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PRESSURE RISE GENERATION BY THE COMBUSTION OF METHANE-AIR IN A CLOSED VESSEL

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ABSTRACT

Experimental investigations were made to measure the variation of pressure development in a confined space at different equivalence ratio of methane-air combustion. A cylindrical vessel combustor that correspond to spherically expanding flame is used in this experiment. The experiment is subjected for only premixed methane-air mixture from five different equivalence ratio, ϕ which are lean (0.7, 0.8), stoichiometric (1.0) and rich (1.2, 1.4). The instantaneous and maximum pressure were recorded using dynamic pressure transducer. The result of pressure profile at stoichiometry condition was compared with the previous work by other researcher. Based on the experimental investigation, the trend line of the buildup pressure profile at various equivalence ratio in this experiment is similar as obtain in previous work done in which shows increment as the equivalence ratio moves from lean to slightly rich mixture. However it will eventually decrease when the mixture is too rich. The knowledge of maximum pressure can further be used to interpret the burning velocity of flame propagation.

Keywords: premixed flame, pressure method, spherical flame, methane.

INTRODUCTION

The combustion behavior of air-fuel mixture using constant volume vessel have been study comprehensively under variety of conditions (Dobashi, 1997; Dahoe and de Goey, 2003).These studies are significant in order to determine the characteristic and performance of the combustible mixture such as the burning velocity and ignitibility. There are two method that can be used to measure the characteristic; one is by using burner flame type and another is a constant volume vessel. In the constant volume vessel, the burning flame travel in a quiescent gas mixture and it follows the shape of the combustor use. It is an interest in the present work to use a cylindrical constant volume vessel that correspond to a spherically expanding flame. This method also been chosen because it resemble the real combustion system like the internal combustion engine in which the common parameter that both have is the cylindrical in volume. Therefore the performance of the pressure rise in the piston engine can be evaluated by isolating all other effects of the system and focus solely on the pressure rise effect. This research is beneficial in establishing a competence locally develop pressure trace method test rig. Thus significance in providing the experimental data for further works in combustion simulation study.

In a closed combustion system with a constant volume, the summation of volume of product mixture and volume of the unburned mixture made up the total volume of the vessel used. At any instantaneous of time the relation between the two given by (Dobashi, 1997)can be represented as follows;

$$\frac{dV_u}{dt} + \frac{dV_b}{dt} = 0 \quad (1)$$

The first term on the left in equation (1) represent the rate of changed of the volume unburned mixture and the second term is of the burned mixture. From the relation,Dobashi (1997)later on computed the pressure rise equation as follows;

$$P - P_i = \frac{CP_i S^3 t^3}{V} \quad (2)$$

where the term on the left is pressure rise, C is a constant coefficient, P_i is the initial pressure, S is the burning velocity and V is the volume of the vessel. Therefore, the pressure generation due to combustion inside a closed vessel is a function of initial pressure, burning velocity, time and volume. When the combustible mixture is completely combust, the pressure reached its maximum. The recorded pressure generation is then used to plot the pressure profile hence the maximum pressure, P_{max} can be observed. By obtaining the value of P_{max}, the combustion characteristic study can be extended to measure the burning velocity in which the responds of the combustible mixture can be estimated.

In the present work, experimental investigation of atmospheric methane-air combustion was done to investigate the pressure generation in a closed combustion chamber at various equivalence ratio. The purpose of this study is to understand the behavior of premixed methane-air combustion in term of pressure under confined environment and different equivalence ratio. The experiment cover selected equivalent air fuel ratio at lean (0.7 and 0.8), stoichiometric (1.0) and rich mixtures (1.2 and 1.4) and was limited only to combustion of methane gaseous fuel. Throughout the literature reviews, it is expected that the variation of pressure during the combustion process for the stated equivalence ratio are identical which suddenly increases in pressure until P_{max} value then followed by gradual pressure reduction. In most equivalence ratio P_{max} is achieved within 100 ms after the ignition starts, except for lean mixture.

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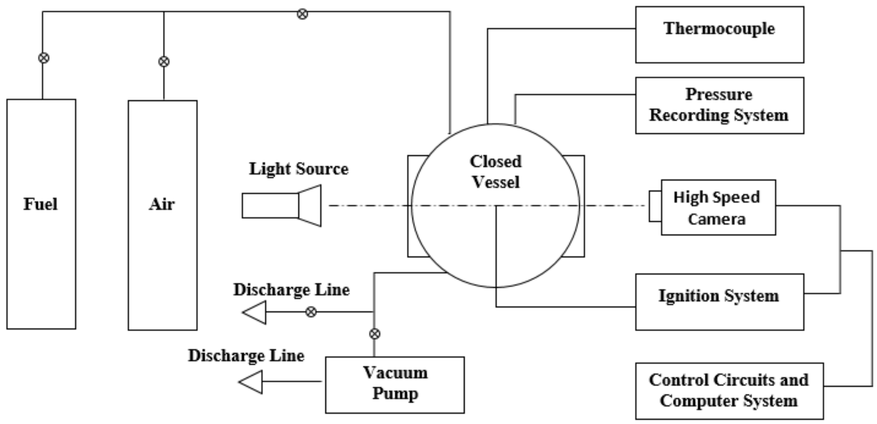

Figure-1. Schematic diagram of experimental setup.

