Effects of fractal grid on spray characteristics and flame development in burner combustion

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Abstract. Turbulence generator plays an important role in enhancing turbulence in combustion and determining the flame characteristics in burner combustion. This research demonstrated the effect of a fractal grid on the spray and flame characteristics in burner combustion. Three geometrical configurations of fractal grid were investigated with different equivalence ratios of 0.5–1.0. The images were captured using direct photographic method. The characteristics of the spray and flame were studied, including the length, angle, and area. The results from this fractal grid were compared with the swirl. The results showed that the fractal geometry and ratio of air-to-fuel mixture affected the performance of the burner. The correct combination of fractal geometry and air-to-fuel ratio resulted in complete combustion and improved the overall performance of the burner.

1. Introduction

Diesel is a natural resource that is consumed heavily in the world because of the increasing demand for energy. It can be used in numerous applications, such as fuel in automotive and burner systems. Therefore, the continuous improvement of controlled diesel combustion is urgently required [1].

The generation of turbulence from fractal grids has attracted many researchers [2-6]. Krogstad [5] investigated turbulence from fractal grids generated by wind tunnels. Measurements using hot wire and laser Doppler anemometry revealed the strong dependency of turbulence on the grid geometry. The advantages of fractal grid were further studied by Soulopolous *et al.* [6]. The fractal grid was used to generate turbulence in the premixed flame. The parameters of the grid were blockage ratio, effective mesh size, and perimeter. Results illustrated the advantages of fractal grids. Under the same heat release and downstream distance, fractal grids created intense turbulence and changed the combustion regime. Compared with regular grids, fractal grids exhibited intense turbulence at a given downstream in which the flame angle and turbulent flame speed increased by 50%. Physically, the curvature and flame brush thickness presented large corrugations and intense burning.

In this research, the effects of fractal grids of different geometry were investigated, focusing on the behaviour of the flame. A closed chamber system (Figure 1) was used with direct photographic methods to study the angle, length, and area of the flame.

2. Experimental Setup

A schematic of the experiment is presented in Figure 1 [7]. The main component was an atomizer with eight nozzle holes of 1 mm in diameter. The atomizer [8] was equipped with an air compressor for primary air, a blower to supply excess air, and a fuel pump. During the operation, the air from the compressor at 1 bar (0.1 MPa) was directed to the bottom inlet of the atomizer, whereas the side inlet was for incoming fuel. Excess air was supplied to assist in combustion in the closed chamber. The spray and flame video images were captured in color using Sony FDA-EV1S. The images were analyzed using GOM Player and ImageJ software.

