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2025 | 438

Effect of turbulence intensity on the spray statistical variation under marine engine-like condition

Visualizations

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ABSTRACT

The utilization of internal combustion engines powered by methanol and ammonia is considered a crucial approach to achieving carbon neutrality. Diesel should be implemented as a pilot fuel to overcome effectively the unfavorable ignition and combustion characteristics of zero-carbon fuels. The cyclic variations of small injection amount diesel spray exert an important influence on the ignition timing, combustion location, and heat release rate in dual-fuel zero-carbon engines. In actual engine cylinders, a complex turbulent field is formed due to inlet and exhaust airflow, heat transfer, and piston motion. Therefore, it is of great significance to investigate the spray-turbulence interaction as well as the cyclic variations of spray characteristic. The constant volume turbulence chamber equipped with four fans that have variable speed and rotation direction is designed and applied. The presence probability image and intersection over union (IoU) methods are proposed to evaluate the cyclic variations of spray. The results demonstrate that the fuel dribbling phenomenon becomes virtually undetectable in the turbulent environment. Furthermore, the peak IoU is approximately 0.35 for both quasi-static and turbulent conditions. However, the IoU under turbulent condition is observed to be lower than that under quasi-static condition, indicating greater cyclic variation in spray characteristics within the turbulent environment. Additionally, the spray area where presence probability equals 1 under the quasi-static condition is found to be greater compared to turbulent condition. This suggests that turbulence significantly affects the spray structure and distribution, leading to more pronounced cyclic variations and potentially influencing combustion efficiency and stability.

1 INTRODUCTION

Internal combustion engines (ICEs) are widely employed in maritime transportation, power generation, and various other fields due to their high thermal efficiency, power density, and reliability [1, 2]. Over the past several years, the development of ICEs powered by zero-carbon and carbon-neutral fuels, such as methanol and ammonia, is considered a crucial approach to reducing carbon emissions [3, 4]. However, the direct application of pure ammonia or methanol in ICEs faces significant challenges, consequently, a high reactivity fuel (such as diesel) should be implemented as a pilot fuel to overcome the disadvantageous ignition and combustion characteristics of main fuels.

The output power of ICEs increases by approximately ten percent for the same amount of fuel consumed when the cycle-to-cycle variations (CCVs) are substantially decreased [5]. In particular, the CCVs of small injection amount diesel spray exert an important influence on the ignition timing, combustion location, and heat release rate in dual-fuel ICEs. In recent years, the CCVs of spray characteristics have been extensively studied and reported. Zhou et al. [6] investigated experimentally that the effects of fuel temperature and injection pressure on the cyclic variation of acetone spray in the constant volume chamber. The results showed that the variations of flash boiling spray are more significant than those of non-flash boiling spray. Nour et al. [7] conducted comprehensive research on twelve multicomponent fuels and three pure component fuels spray characteristics under subcooled, transitional, and superheated conditions. The results indicated that the spray structure is influenced by the blending ratio of high volatility components. Specifically, the total collapsed spray exhibited greater cyclic variation compared to the non-collapsed spray. Qi et al. [8] adopted statistics methods, including intersection over union (IoU), presence probability image (PPI), and coefficient of variation, to assess the variations of spray morphology. The application of these statistical methods in characterizing and understanding the CCVs of fuel spray has demonstrated their effectiveness. However, the previous researches have predominantly concentrated on spray characteristics on quasi-static environment and neglecting the significant role of turbulence. In actual ICE cylinders, a complex turbulent field is formed due to inlet and exhaust airflow, heat transfer, and piston motion [9, 10]. To investigate the impact of turbulence on fuel spray characteristics, Zhang et al. [11] designed an experimental apparatus equipped with eight fans which mimic a varying turbulent field. Their results revealed that the auto-ignition delay of a single droplet initially decreases and subsequently increases with the increase of turbulence intensity. Arabkhalaj et al. [12] studied the effect of droplet size on the vaporization rate of butanol fuel under turbulent flow conditions. Their study demonstrated that turbulence exerts greater impact on the vaporization of fuels with lower gas-phase mass diffusivity and higher thermal diffusivity. The objective of this study is to identify spray-turbulence interaction, as well as to evaluate the effect of turbulence intensity on the spray statistical variation. This research offers quantitative data for evaluating the CCVs of pilot injection spray and provides an insightful analysis of combustion instability in dual-fuel ICEs.

