SPRAY AND COMBUSTION CHARACTERISTICS OF HYDROCARBON FUEL INJECTED FROM PRESSURE-SWIRL NOZZLES

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Abstract

This paper presents spray and combustion characteristics of hydrocarbon fuel injected from pressure-swirl nozzles. Three commercial nozzles with orifice diameters of 0.256, 0.308 and 0.333 mm and injection pressures ranging from 0.7 to 1.3 MPa were selected for the experiments. Spray characteristics such as breakup length, spray angle and drop size (SMD) were analyzed using photo image analyses and Malvern Particle Size Analyzer. The drop size was measured with and without a blower at the same measuring locations. The flame length and width were measured using photo image analyses. The temperature distribution along the axial distance and the gas emission such as CO, CO_2 and NOx were studied. The breakup length decreased with an increase in injection pressure for each nozzle but increased with an increase in nozzle orifice diameter. The spray angle increased and SMD decreased with an increase in injection pressure. The flame length increased linearly with an increase in injection pressure and in nozzle orifice diameter. The flame temperature increased with an increase in injection pressure but decreased along the axial distance. The maximum temperatures occurred closer to the burner exit and flame at axial distance of 242 mm from the diffuser tip. The experimental results showed that the level of CO decreased while that of CO_2 and NOx increased with an increase in injection pressure and nozzle orifice diameter.

Keywords: Spray Characteristics, Combustion Characteristics, Pressure-Swirl Nozzle, Temperature, Emission Gas Analyses

1. Introduction

Pressure -swirl nozzle is noted to be the most efficient devices to produce a fine spray by pressurizing the liquid for a given flow rate. The method requires the minimal supply pressure to provide a given drop size [1]. Many researches [2-4] have been conducted to analyze the effects of nozzle design, operating conditions, fuel properties, etc. on spray and combustion characteristics of hydrocarbon fuels injected from pressure-swirl nozzles.

Most of the previous studies have concentrated on pressure-swirl nozzles of the type used in aircraft gas turbines and in utility boilers. The small-scale burners with pressure-swirl nozzle are widely adopted to generate heat for drying the agricultural products in Korea. The oil burners rely on the atomizers for their ability to create fine sprays.

So far most of the studies conducted were based on techniques and methods likely to improve combustion efficiency and atomization quality. Burner efficiency improvement necessitates the study of the spray characteristics of the nozzle in application, as well as other parameters that are noted as efficiency improver. It is known that spray combustion is controlled by several phenomena such as atomization of the liquid jet, droplets vaporization, mixture between fuel and oxidizer [5].

Recently, more investigations have been conducted into spray characteristics in the commercial pressure-swirl nozzles for the small-scale burners [6-9]. Hollow-cone types of nozzles are known to provide better atomization due to their effective radial liquid distribution. This therefore made the pressure-swirl nozzle more preferable for combustion applications [1]. The pressure-swirl nozzle has been used to study the spray characteristics such as breakup length, spray angle and drop size distribution for both conventional and basic electrostatic applications [6-9].

In one of our previous papers, it was found from the analysis that discharge coefficient does not solely depend on nozzle orifice diameter as stated by other researchers. In order to determine discharge coefficient for pressure-swirl nozzles, there is a limitation for the application [6].

The purpose of this study is to find the design data that could be applicable for the development of electrostatic nozzle for oil burner application. It is also to find the relationship between spray and combustion characteristics in the pressure-swirl nozzles.

2. Experimental methods and materials

This attempt is to provide a set of experimental information that can be used to design electrospray nozzles for combustion applications. A small-scale oil burner for drying agricultural products, industrial heating processing equipment, boiler, incinerators, etc. was selected for the experiment. The specification of the burner and the properties of the tested fuel can be found in Tables 1 and 2 respectively and in literature [6,10]. The air velocity supplied from the burner to the furnace was kept constant at 8 m/s and the volumetric air flow rate was 185 m^3/h.