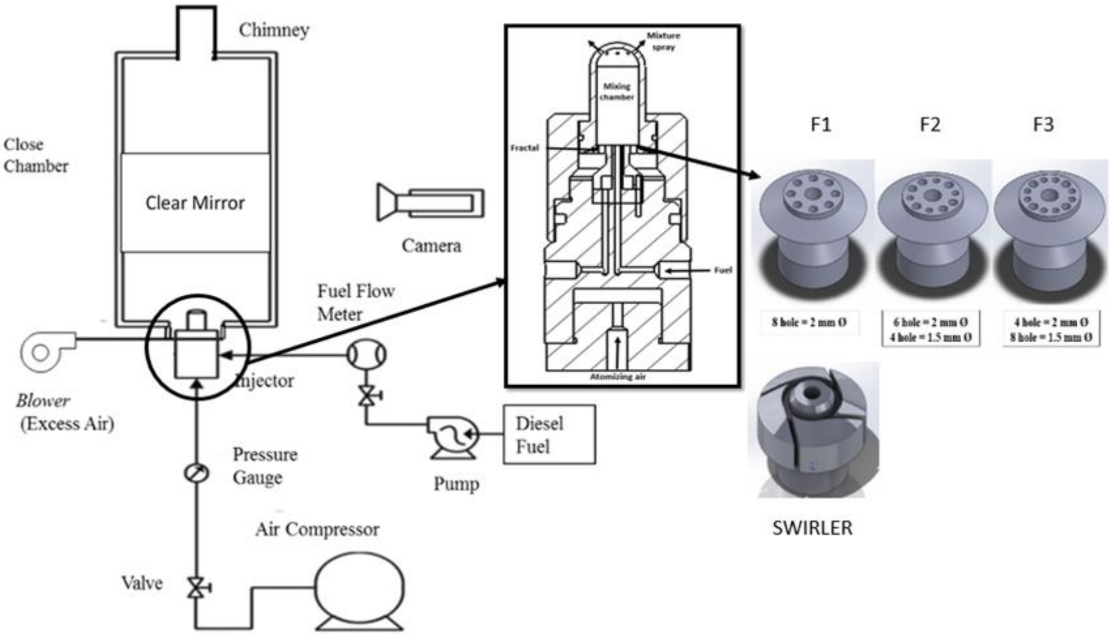

Figure 1. Schematic diagram of experimental setup

Table 1 shows the properties of diesel used in this experiment . The density of the diesel fuel is 0.83374 g/cm^3. The details of the experimental equipment and testing conditions are presented in Table 2. The primary air pressure P_i was constant at 0.1 MPa, which corresponded with the primary air flow rate of 40 L/min. The adjustable parameters were fuel mass flow rate and secondary air mass flow rate. Diesel was sprayed via the 8-hole atomizer with a diameter of 1 mm using three different fractal geometries. The following fractal grids were fabricated and tested in this system: Fractal 1 with eight holes of 2 mm, Fractal 2 with six holes of 2 mm and four holes of 1.5 mm; and Fractal 3 with four holes of 2 mm and eight holes of 1.5 mm.

3. Result and Discussion

Figure 2 shows the spray formation of Fractal 1 at the equivalence ratio of 0.6 to 0.9 (lean) and 1.0 (stoichiometry). The diesel fuel was sprayed upward as the mixtures were directed into the injector. As time increased by 0.03 s for each image, spray penetration rose. Analysis of spray penetration (at 0.12 s when the penetration peaked) showed that the penetration also increased as the equivalence ratio increased (Table 3). The highest penetration was achieved at stoichiometric conditions (equivalence ratio of 1.0) of 587 mm.

Figure 3 shows the flame images of Fractal 1 developed from 0 s to 0.12 s at different equivalence ratios. An increase in the air–fuel ratio affected flame stability and burner combustion. At a high equivalence ratio, the flame area increased because of the increment of the air–fuel ratio. Table 3 indicates that the highest flame area was 317,585 mm^2 under stoichiometric conditions. The image of the flame area obtained from ImageJ is highlighted in Figure 4.

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Table 1. Properties of diesel fuel

Properties	Value
Density (g/cm^3)	0.83374
Kinematic viscosity (Cp)	3
Flash point (°c)	80
Water content (%)	0.00796
Acid value (mgKOH/g)	0.423

Table 2. Equipment and experimental condition [7]

Air Compressor	Model	QUASA HDC-D3050
	Capacity, L/min	200
	Pressure, kg/cm^2	8
Water Pump	Model	SFDP1-014-080-22-Seaflo
	Voltage, V	12
	Flow rate, L/min	5.1
Fuel Pump	Model	CNY-3805
	Pressure, bar	3
	Flow rate, L/hr	100
DC Voltage Regulator	Model	Teletron TC-1206A
	Current, A	64 (max)
Operating condition	Air Pressure, MPa	0.1
	Air Density, kg/m^3	1.16
	Ambient Temperature, K	300
	Equivalence Ratio	0.5 - 1.0

