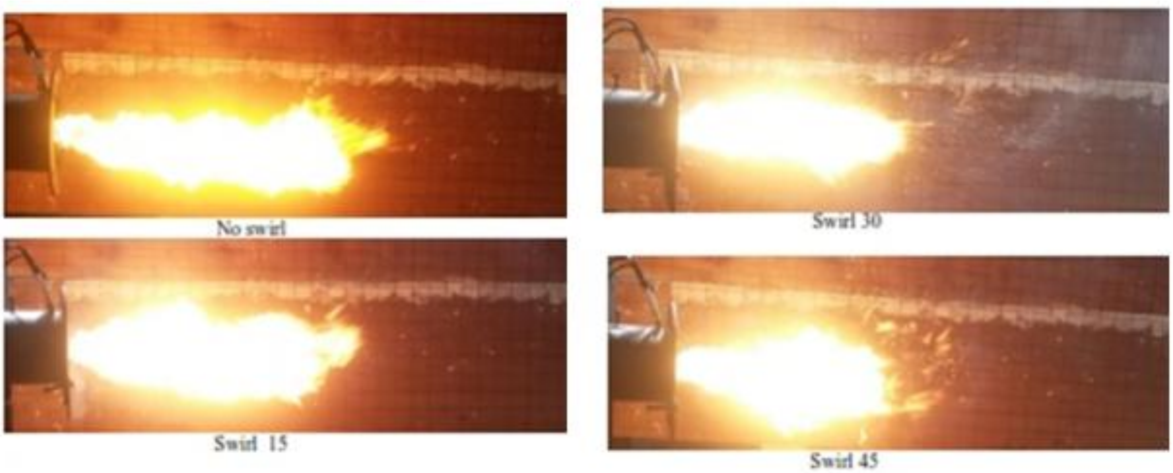


Fig. 10. Free visualization of the flame at different swirl angles.

5.4 Cooling water heat flux

Figure 11 shows the heat flux to the water jacket for different values of atomizing air swirl angle. It can be seen that, as the atomizing air swirl angle increases, the heat flux increases in the flame region near the atomizer tip because of good mixing and high temperature as illustrated previously in Fig. 4. At small swirl angle, the trailing edge heat flux is higher than those of high swirl angle. This behavior can be interpreted as decreasing in the atomizing air swirl angle leads to increase the flame length as shown in Fig. 9. Increasing the flame length enhances the heat transfer, hence increasing the total heat transfer rate. The effect of atomizing air swirl angle on heat flux can be interpreted clearly using the contours of flame temperature radially and axially in the combustor at different values of atomizing air swirl angle as shown in Fig. 12. There is a good agreement between the temperature distribution in the combustor and the trends of heat flux.

5.5 Exhaust gas temperature measurements

Figure 13 shows the variation of the exhaust temperature in the stack outside the combustor at different atomizing air swirl angles. It is observed that the exhaust temperature decreased with increasing the atomizing air swirl angle. The main reason of this behavior is that the flame length decreases and the gas products lose more heat to water jacket due the travel of long distance up to temperature measuring locationwith increasing the atomizing air swirl angle as discussed in section 5.3.

5.6 Emission concentrations

Figure 14 presents the variation of CO and NOx emissions at different values of atomizing air swirl angle. The emissions of those gases are decreased with increasing atomizing air swirl angle. As mentioned before, the peak flame temperature lies near the atomizer. This relatively high temperature starts to stimulate the kinetic path of NOx formation. But, on the other hand, the NOx reaction mechanism has significantly slow reaction due to its higher activation energy. So, the significant production of NOx starts further away downstream. At this location, the flame temperature governs the production rate of NOx. It was shown previously in Fig. 4 that the no swirl air has the highest temperature in the NOx formation zone which reflects the higher NOx emissions for the no swirl air.

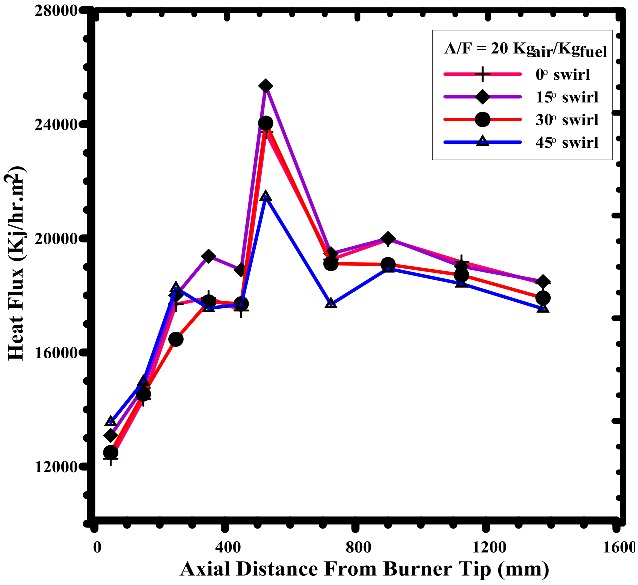


Fig. 11. Total heat flux to the water jacket for different values of atomizing air swirl angle

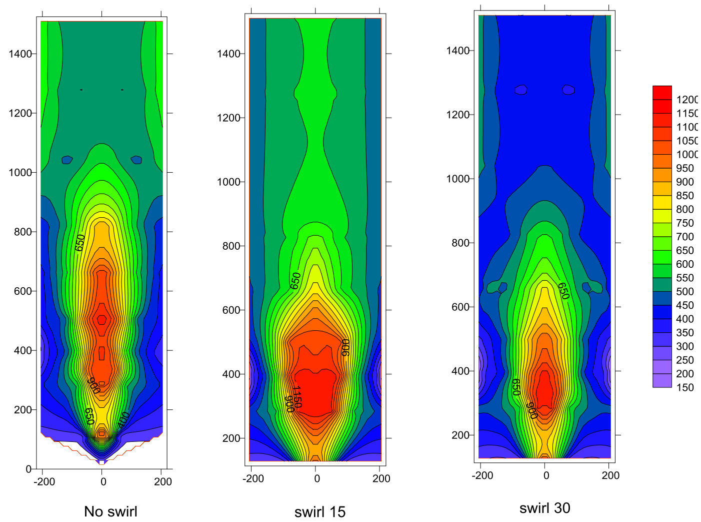


Fig. 12. Contours of flame temperature radially and axially in the combustor at different values of atomizing air swirl angle and AF=14

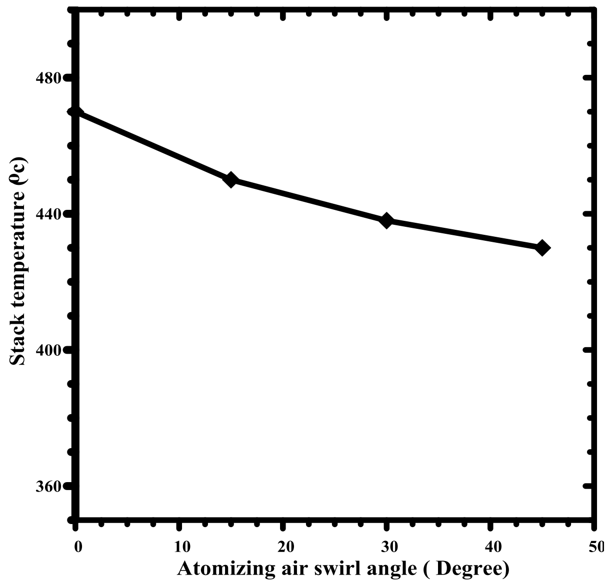
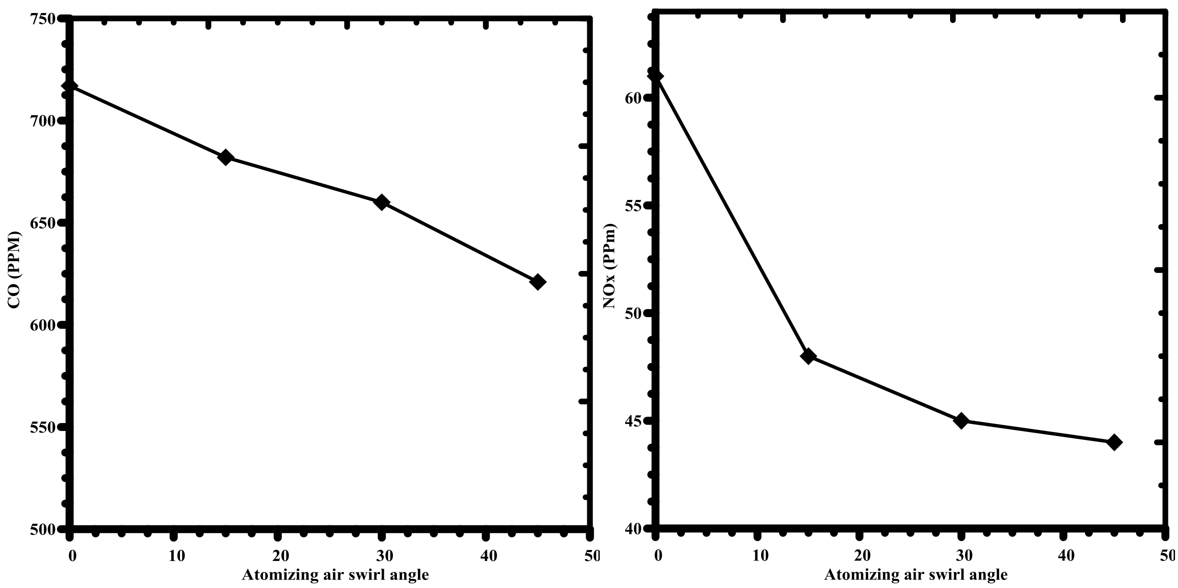


Fig. 13. Stack temperature at different values of atomizing air swirl angle



(a) CO (b) NOx

Fig. 14 Effect of atomizing air swirl angle on emissions at Pa=1.5 bar and A/F=20 Kg_{air}/Kg_{fuel}

VI. Conclusions

In the present study, the spray combustion characteristics of the external mixing air assist atomizer were investigated experimentally at different values of atomizing air swirl angles. The following conclusions are obtained:

1. The air swirl intensity represented by atomizing air swirl angle has pronounced effects on spray flame structures and exhaust emissions.
2. As the atomizing air swirl angle increases, the flame temperature increases in the flame region near to atomizer tip because of good atomization and mixing. At small swirl angle, the trailing edge flame temperature is higher than those of big swirl angle.
3. Increasing the atomizing air swirl angle up to 45^o reduces the flame length (by 36.1 % relative to the length at $\theta s = 0^o$) at the same air-to-fuel ratio.
4. Increasing the atomizing air swirl angle increases the heat flux in the flame region near to atomizer tip because of good mixing and high temperature. At small swirl angle, the trailing edge heat flux is higher than those of big swirl angle.
5. The NOx emissions is decreased with increasing the angle up to $\theta s = 45^o$

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