Table 1. Burner specification

Kerosine/Light Oil	
Power source [V]	AC 220V/50Hz, 60Hz
Motor [W]	110
Oil pump [kcal/kg]	Gear pump
Ignition trans[kV]	8.5 kV/18 mA
Pump pressure [MPa]	1.1
Nozzle range [mL/min]	50 ~ 140
Dosage [MJ/h]	125.6 ~ 293.1

Table 2. Kerosine properties at 295 K

Surface tension [kg/s^2]	2.6x10^{-1}
Dynamic viscosity [kg/m s]	1.04x10^{-3}
Density [kg/m^3]	790

Three commercial pressure-swirl nozzles (Danfoss) with hollow cone spray pattern having orifice diameters of 0.256, 0.308 and 0.333 mm and injection pressures of 0.7, 0.9, 1.1 and 1.3 MPa, respectively, were used for this experiment. A schematic diagram of the combustion test rig used for the experiment is a steel rectangular ceramic-lined tunnel furnace showed in Fig. 1. The burner fires horizontally into the furnace chamber of a rectangular shape with dimensions of 1.2 m (L) x 0.76 m (W) x 0.76 m (H) and 0.11 m in refractory wall thickness. The rig was fitted with a quartz window and a stainless steel to enable access to the combustion chamber for in-flame visualization.

For visualization analyses, a 3-CCD video camera (SONY) was used to capture multiples of spray and combustion images and then stored in a computer for off-line image analyses using PHOTOSHOP software. The image gave access to geometrical information to analyze the breakup length, spray angle, flame length and width. The flame width was measured at the selected axial distances of 32, 72 and 272 mm from the diffuser tip. The drop size was measured using a Malvern Particle Size Analyzer (Mastersizer S) at the axial distance of 18 mm from the nozzle tip to the center of the laser beam without the burner blower. Again, the SMD was also measured with and without the blower at axial distances of 32, 142 and 242 mm from the nozzle tip, to study how the drop sizes affect the combustion characteristics.

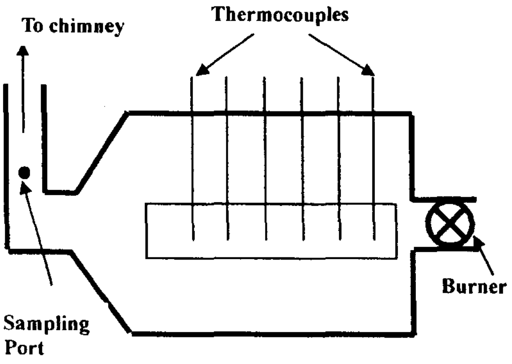


Figure 1. Schematic diagram of a steel rectangular ceramic-lined tunnel furnace

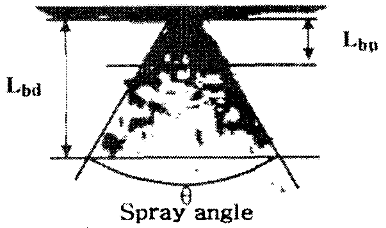
Six R-type (Ø0.5 x 500L x SSA - SØ13 x 1/2" PT) thermocouples were installed on the combustion test rig at different axial distances of 142, 242, 392, 542, 692 and 842 mm from the nozzle tip to measure the flame temperature. The temperatures were recorded 20 minutes after start of combustion, using a hybrid recorder (KONICS, KM 100, Yokogawa, Japan) after flame stabilization.

A sampling port was provided at the furnace outlet to enable access for gas analyses. The flue gases emission such as CO, CO_2 and NOx were recorded after every 4 min using a gas analyzer (Quintox, KM9106, Kane-May, USA).

3. Results and discussion

3.1. Effect of injection pressure on breakup length

Two criteria used to determine liquid sheet breakup lengths are by perforation and drop formation. In this experiment, the later one has been adopted. A typical photograph of a spray issued from a nozzle is shown in Fig. 2 indicating where a liquid sheet breakup occurred. The



L_{bp} : breakup length based on perforation

L_{bd} : breakup length based on drop formation

Figure 2. A typical photograph indicating the measurements criteria for a breakup length and a spray angle.