2 EXPERIMENTAL SETUPS

2.1 Construction of Constant Volume Turbulence Chamber

The constant volume chamber can simulate engine-like conditions and is widely used by researchers for spray characterization. It offers several advantages, including full control, well-defined boundary conditions, and good optical access. In order to induce turbulence and study its effects on spray characteristics, the constant volume turbulence chamber is specifically designed and manufactured. Figure 1 shows a schematic diagram of the constant volume turbulence chamber (CVTC). Due to spatial and geometric limitations, the turbulence condition is generated by four identical opposed fans in the CVTC. A three-blade fan with an external diameter of 70 mm is connected to an electric motor (POWSM-W-060-00630-A2) via a metal shaft. The rotating speed of the electric motor is controlled by a driver (SERVODRIVE, POWSD-E-15APB) and its maximum speed is up to 3000 rpm. The fan speeds are set at 0 and 3000 rpm which corresponding to the lowest and highest turbulence intensity levels, respectively. The high-speed marine diesel engine injector is mounted on the top of the CVTC. The nozzle diameter of the single-hole injector is 0.355 mm. The optical quartz windows of the CVTC are 170 mm in diameter, represent the bore dimensions of a commercial high-speed marine engine. The experiment is carried out in the CVTC using schlieren imaging technology. The CMOS camera (Phantom V2640) equipped with TAMRON A035 lens captures the spray images. These images are recorded at 25,000 frames per second with a maximum spatial resolution of 1024 * 976 pixel^2 and an exposure time of 3 us.

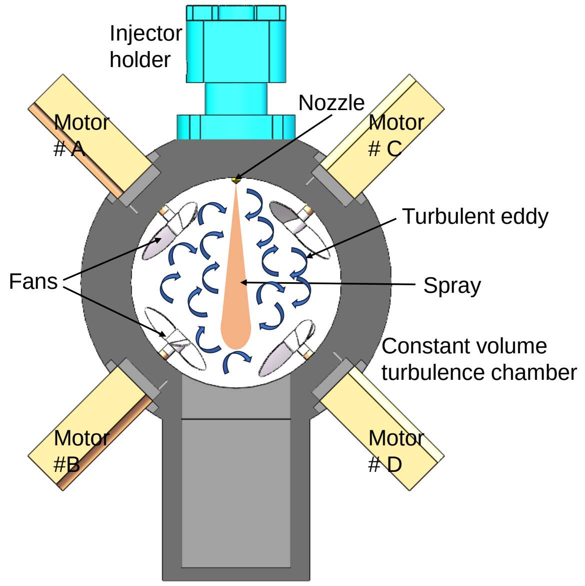

Figure 1. Schematic of the constant volume turbulence chamber.

2.2 Particle Image Velocimetry System

In order to analyze the turbulence characteristics, a transparent prototype CVTC is made by polymethyl methacrylate (PMMA) material. The turbulence characteristics are measured using a 2D Particle Image Velocimetry (2D PIV) system developed by Revealer. The system comprises a dual-head laser device and a high-resolution CCD camera (Revealer X150). The camera is set to a resolution of 2560 * 1920 pixel^2 and an exposure time of 1 µs. The dual-head Nd: YAG laser is located in the X direction and provides laser rays of 500 mJ/pulse at 532 nm wavelength with a maximum frequency of 15 Hz. This laser system is used to illuminate the tracer particles in the X-Y plane. The hollow glass microsphere particles, with an average size of 10 µm are used as solid tracer particles. Three test cases are designed to investigate the effects of fan speeds (0 and 3000 rpm) and fan rotation directions (clockwise and counterclockwise) on turbulence intensity in the transparent CVTC. The three test cases are summarized in Table 1. The symbol "+" represents that the fan rotates in a clockwise direction, on the other hand, the symbol "-" indicates that the fan counterclockwise rotation. The maximum turbulence intensity is observed in Case 2, while Case 1 represents a quasi-static condition with minimal turbulence intensity. The global turbulence intensity is primarily concentrated within the range of 1 to 2 m/s, while the peak wind velocity reaching up to 2.5 m/s in certain regions. The intensity of turbulence is ranked in descending order as follows: Case 2 > Case 3 > Case 1. In addition, PIV experiment conducting 50 repetitions of each event is sufficient to obtain stabilized results and minimize errors caused by turbulence instability. The central region velocity field of Case 3 is illustrated in Figure 2.

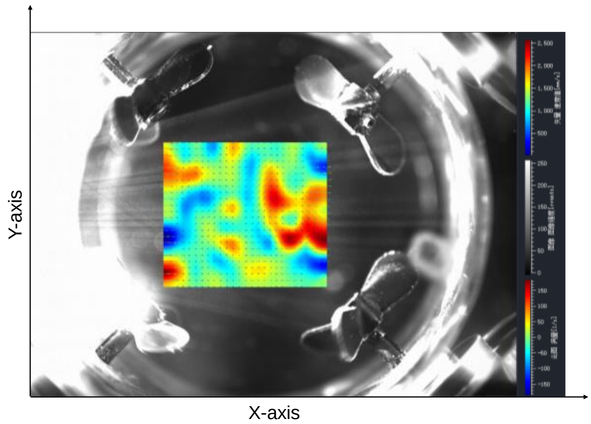

Figure 2. Central region velocity field of Case 3.

Table 1. Fan speed and rotation direction.

Case	Fan #A	Fan #B	Fan #C	Fan #D (rpm)
1	0	0	0	0
2	+3000	+3000	+3000	+3000
3	-3000	-3000	-3000	-3000

2.3 Experimental Conditions and Uncertainty Analysis

Considering the safety limits of the CVTC, the ambient pressure and the temperature are maintained at atmospheric and room temperature, respectively. A total of fifty-two sampled data are used to evaluate the spray characteristic and variability under each experimental condition. The experimental conditions for this study are presented in Table 2, while the experimental uncertainty is summarized in Table 3. In this experiment, a measurement error of less than 1.5% is considered acceptable to ensure the reliability of the results.

Table 2. Experimental conditions.

Parameter	Value (units)
Injection pressure	40 MPa
Pulse width	0.4 ms
Nozzle diameter	0.355 mm
Ambient pressure	1 bar
Ambient temperature	300 K
Number of injections	52

Table 3. Experimental uncertainty.

Measurements	Parameter	Accuracy
Injection pressure	40±0.5 MPa	1.25%
Fan speed	3000±3 rpm	0.1%
Image calibration	170/960±2 mm per pixel	0.21%

2.4 Statistical Analysis Methods

The statistical analysis methods, including the presence probability image (PPI) and intersection over union (IoU), are adopted to evaluate the CCVs of spray morphology. The detailed computation method for PPI is reported in references [13]. The IoU is defined as the ratio of the spray area where the presence probability (PP) is 1 to the total area where PP is greater than 0, as shown in Eq. (1). A smaller IoU indicates a greater variation in spray characteristics. Figure 3 presents the definitions of pp=1 and pp>0.

$$\mathrm{IoU} = \frac{\mathrm{spray}_1 \cap \mathrm{spray}_2 \cap \mathrm{spray}_3 \cdots \cap \mathrm{spray}_n}{\mathrm{spray}_1 \cup \mathrm{spray}_2 \cup \mathrm{spray}_3 \cdots \cup \mathrm{spray}_n} = \frac{\mathrm{Area}_{pp=1}}{\mathrm{Area}_{pp>0}} \quad (1)$$

Where n indicates the number of experiments.