EXPERIMENTAL METHOD

The pressure trace method of methane-air premixed combustion experiment was obtained using a closed cylindrical vessel with the capacity of 22L in volume. The experiment conducted was perform at room temperature 27°C, initial pressure of 100kPa and at various equivalence ratio (ϕ) ranging from lean (0.7, 0.8), stoichiometric (1.0) and at rich mixture (1.2, 1.4).

The cylindrical vessel follows the design of a spherical combustor for Navy used (Buckley, 2011). It is made of stainless steel which is 305 mm external diameter and 300 mm in length and be able to withstand maximum pressure of 10 bar. A pair of quartz windows placed at both ends with each of it measuring 190 mm in diameter. Two spark electrodes are placed at the bottom and another on the top of the vessel and the spark electrode tip is met at the centre of the vessel. The fuel-air mixture in the vessel was centrally ignited by means of an electric spark with the approximation energy capacity of 25mJ. A Kistler pressure transducer model of 211B2 is used and fitted at the vessel wall to record the simultaneous build up pressure throughout the combustion process. Figure 1 shows a schematic diagram that resemblance the experimental setup of the closed vessel with other system.

The oxidizer used was compressed air from the surrounding and the methane is 96% of purity. The combustible mixture is prepared by using partial pressure technique. Prior to experiment, the vessel were evacuated and flushed with air to remove residuals from previous experiments. Then the vessel is vacuumed before the fuel-air being injected into the vessel. It is then left to quiescent for about 10 minutes before the ignition takes place. In order to avoid the influence of wall temperature, the experiment is repeated after a half an hour for the wall to cool down. For each equivalence ratio, the experiment is repeated for three times to ensure the consistency of the recorded pressure. The pressure rise in the cylindrical vessel is absorbed by the pressure transducer and produce voltage reading. It is then transmitted to the LabVIEW software and computed to Pascal unit. The overall experimental setup and the computed system is presented in Figure-1.

RESULTS AND DISCUSSION

Pressure generation at various equivalence ratio

The pressure versus time graph were plotted in which the change of pressure with respect to time indicates that a combustion process takes place. The raw data was normalized using polynomial regression in order to eliminate electromagnetic noise generated and form a smooth plotted line. This step was crucial in providing relevant data later on in calculation of radius of burn and unburned mixture to obtain burning velocity of combustible mixture.

Figure-2 shows a variation of pressure with time during the combustion that corresponded to stoichiometric methane-air mixture where the pressure is in bar and the time is in milliseconds. The initial pressure Pi for the combustion of all type of equivalence ratio is set to be at atmospheric which approximated of about 100 kPa. From the result in Figure-2, in the first 40 millisecond the response of the pressure recorded is slow and uniform.

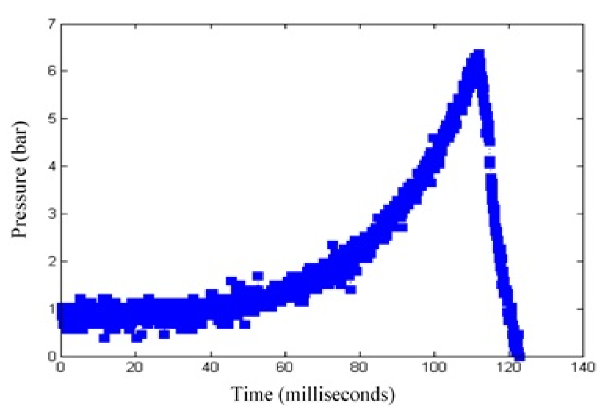

Figure-2. Pressure generation of stoichiometric methane-air combustion at initially atmospheric condition.

During this phase, the mixture had just started to combust and the volume of the burned mixture expand. The expansion of volume burning mixture that starts at the center now travelling in the outward direction towards the cylindrical vessel wall. This movement created a combustion wave that causes a rise in pressure(Lewis & Elbe, 1987).

However, as the combustion process enters over 40 milliseconds, the pressure starts to increase exponentially until it reach its peak pressure of about 6.49 bar. As the combustion wave propagates and echoed back once it hit the vessel wall, the rapid movement interacts with the burning flame front. The small disturbance over the flame front increases the rate of combustion in a way that the unburned mixture is compressed towards the flame front. Thus increase the rate of pressure rise. From this observation it is evidence that the pressure in the vessel increase as the rate of pressure rise increases (Dahoe and de Goey, 2003; Dobashi, 1997). Once the pressure met its peak, the air-fuel mixture was completely combust and forms no more combustion wave. Therefore the pressure profile trend was gradually decreased. Such explanation of pressure-time profile was also applicable for other equivalence ratio except the magnitude of the maximum pressure and time of combustion process.