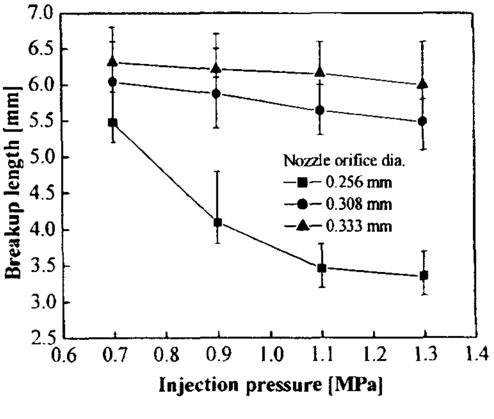


Figure 3. Effect of injection pressure on breakup length.

photograph represents a gray-level threshold of 80 % of the captured image. Average values obtained from 30 images are plotted in Fig. 3.

The results showed that the breakup length decreased with an increase in injection pressure but increased with an increase in nozzle orifice diameter. The breakup length was measured under the condition without the blower. The variation of errors from the measurement of breakup length were in the ranges of 5.1 to 14.8 %, 2.3 to 8.5 % and 1.8 to 9 % for nozzles with orifice diameters of 0.256, 0.308 and 0.333 mm respectively.

3.2. Effect of injection pressure on spray angle

The spray cone angle was difficult to measure accurately from the nozzle due to the effect of air interaction on the curved boundaries of the spray. Two straight lines were therefore drawn on the captured images from the nozzle's orifice to cut the spray contours at drop formation points. A typical photograph of the measurement procedure is shown in Fig. 2. The average values with error bar obtained from the analyses are presented in Fig. 4. The spray angle increased with an increase in injection pressure and also the nozzle orifice diameter.

The variation of errors from the spray angle measurement were in the ranges of 1.3 to 5.3 %, 1.9 to 5.6 % and 2.1 to 6.2 % for nozzles with orifice diameters of 0.256, 0.308 and 0.333 mm respectively.

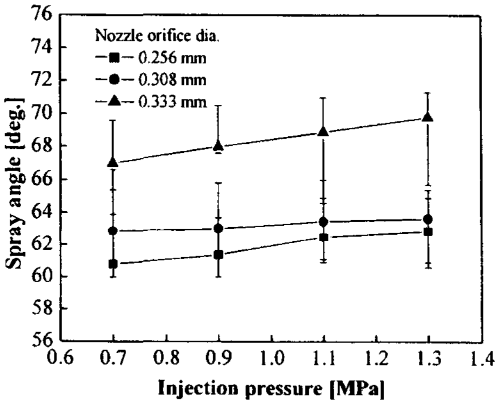


Figure 4. Effect of injection pressure on spray angle for three different orifice diameters.

3.3. Effect of injection pressure on drop size (SMD)

The effect of injection pressure on drop size was investigated under two conditions (with and without the burner blower) at various axial distances. The average values of the measured SMD without the blower for various nozzles at a fixed axial distance of 18 mm from the nozzle tip are shown in Fig. 5. The results showed that the droplet size decreased with an increase in the injection pressure, indicating a good atomization quality. From Fig. 5, it is observed that, the drop size increased with an increase in nozzle orifice diameter.

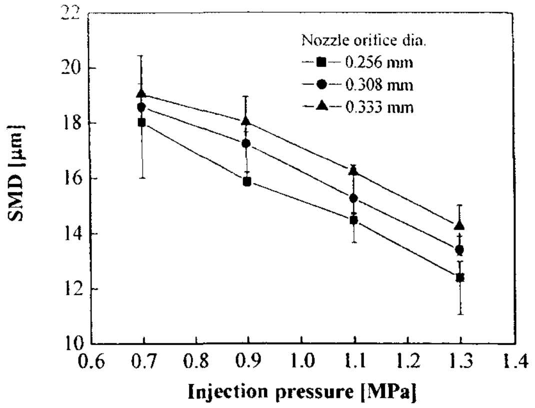


Figure 5. Effect of injection pressure on SMD without blower for three different orifice diameters.

The error variations from the mean drop size measurement were in the ranges of 1.9 to 10 %, 1.6 to 9.9 % and 0.6 to 7.2 % for nozzles with orifice diameters of 0.256, 0.308 and 0.333 mm respectively The mean drop sizes increased with an increase in liquid flow rate. This result is similar to the one reported by Lefebvre [11].

The average values of the measured SMD with and without blower for the three nozzles at different axial distances from the diffuser are shown in Fig. 6. In both cases, the mean drop sizes decreased with an increase in the injection pressure but increased with an increase in axial distance. This may was due to droplet coalescence caused by turbulence created from the blower.

In the case of the nozzle with orifice diameter of 0.333 mm, at axial distance of 242 mm from the diffuser, the measuring equipment could not give good results due to vignetting. This problem could therefore leads to high probability error due to overlapping of drops. It may also be due to the wide spray angle formation at this distance.

It can be seen from Fig. 6. that, irrespective of nozzle's orifice diameter, the SMD increased with the blower application. The error variations from the mean drop size measurement under this conditions are in the range of 0.25 to 2 %, 1.7 to 11 % and 4.2 to 12 % at axial distance of 32, 142 and 242 mm respectively, for the nozzle with orifice diameter of 0.256 mm.

In the case of the nozzle with orifice diameter of 0.308 mm, the errors were in the ranges of 0.4 to 8.9 %, 0.8 to 7.6 % and 3.6 to 11.6 % along axial distances of 32, 142 and 242 mm respectively.

The error analysis for the nozzle with orifice diameter of 0.333 mm, were in the ranges of 0.24 to 14.6 % and 0.43 to 17.7 % at axial distances of 32 and 142 mm respectively.

By using three similar atomizers, it has been concluded that, the mean drop size declined with an increase in flow rate [11]. From this experiment, it was observed that, this phenomena may also depend on the measuring location (i.e. axial distance).

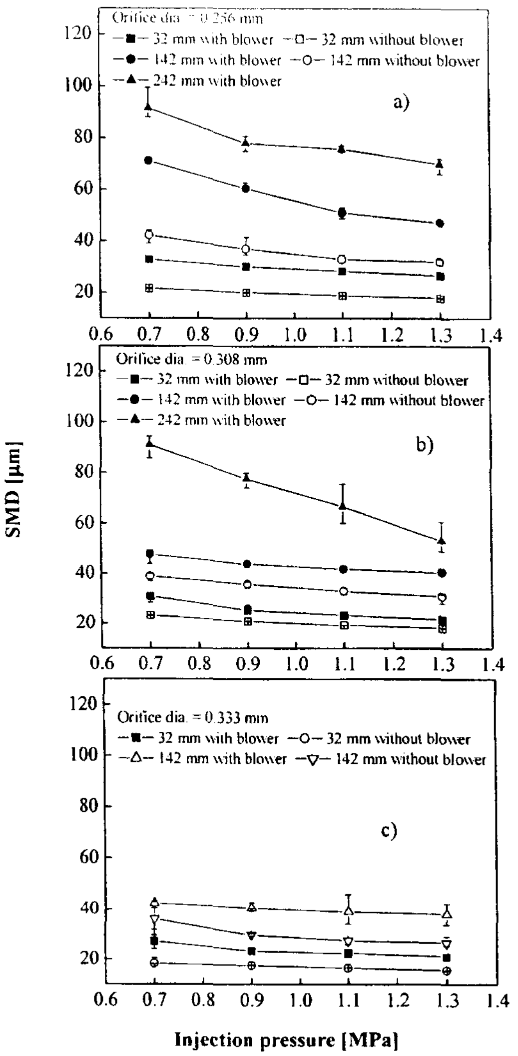


Figure 6. Effect of blower on SMD for nozzles with orifice diameters of a) 0.256, b) 0.308 and c) 0.333 mm.