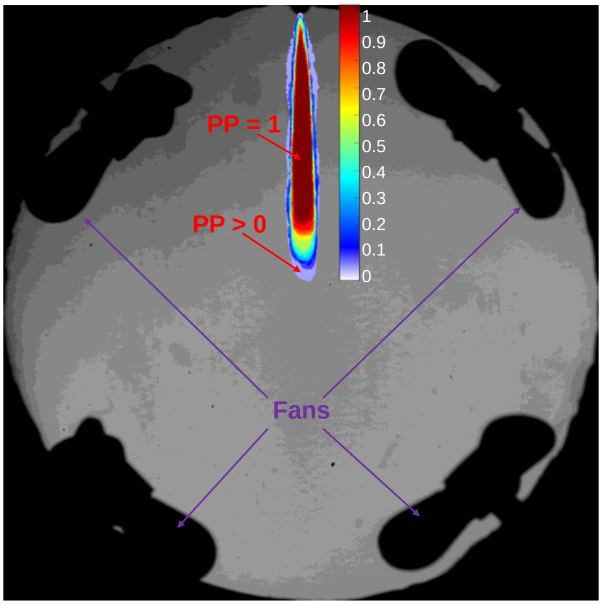

Figure 3. Definitions of pp=1 and pp>0.

3 RESULTS

3.1 Spray Image Analyze

The spray images for Case 1, Case 2, and Case 3 are presented in Figure 4. The injection duration is about 400 μs, which is attributed to the separation of the spray trail from the injector nozzle tip. The spray head becomes invisible at ASOI 1200 μs. Although the fan speed reaching up to 3000 rpm (equivalent to 18 °/ms), a single blade completes a rotation of less than 90° throughout the entire spray process. In comparison to Case 1, the spray shapes in Cases 2 and 3 become more irregular because of the effect of ambient gas turbulence at ASOI 1600 μs.

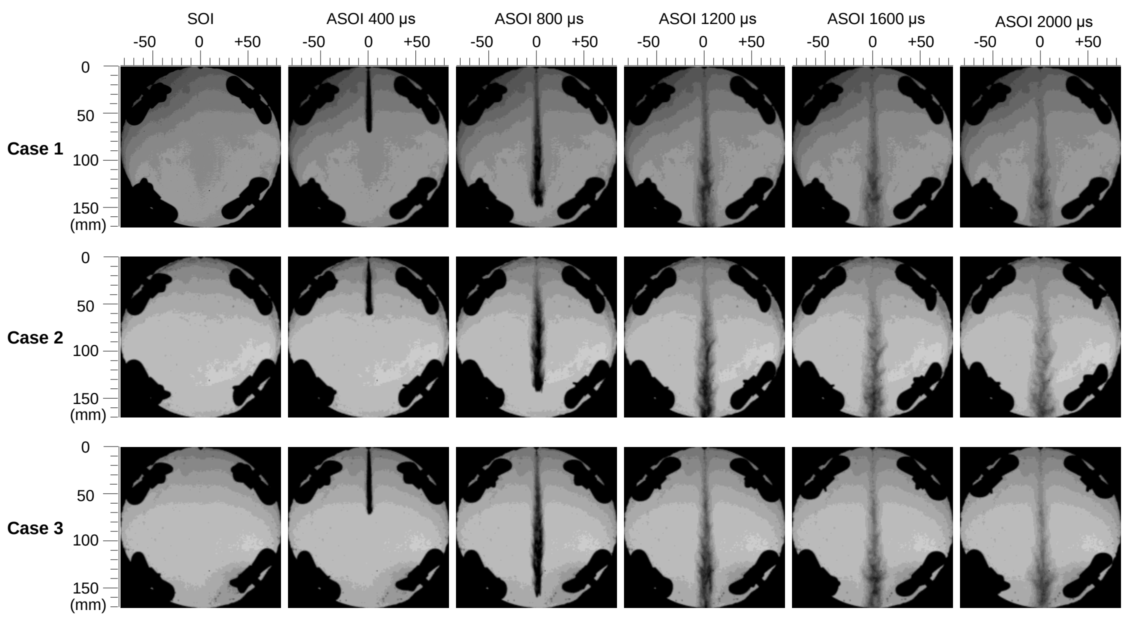

Figure 4. Temporal evolution of the spray image.