Figure-3 shows a variation of pressure with time at difference equivalence ratio from 0.7 up to 1.4 for methane-air combustion. In general the variation of pressure during the combustion process is identical; suddenly increases in pressure until Pmax value then followed by gradual pressure reduction. The results shows that combustion of rich mixture (ϕ=1.2) and stoichiometric react faster than lean mixture of ϕ=0.7 and 0.8. In the combustion of lean mixture, the pressure starts to increase significantly only after 100 milliseconds whereas for the stoichiometric and slightly rich (ϕ=1.2) mixture the responds are exponentially increased at about 50 milliseconds. Even though the slightly rich mixture burned faster but increasing it further too rich mixture will only slows the combustion respond. Such observation of the slow responds of burning rates in lean and too rich mixture can be explained by the effect of Lewis number in the combustion reaction zone. Lewis number generally can be described as the ratio of thermal diffusivity to the mass diffusivity (Turn, 2012). In the slow responds of combustion reaction, the effect of thermal diffusivity is stronger in lean mixture and the effect of mass diffusivity is feasible in too rich mixture. This imbalance heat-mass transfer creates variation in heat diffusion and further varies the combustion reaction and propagation.

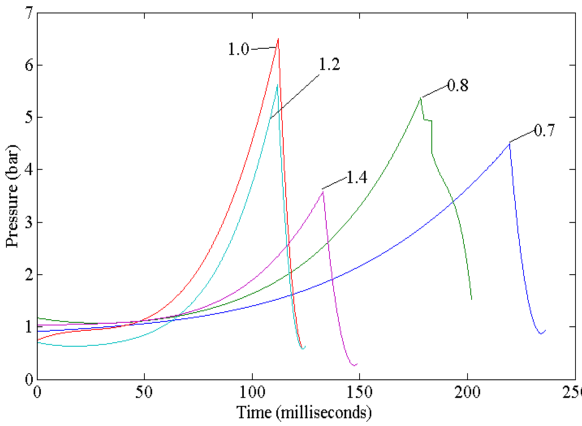

Figure-3. Comparison of combustion pressure profile at various equivalence ratio of methane-air mixtures.

Maximum pressure generated at various equivalence ratio

Presented in Figure-4 is the variation of maximum pressure generated from methane-air combustion at various equivalence ratio. The equivalence ratio ranging from 0.7 up to 1.4 and the maximum pressure generated were between 3 to 9 bar. Also included in the Figure-4 is the comparison of the present work with the experimental work reported by Cahsdollar and Hertzberg (1985) and the simulation work done by Dahoe and de Goey (2003).

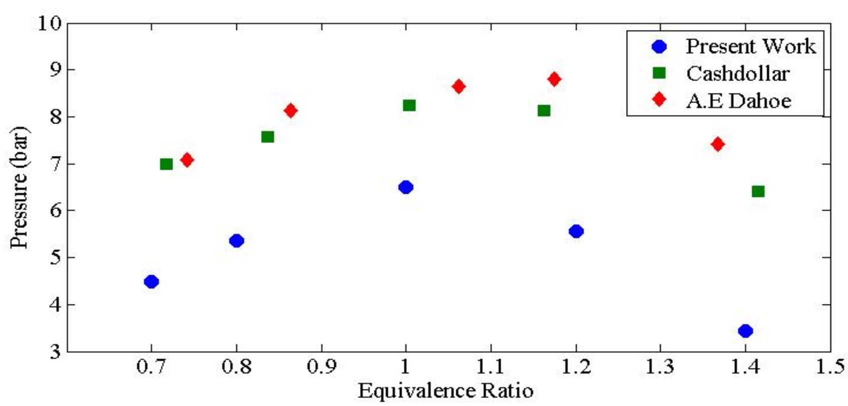

Figure-4. Variation of maximum pressure at various equivalence ratio(A.E Dahoe & L.P.H de Goey, 2003; Cahsdollar & Hertzberg, 1985).

Variation of maximum pressure with various equivalence ratio from present work and other researchers are presented in Figure-4. In general, the maximum pressure at various equivalence ratio follows the similar parabolic curve which shows increment as the equivalence ratio moves from lean to slightly rich mixture. However it will eventually decrease when the mixture becomes too rich. Although the present work results follows the general trend of the two researchers, the individual value of each equivalence ratio shows lower value with the other. This dissimilarity between the two with the present was about 25%. This discrepancy was probably caused by the mixture preparation and the measurement device used which further yield the difference in the initial pressure before the combustion take place. In this present work it was recorded that the maximum pressure profile for ϕ=0.7.

CONCLUSIONS

Based on the experimental work on pressure variation in a constant volume cylindrical vessel, the pressure generation during combustion methane-air has been successfully recorded. In general, the pressure generation of atmospheric methane-air combustion in a closed vessel is initiated by sudden pressure increase of about 50-100ms before reaching the peak and then followed by pressure reduction. Such behaviour was identical in other equivalence ratios except the magnitude of maximum pressure and the time duration of pressure development. By comparing the maximum pressure generated at different equivalence ratio and with the previous related work, several discrepancies were found. This differences probably related to the preparation of gaseous fuel using partial pressure technique and unsuitable of measuring device during pressure recording process. