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STAGNATION LAMINAR PREMIXED CH_4/AIR FLAME SUBJECTED TO THE EQUIVALENCE RATIO OSCILLATIONS

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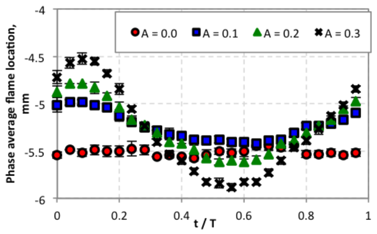
Graphical abstract



Abstract

The effect of the equivalence ratio oscillation on a premixed laminar CH_4/air flame motion was studied experimentally with equivalence ratio oscillation frequencies of 2 to 15 Hz at lean equivalence ratio using stagnation flow field burner. Novel oscillator does the oscillation conditions and turbulence reduction method is used to suppress the velocity perturbation. The flame position variations at 2, 5, 10 and 15 Hz oscillation frequencies were significantly small when the amplitude of the equivalence ratio oscillation was zero. On the other hand, increase in amplitudes of the equivalence ratio oscillation increased the flame position variation significantly. The flame moved in sinusoidal shape and it can be clearly seen that the flame movement's amplitude was proportional to the amplitudes of the equivalence ratio variations. This result showed that the velocity perturbation is significantly suppressed by turbulence reduction method in the examination range.

Keywords: Laminar premixed flame, equivalence ratio oscillation, turbulence reduction method

Abstrak

Kajian kesan salingan nisbah kesamaan terhadap nyalaan lamina pra-campur CH_4/udara dijalankan secara eksperimen dengan frekuenci salingan dari 2 Hz hingga 15 Hz pada nisbah kesamaan kurang bahan api menggunakan pembakar. Sejenis salingan yang tersendiri digunakan untuk menyalurkan campuran bahan api dan udara serta kaedah pengurangan turbulan digunakan untuk menghapuskan gangguan kelajuan. Kedudukan nyalaan api pada 2, 5, 10 dan 15 Hz frekuensi salingan adalah terlalu kecil apabila nisbah kesamaan bahan api bersamaan kosong. Pada ketika lain, peningkatan amplitud nisbah kesamaan meningkatkan kedudukan nyalaan api. Nyalaan api bergerak dalam bentuk sinusoidal dan berkadar terus dengan amplitud nisbah kesamaan. Berdasarkan kepada keputusan yang diperolehi, gangguan kelajuan berjaya dihapuskan dengan jayanya menggunakan kaedah pengurangan turbulan dalam julat yang dijalankan.

Kata kunci: Nyalaan lamina pracampur, salingan nisbah kesamaan, kaedah pengurangan turbulan

1.0 INTRODUCTION

Regulation on the NO_x emission is very strict, percentage of the NO_x releases by combustor to the atmosphere need to be reduced every year. Currently, combustor that would release low emission is a lean premixed combustor. This combustor operates at lean condition where in this regime emission of both NO_x and