Figure 5 illustrates the temporal development of the PPI. It is already known that the area of high repeatability is in the spray core region, while the area characterized by high fluctuation is located in the spray periphery. In the near-nozzle region of Case 1, the presence of slow-moving large droplets and liquid ligaments is prominently observed. This phenomenon, commonly referred to as fuel dribbling, results in incomplete combustion and consequently leads to increased soot emissions [14]. Conversely, in the strong turbulent environments of Cases 2 and 3, fuel dribbling is virtually undetectable. Therefore, to mitigate soot emissions for the ICE, it is advisable to enhance turbulence intensity in the cylinder.

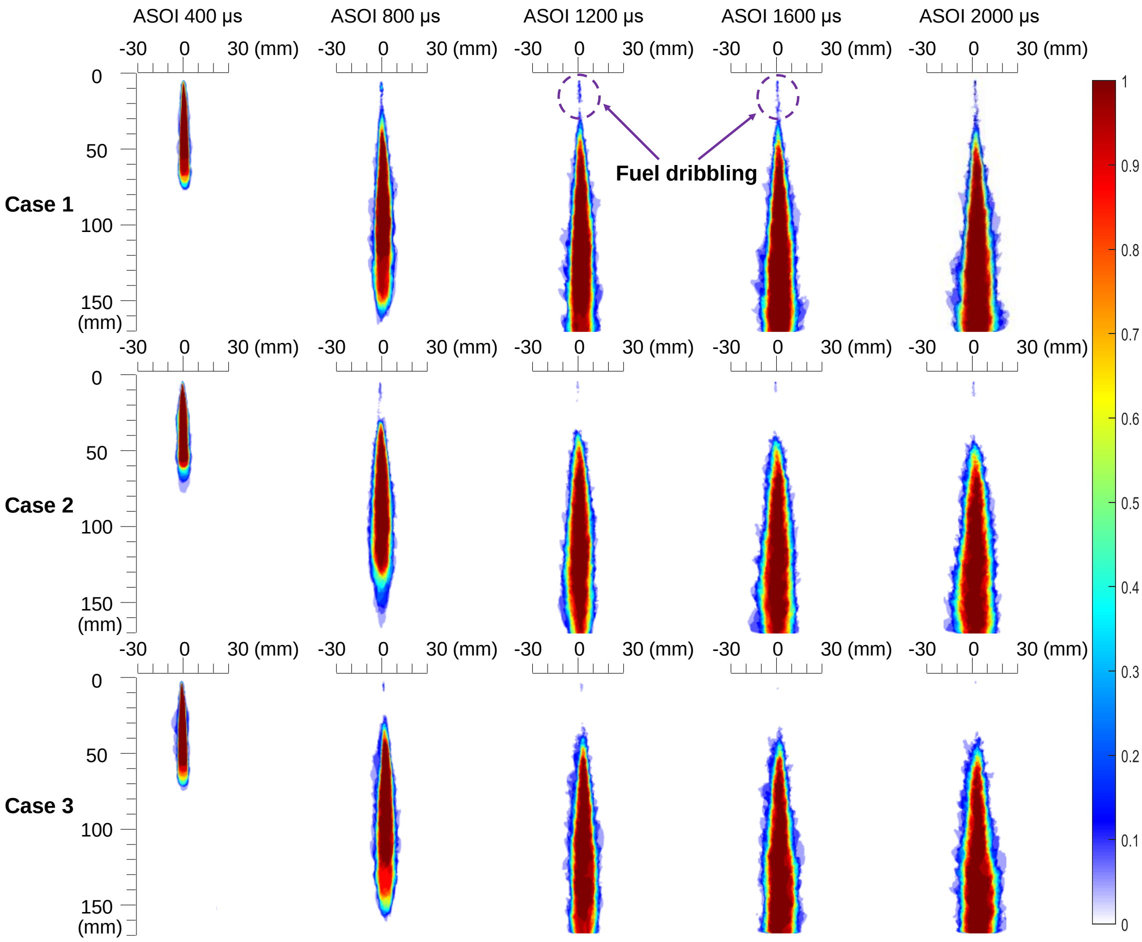

Figure 5. Temporal development of the PPI.

3.2 Spray Area and Intersection Over Union

The spray area where the PP equals 1 for each case, is shown in Figure 6. It is no doubt that the $Area_{pp=1}$ of Case 1 is larger than that of Cases 2 and 3. Specifically, the $Area_{pp=1}$ of Case 1 remains consistently at 1100 mm^2 at ASOI 1100 µs. However, the $Area_{pp=1}$ of Cases 2 and 3 stabilizes at 800 mm^2. The larger droplets are more prone to break up into a greater number of smaller droplets in turbulent environments. Consequently, the spray area in the turbulent condition is subject to increased fluctuations. This variability is primarily driven by the inherent randomness in the behavior of droplets, which includes their size distribution, velocity, and collision dynamics [15, 16].

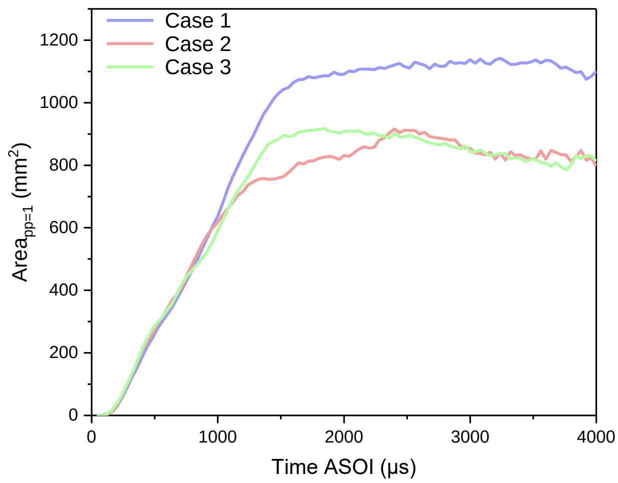

Figure 6. Spray area where the presence probability

equals 1.

The spray area where the PP greater than 0 for all three cases is showed in Figure 7. The growing trend towards $Area_{pp>0}$ of the all three cases exhibit a similar “Initial rapid increase followed by a gradual slowdown” trend before 1000 μs. The main reason is that the nozzle outlet speed can reach up to 300 m/s according to the Bernoulli principle, and the spray tip penetration speed is on the order of tens of meters per second. This phenomenon is attributed to the high velocity of the spray, which dominates the initial dynamics, making the influence of the comparatively lower wind speed negligible in the initial phase of spray development. In the final stage of spray development, the Case 2 demonstrates the smallest $Area_{pp>0}$, whereas $Area_{pp>0}$ of Case 1 is maximum. This difference can be attributed to the small droplets tend to break up into ultra-small sizes, which become increasingly challenging to discern and quantify accurately.