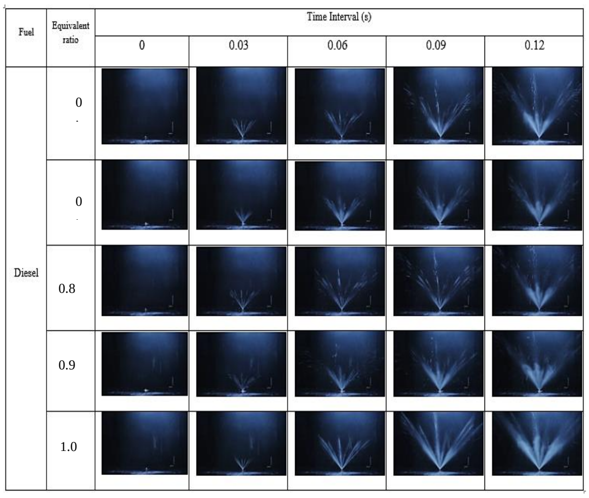

Figure 2. Spray development using Fractal 1 (8 holes of Ø2 mm)

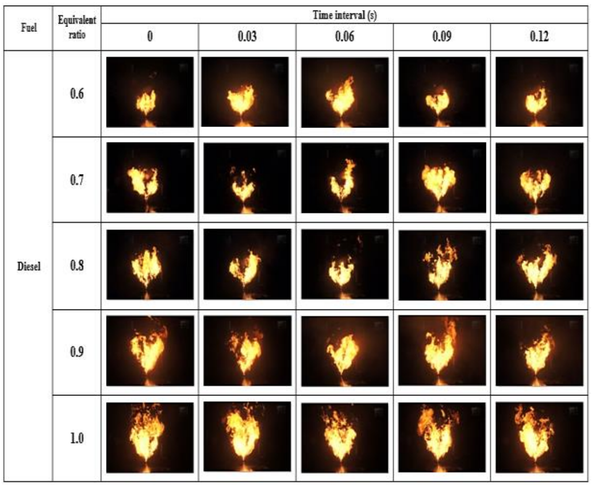

Figure 3. Flame development using Fractal 1 (8 holes of Ø2 mm)

Table 3. Spray penetration and flame area of Fractal 1

Equivalence ratio	0.6	0.7	0.8	0.9	1.0
Spray penetration (mm)	310	407	502	547	587
Flame area (mm^2)	118,669	170,264	183,295	260,237	317,585

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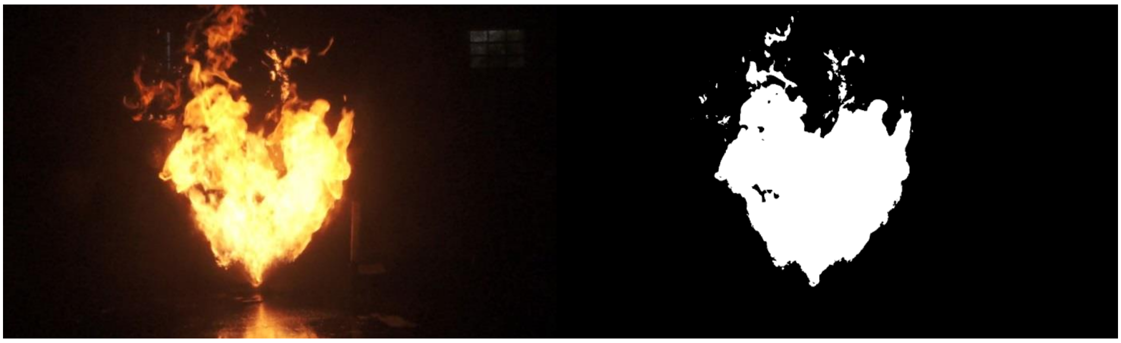

Figure 4. Flame area (indicated by the white area) of an image from Fractal 1 at equivalence ratio 1.0

The flame characteristics consisted of the flame length, flame angle, and flame area. Figure 5 exhibits the characteristics of the three fractals. In general, the flame length, angle, and area showed an increasing trend with the equivalence ratio for each type of fractal. This trend indicated the strong relation between the air–fuel ratio and burner combustion.

For Fractal 1, the flame length was higher compared with the swirl. However, the swirl showed a larger flame area and angle as the equivalence ratio approached stoichiometric conditions (0.8, 0.9, and 1.0). For Fractal 2, the swirl showed a higher flame length and flame area. Fractal 3 exhibited higher flame length, flame angle, and flame area compared with the swirl. Therefore, Fractal 3 displayed potential as a turbulence generator in the burner system with better flame characteristics compared with the swirl.