CO_2 are low. Moreover, lean premixed combustion is economical because it used less fuel. The lean premixed combustion is used in power plants and factories to reduce the NO_x emission[1,2] . On the other hand, an operating condition of the lean premixed combustor in the lean regime has lead to some technical problems that have not yet been solved, such as combustion instability. Combustion instability is one of the main subjects of current combustion science. Combustion instability as functions of combustor geometry, operating conditions and fuel have not yet been clarified[3]. Moreover, Ref. 4 showed that reactant un-mixed also could drive strong instabilities in a lean premixed combustor. Combustion instability occurs when the pressure oscillation is in phase with the heat release oscillation, then induces poor performance of the combustor and to some extend it may break the combustor. One approach to solve the combustion instability is by modulating the equivalence ratio injected into the combustion chamber. References 5 and 6 have studied the modulating of the equivalence ratio and found that the instability can be suppressed by this approach. Practically, the combustion instability can be controlled by equivalence ratio perturbation. This is because the heat release oscillation can be stabilized by repeating the conditions at it or lower frequency than that the heat release oscillation frequency[5]. Unfortunately, there are no general rule to design the system because as mention by Ref. 3, the combustion instability depends on combustor geometry, operating conditions and fuel. Thus, understanding of fundamental mechanism of the flame response to the equivalence ratio perturbation is needed. In the combustor, turbulent combustion is occurred. It is very difficult to understand the fundamental structure and dynamic response of the turbulent. Therefore, the simplest and an easy way to understand the turbulent combustion is by analyzing the laminar flames. The laminar flame is significantly contributes to the better understanding of the turbulent combustion[7]. Spatial and temporal perturbations are related with the oscillation case. This oscillation could be in lean, rich or crossover lean rich cases. Fundamentally, in the spatial and temporal perturbations, flame zone thickness could be smaller, equal or larger than that wavelength of the equivalence ratio oscillation. Therefore, effect of the oscillation frequency is significant. These cases have been studied widely in numerical and less effort in an experimental work. Experimental work of the flame response to the equivalence ratio oscillation is complicated due to an incorporated of the velocity perturbation. Velocity perturbation is a major problem that needs to be solved in the equivalence ratio oscillation case. Low-pressure environment[8] and porous structured[9,10] were used to reduce the velocity perturbation. Experiment on a conical laminar premixed CH4/air flames could not diminish the velocity oscillation and concluded that the velocity perturbations imparted to the mainstream induced by the modulation mainly determined response of the weakly turbulent flame subject to equivalence ratio oscillation[11]. Combination of the honeycomb and wire mesh screen is use in the wind tunnel system to reduce the turbulence in the flow[12]. Basically, wire mesh screen reduces axial fluctuation[13] and honeycomb reduces lateral fluctuation[14]. Therefore, combination of the honeycomb and wire mesh leads to reduction of turbulence in the flow[15]. Recently, Ref. 16 conducted a study on a stagnation laminar-premixed flame responses at low oscillation frequency and concluded the flame is response due to equivalence ratio perturbation without velocity perturbation. Therefore, the objective of this paper is to investigate a stagnation laminar-premixed CH4/air flame response to the equivalence ratio oscillation using turbulence reduction method.

2.0 EXPERIMENTAL

Figure 1 shows the schematic diagrams of the flow system. A primary flow of CH4/air mixture of the system was in lean condition. The CH4 and air were supplied from the pressurize cylinder and the air compressor respectively. Moreover, mass flow controller measured flow rate of both CH4 and air. The primary flows mass flow controller of Azbil (Yamatake Corp.) was used with measurement ranges of 0.04 - 5.0 lpm for CH_4 and 0.4 - 50.0 litres per minute (lpm) for air. The flow mixture of the CH_4/air at the nozzle exit burner was a combination of flow from the primary and secondary flow. The secondary flow consists of lean and rich of the CH4/air mixture. The mass-flow rates of lean and rich secondary air and also the lean and rich secondary CH_4 were measured and controlled using Azbil digital mass-flow controller (Yamatake Corp.) with measurement ranges of 0.2 - 20.0 lpm, 0.04 - 5.0 lpm, 0.02 - 2.0 lpm and 0.04 - 5.0 lpm respectively. The lean and rich CH_4/air mixture was supplied to the burner from an oscillator.

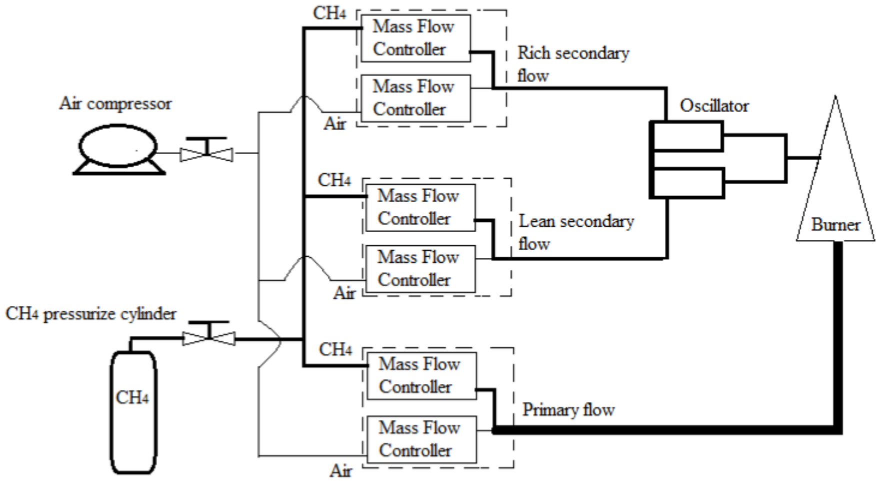


Figure 1 Schematic diagrams of the flow system

The oscillator supplied the lean and rich CH_4/air mixture at 180º phase difference respectively. Therefore, the combination of the primary and the secondary flows were mixed at the mixing zone of the burner and produced equivalence ratio variation at the exit of the nozzle burner.

2.1 Burner System

An overview of the nozzle section with coordinate system and detailed is shown in Figure 2. Primary flow of the CH_4 and air was mixed in mixing chamber of the burner. In this study, we implemented the combination of honeycomb and wire mesh screen to reduce the velocity fluctuation in mixing chamber before it reach to the nozzle burner. Furthermore, flat velocity profile at exit of the nozzle was produced using convergent nozzle. Stagnation flow field condition was established by installing the stagnation plate at the top of the nozzle burner exit with ratio between the length of the stagnation plate from burner nozzle exit, *L* to the burner diameter, *Dia*, is *L*/*Dia* = 1.0. The stagnation plate is made of a ceramic disk with 76 mm diameter. Flat laminar premixed CH_4/air flame was formed in the stagnation region when CH_4/air mixture issued form the nozzle with 20 mm diameter ignited. Co-flow of the N_2 was issued surrounding the main nozzle burner to minimize the interaction of the flame edge with the ambient air, to make the flame flat and increased the flatness of the flame shape. The coordinate *y* and *r* were defined as the upstream direction from the stagnation plate along the center axis and in radial direction of the burner nozzle respectively.

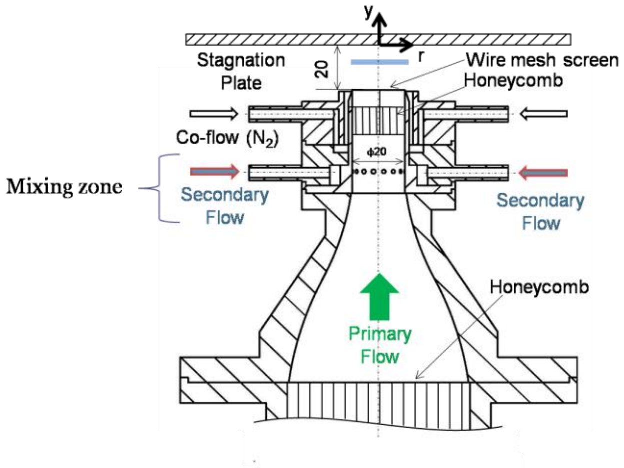


Figure 2 Schematic of the nozzle section with coordinate system

2.2 Equivalence Ratio Oscillation System

The equivalence ratio oscillation was produced by injecting lean and rich equivalence ratio into the primary flow from a secondary flow pipes at the mixing zone of the burner (Figure 2). A detail of the mixing zone is shown in Figure 3. Injection port consists of 16 holes with 1.5 mm in diameter at 32 mm upstream of the burner nozzle exit to inject CH_4/air mixture into the primary flow. The CH_4/air mixture was supplied into the injection port from 8 holes with 4.0 mm in diameter. Each incoming port was connected with two tubes, one for lean mixture and the other rich mixture. The CH_4/air mixtures with lean and rich equivalence ratios were supplied from the oscillator system simultaneously.

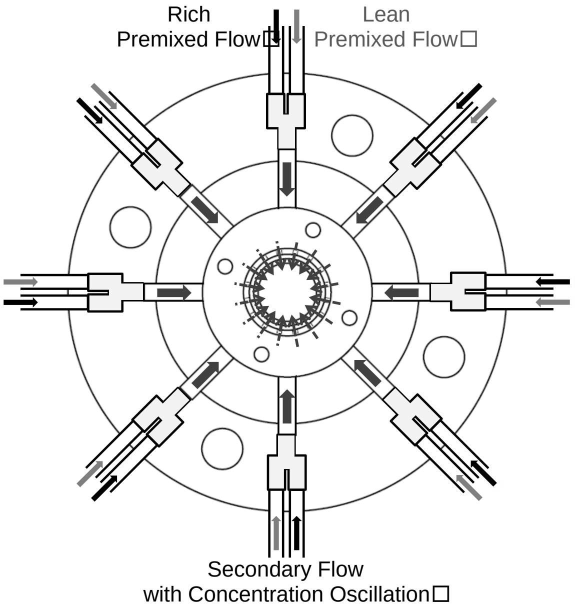


Figure 3 Injection port

2.3 Oscillator System

Novel oscillator consists of two chambers with volume of 785 mm^3 each (bore × stroke = 10 mm × 10 mm) was developed. The oscillator body was made from an aluminum alloy. Moreover, the chambers lining and the pistons of the oscillator were made from high tempered glass. The oscillator piston moved by crank mechanism that connected to the DC motor (Oriental Motor Co., Ltd., brushless DC motor BLF46A-A-3) by pulley-belt system. This motor can produced 80 ~ 4000 rpm of the rotational speed with the accuracy ± 0.2 %. The piston moved up and down sinusoidal with a 180-phase lag for each. Sinusoidal movement of the piston caused the alternate supply of the CH$_4$/air mixture to the injection chamber. Flame position was measured by direct photograph using binaries image. Measurement was conducted by taken the flame movement images using high-speed video camera (KEYENCE VW-6000) with Nikkor lens (Nikkor 58 mm F 1.2). Still images were extracted from the video images using open source video playback software called GOM Player. Image analysis tools in *Mathematica 8* were used to convert the image into binaries and measured the flame position. Figure 4 shows the definition of the flame positions. Flame positions were determined as the lowest point of the binaries still image from the nozzle exit along the central axis of the burner exit nozzle.

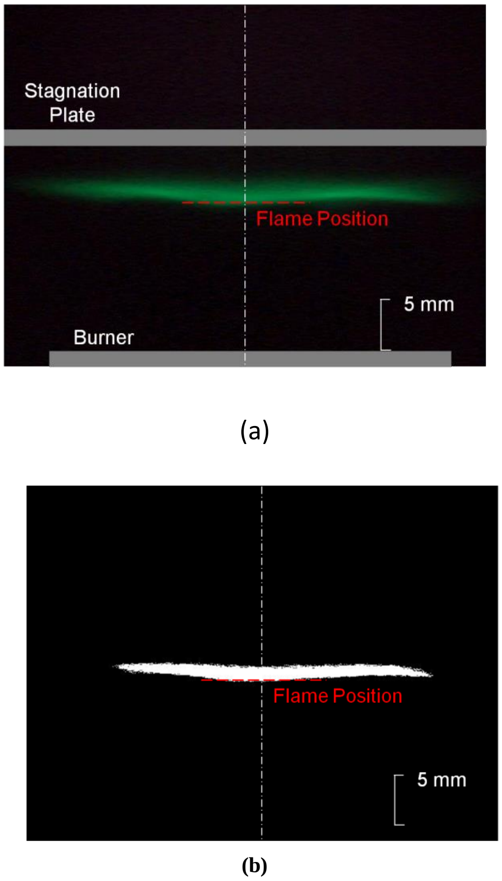


Figure 4 Flame position (a) direct flame image (b) binaries image

3.0 RESULTS AND DISCUSSION

Stagnation laminar CH$_4$/air premixed flame was formed by issuing inlet velocity 0.8 m/s. Mean equivalence ratio was, $\emptyset_M$ = 0.7 with the equivalence ratio oscillation amplitude of $\emptyset_A$ = 0.0, 0.1, 0.2 and 0.3 at the oscillation frequency of f = 2, 5, 10 and 15 Hz were investigated. The equivalence ratio oscillation amplitude was focused in the lean region because the flame position was proportional to the equivalence ratio as shown in Figure 5.