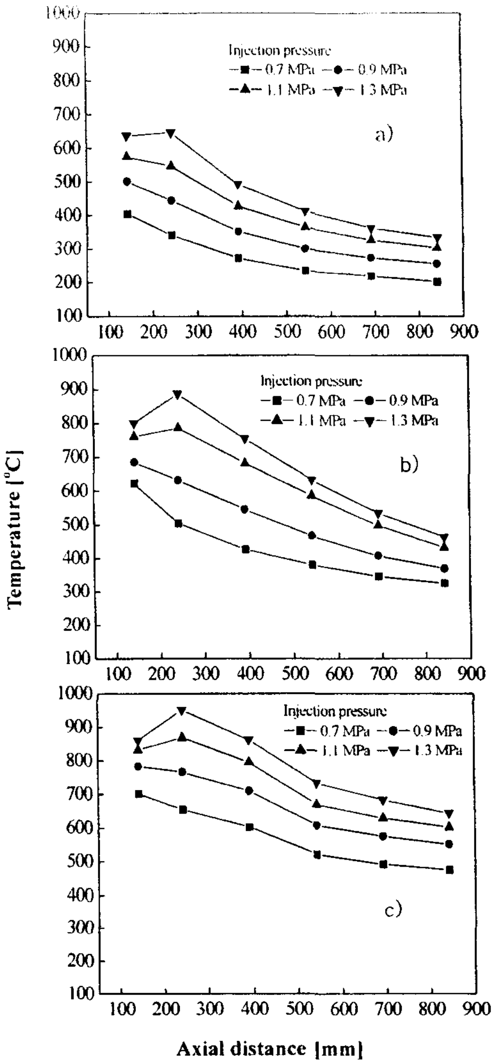


Figure 7. Effect of injection pressure and axial distance on temperature for nozzles with orifice diameters of a) 0.256, b) 0.308 and c) 0.333 mm.

3.4. Effect of injection pressure and axial distance on temperature

In this experiment, the flame theories that can be applied to temperature distributions at locations such as preheat or preflame zones were not considered. Only the injection pressure and axial distance effects on temperature distributions have been discussed. The temperatures were recorded at 20-minute intervals, time at which flame becomes stabilized. The mean values have been plotted in Fig. 7. The temperature increased with an increase in injection pressure. This was due to an increase in number Again, the temperature decreased with an increase in axial distance. This may be due to chemical reaction zone effect.

Figure 7 also showed that, at high injection pressures especially at 1.3 MPa the temperature increased as the distance from the diffuser was increased and then decreased with an increase in axial distance for each nozzle. The maximum temperature was recorded at axial distance of 242 mm from the diffuser.

3.5. Effect of injection pressure on flame length

The flame length was measured using visualization technique with 30 captured images. The average values from the pixel/mm relationship are presented in Fig. 8. This figure shows the effect of injection pressure on flame length for three different nozzles. The flame length increased with an increase in injection pressure and nozzle orifice diameter. Although liquid sheet breakup decreased with an increase in injection pressure, the increase in flame length may be due to the availability of droplet at further distance from the nozzle tip. Also it may assumed that, a high evaporation rate could be a factor after good atomization process at high injection pressures.

The error analysis from the measured data were in the ranges of 9 to 13 %, 8 to 12.6 % and 2 to 12.8 % for nozzles with orifice diameters of 0.256, 0.308 and 0.333 mm respectively.

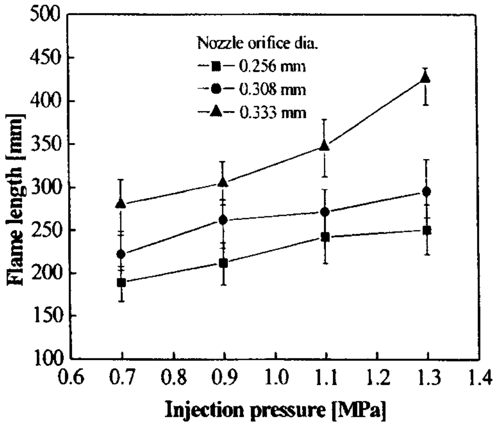


Figure 8. Effect of injection pressure on flame length for three different nozzles.