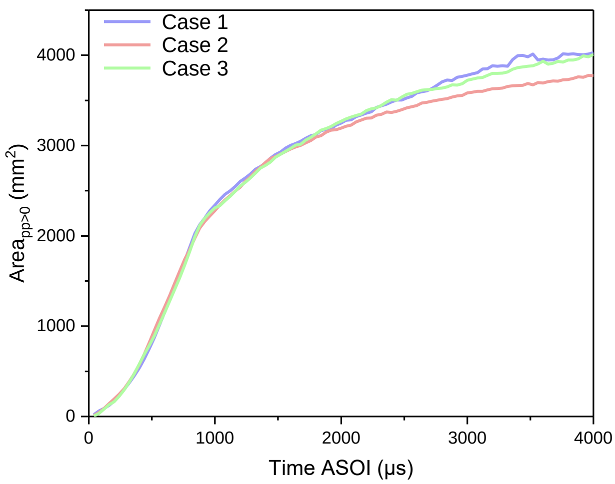

Figure 7. Spray area where the presence probability is greater than 0.

The IoU of spray morphology is observed in Figure 8. The peak IoU for all three cases is about 0.35. Notably, the IoU of Cases 2 and 3 is lower than that for Case 1. Namely, the spray under quasi-static condition (Case 1) exhibited greater CCVs compared to the spray under turbulent condition (Cases 2 and 3). This observation provides that the spray characteristics under turbulent condition is more susceptible to fluctuations, potentially due to the abundance of turbulent mixing. Furthermore, the IoU for all three cases decreases gradually in the late spray development stage. This trend is consistent with previous investigations [13].

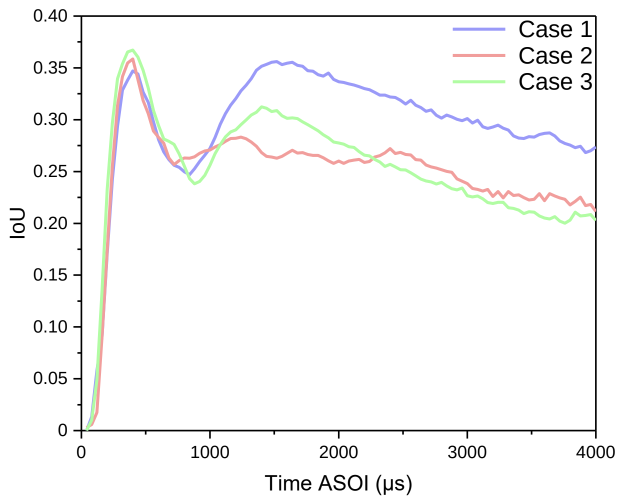

Figure 8. IoU of spray morphology.

4 CONCLUSIONS

In the present work, the cyclic variations of pilot diesel injection spray under turbulent condition are investigated experimentally and compared with those under quasi-static condition. The cyclic variations in spray morphology are quantitatively characterized using statistical methods. The main findings can be summarized as follows:

1) In order to explore the effects of varying turbulence intensity on the statistical variation of spray and the interaction between spray and turbulence under marine engine-like conditions, a CVTC system has been designed and implemented.

2) The fuel dribbling phenomenon becomes virtually undetectable in the turbulent environment. This is because turbulence enhances the breakup of larger droplets into smaller ones. To reduce the incomplete combustion and soot emissions, it is advisable to increase the turbulence intensity within the engine cylinder.

3) The maximum IoU is approximately 0.35 for both quasi-static and turbulent conditions. The IoU under turbulent condition is observed to be lower than that under quasi-static condition. Concurrently, the $area_{pp=1}$ under the quasi-static condition is found to be greater than that under turbulent condition.

5 FUTURE WORK

In the future, experimental studies on spray cyclic variations under high temperature and high pressure condition will be conducted. The investigation of spray-turbulence interactions will be expanded to include net-zero carbon fuels, such as methanol, dimethyl ether (DME) and liquid ammonia. These fuels, characterized by their higher volatility and tendency for flash boiling, readily transition into the gaseous phase, and are more susceptible to the influence of turbulence within the engine combustion chamber. Additionally, a novel spray penetration model will be developed, incorporating the concept of presence probability to enhance predictive accuracy. Furthermore, a more comprehensive study by computational fluid dynamics (CFD) and a marine optically accessible engine (bore = 170 mm, stroke = 190 mm) will be carried out.

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