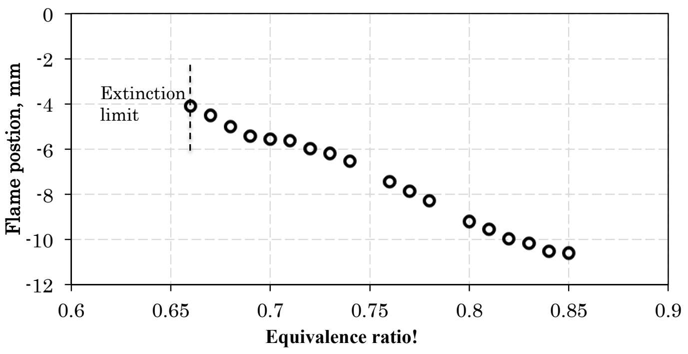


Figure 5 Flame position in a steady state case at various equivalence ratio

The extinction limit of CH_4/air mixture in this experiment is at the equivalence ratio $\emptyset = 0.66$ and it is considering a bit higher than that the normal case. This is happened probably due to the insertion of honeycomb and wire mesh. The equivalence ratio oscillation amplitude was defined as the value of an equivalence ratio injected from the secondary flow and not a local value at a flame front in the present study. Initially, it is important to verify an effect of the velocity perturbation on the flame dynamics. Velocity perturbation was examined by injecting the secondary flow that had an equal equivalence ratio as in primary flow. Injected equal equivalence ratio from secondary into primary flows suppressed the equivalence ratio variation. Thus, a movement of the flame at this condition was strongly due to velocity perturbation in the primary flow. Figure 6 shows the response of the flame position at various oscillation frequencies with $\emptyset_A = 0.0$ equivalence ratio oscillation amplitude. In Figure 6, it can be clearly seen that at 2, 5, 10 and 15 Hz oscillation frequencies, the flame position variations are significantly small. Thus, it can be concluded that the velocity perturbation is significantly suppressed in the examination range.

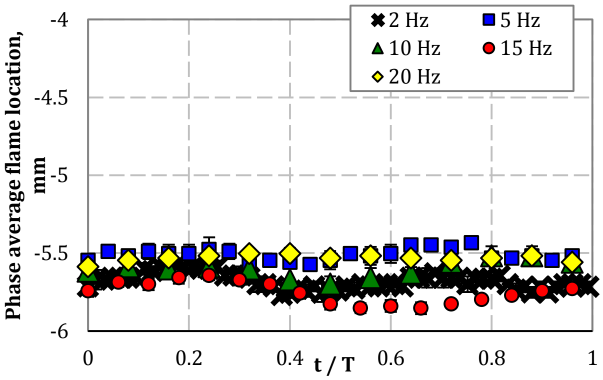


Figure 6 Cyclical variations of the flame position at 0.0 oscillation amplitude for various equivalence ratio oscillation frequencies

Figures 7, 8, 9 and 10 show cyclical variations of the flame position response to the equivalence ratio oscillation at *f* = 2, 5, 10 and 15 Hz of the oscillation frequency with the oscillation amplitude, $\emptyset_A = 0.0$, 0.1, 0.2 and 0.3. It is important to determine the initial position of the flame movement because it indicates the phase lag. Therefore, synchronizing system was used to evaluate the starting point of each oscillation case. In synchronizing system, each starting point was at the same location by referring to rotations of the oscillator pulley. Thus, every equivalence ratio oscillation case was in a same phase. In Figures 7, 8, 9 and 10 flame moves in sinusoidal shape and it is clearly seen that the flame movements was proportional to the amplitudes of the equivalence ratio variations. Since the velocity perturbation was significantly suppressed as shown in Figure 6, the flame movement in Figures 7, 8, 9 and 10 was primarily due to the equivalence ratio oscillations. At $\emptyset_A = 0.1$, amplitude of the flame movements was low but it variations was larger than $\emptyset_A = 0.0$ case. Significantly increment in the flame movement amplitude was observed at $\emptyset_A = 0.3$ compared to $\emptyset_A = 0.1$ and 0.2 oscillation amplitudes cases.