3.6. Effect of axial distance on flame width

The flame width was measured using visualization technique from 30 captured images at the threshold level of 85 %. The average values from the pixel/mm relationship are presented in Fig. 9. The figure showed the effect of axial distance on flame width for three different nozzles. The flame width increased with an increase in axial distance and then decreased depending on the nozzle orifice diameter. The effect of orifice diameter on flame widths can clearly be seen about 142 mm downstream from the diffuser. This may be due to atomization quality. It can also be observed that, there was a combustion process going on at further distances when injection pressure was increased.

The error analysis from the measured flame width data were in the ranges of 1.6 to 15 %, 4 to 15 % and 7 to 14.2 % for nozzles with orifice diameters of 0.256, 0.308 and 0.333 mm respectively.

3.7. Effect of injection pressure on flue gas emissions

The results of the flue gases analyses such as CO, CO_2 and NOx profiles have been presented in Fig. 10a, b and c, respectively. From Fig. 10a, it was observed that, at injection pressure of 0.7 MPa, the CO increased with an increase in nozzle orifice diameter but at an injection pressure of 1.3 MPa, the CO is decreased with an increase

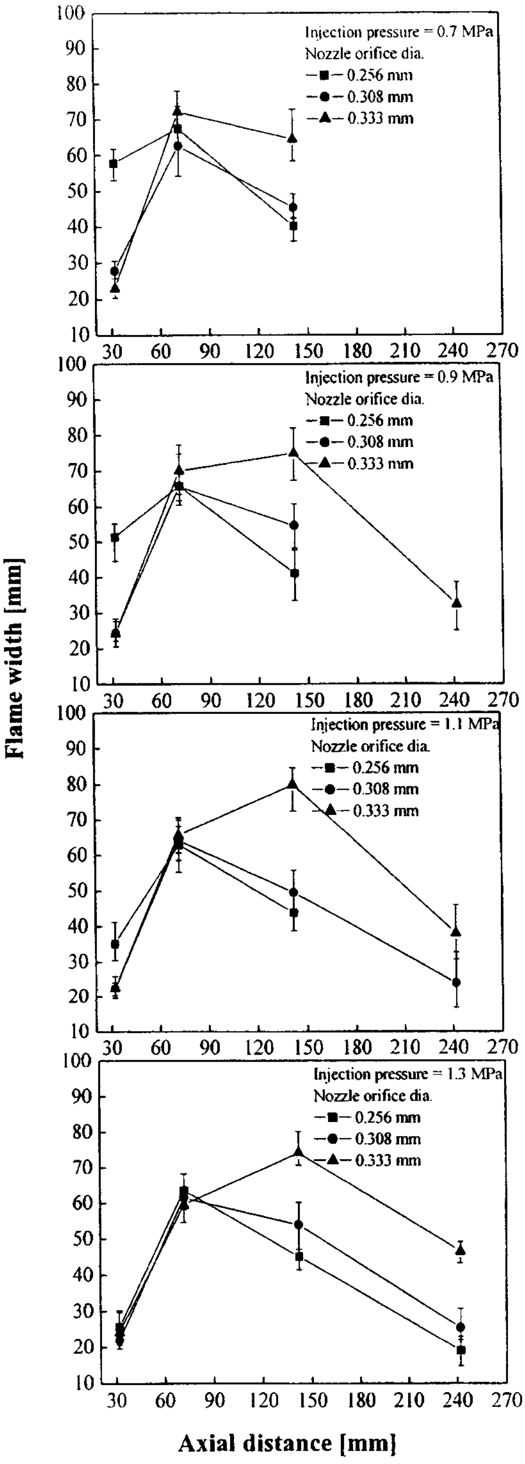


Figure 9. Effect of axial distance on flame width for three different nozzles

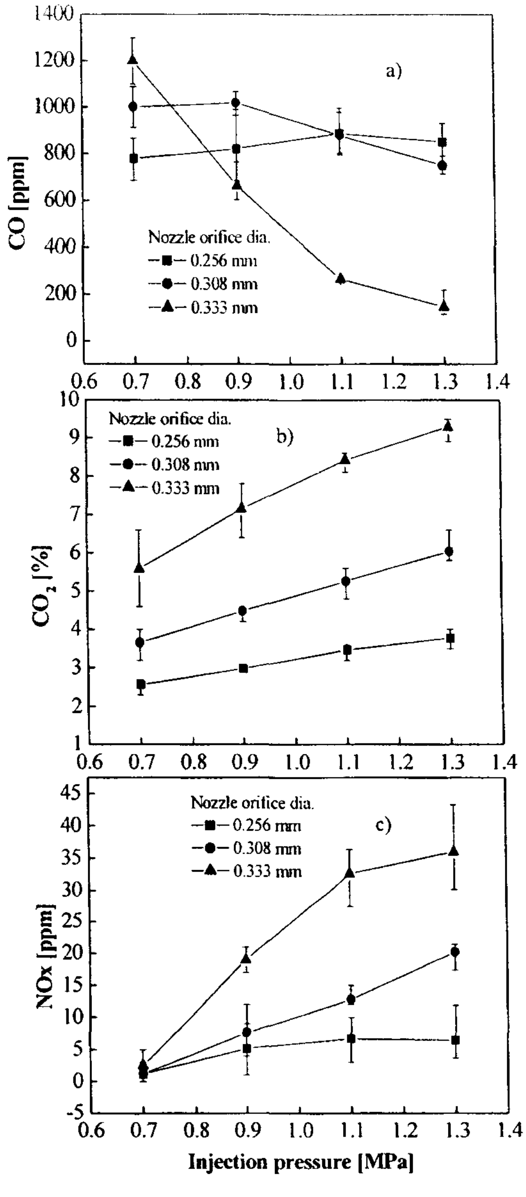


Figure 10. Effect of injection pressure on a) CO, b) CO_2 and c) NOx for three different nozzles.

in nozzle orifice diameter .

In Fig. 10b, the CO_2 increased with an increase in injection pressure and nozzle orifice diameter. In Fig. 10c, the NOx increased with an increase in injection pressure especially at injection pressure of 1.3 MPa. The increase in nozzle orifice diameter caused an increase in NOx.

For future work, the influence of the spray angle on ignition performance, flame blowout limits and the pollutant emissions of unburned hydrocarbons and smoke is required.