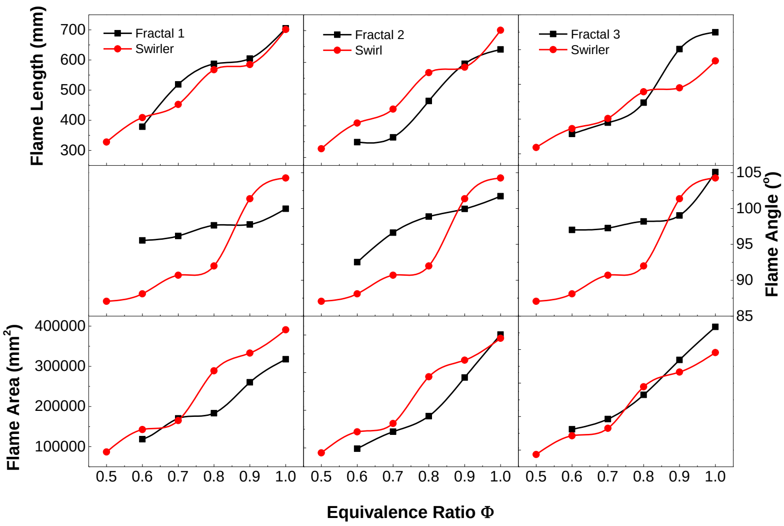

Figure 5. Flame characteristics of each Fractal

Figure 6 shows the influence of fractal geometry on the flame characteristics in the burner. The changes in the flame length, angle, and area of the flame were also influenced by the equivalence ratio. The equivalence ratio of 1.0 produced the largest flame angle, highest flame length, and highest flame area. The figure also indicated that Fractal 3 demonstrated the highest flame length, flame angle, and flame area, especially at the equivalence ratios of 0.8, 0.9, and 1.0. Therefore, Fractal 3 at the equivalence ratio of 1.0 resulted in the highest combustion performance.

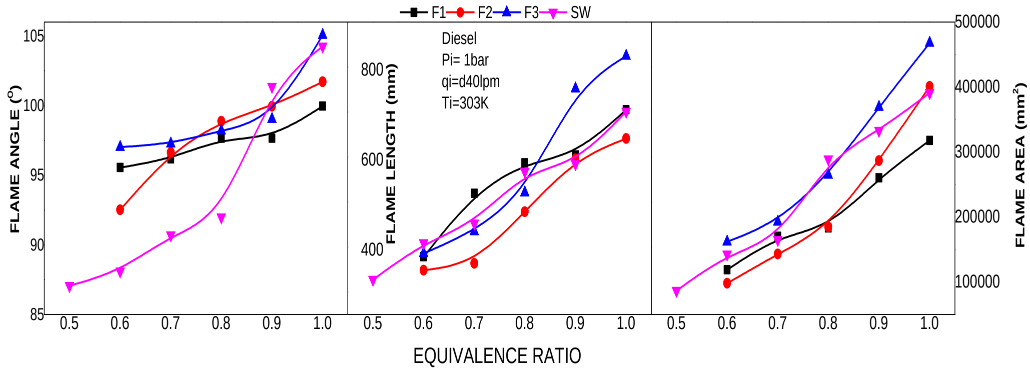

Figure 6. Flame characteristics of all Fractals

4. Conclusion
A fundamental study on the effect of fractal grid in the rapid mixing injector using diesel fuel in the burner system was conducted. Discussion focused on the relation between the equivalence ratio and flame development during the burning process. Results are summarized as follows:

1. A high equivalence ratio will result in a long flame length, wide flame angle, and large flame area. The flame length will affect the flame area. As the equivalence ratio increased, the intensity of the flame also increased.
2. The results of the flame length were dependent on the fractal geometry. The fractal grid significantly influenced combustion. Fractal 3 was found to improve combustion compared with the other fractals and swirl.

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