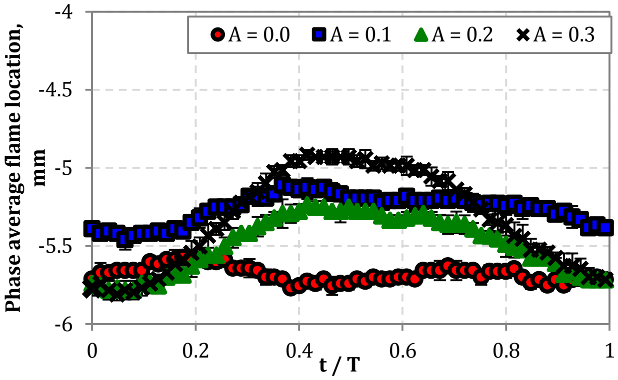


Figure 7 Cyclical variations of the flame position for 2 Hz case at various equivalence ratio oscillation amplitudes

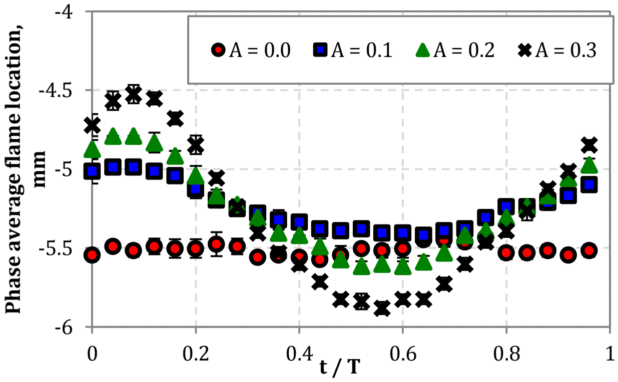


Figure 8 Cyclical variations of the flame position for 5 Hz case at various equivalence ratio oscillation amplitudes

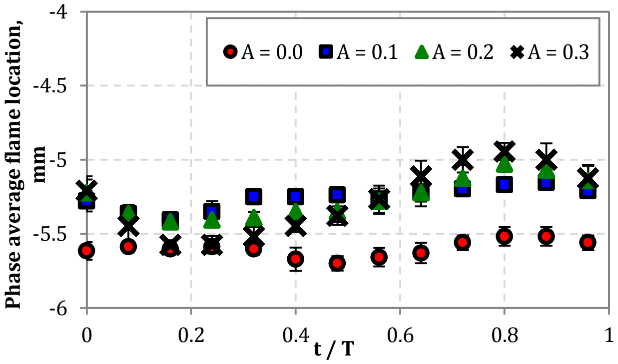


Figure 9 Cyclical variations of the flame position for 10 Hz case at various equivalence ratio oscillation amplitudes

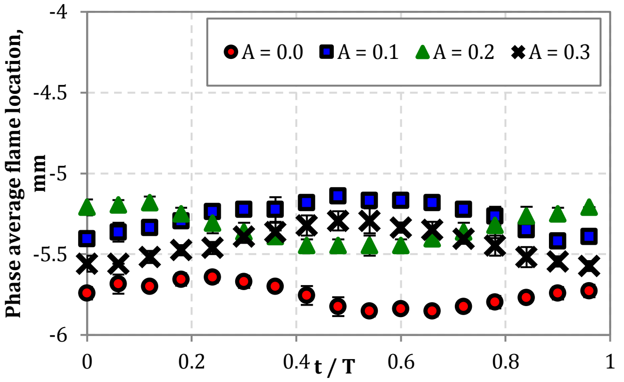


Figure 10 Cyclical variations of the flame position for 15 Hz case at various equivalence ratio oscillation amplitudes

4.0 CONCLUSION

Effect of the equivalence ratio oscillation on a premixed laminar CH4/air flame motion was studied experimentally using stagnation flow field burner. The flame response to the oscillation frequencies of the equivalence ratio of 2 to 15 Hz at lean oscillation case was investigated. Novel oscillator does the oscillation conditions and significant suppression of the velocity perturbation was achieved by turbulence reduction method. On the other hand, flame moved in sinusoidal shape and it can be clearly seen that the flame movement's amplitude was proportional to the amplitudes of the equivalence ratio variations. It can be concluded that the velocity perturbation is significantly suppressed by turbulence reduction method in the examination range.

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