The error analysis obtained from the recorded data was in the ranges of 5 to 10 %, 4 to 13 % and 7 to 15 % for the CO, CO_2 and NOx respectively.

4. Conclusion

The spray and combustion characteristics of hydrocarbon fuel injected from pressure-swirl nozzles have experimentally been studied. The results obtained in this study can be summarized as follows:

1) The breakup length decreased with an increase in injection pressure but increased with an increase in nozzle orifice diameter.
2) The spray angle increased with an increase in injection pressure.
3) The droplet size decreased with an increase in the injection pressure but increased with an increase in nozzle orifice diameter. The blower affects the atomization process by increasing the drop size.
4) The temperature increased with an increase in injection pressure but decreased with an increase in axial distance. For each nozzle at high injection pressure of 1.3 MPa, the maximum temperature was recorded at axial distance of 242 mm from the diffuser tip.
5) The flame length increased with an increase in injection pressure and nozzle orifice diameter.
6) The flame width increased with an increase in axial distance and then decreased depending on the nozzle orifice diameter.
7) At injection pressure of 0.7 MPa, the CO increased with an increase in nozzle orifice diameter but at an injection pressure of 1.3 MPa, the CO is decrease with an increase in the nozzle orifice diameter. CO_2 and NOx increased with an increase in injection pressure and nozzle orifice diameter.
8. It can be recommended that, the nozzle with orifice diameter of 0.256 mm and injection pressure less that 1.1 MPa would be suitable for drying agricultural product and heating processes. The condition is also favourable for a minimum gas emission.

5. Acknowledgement

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6. References

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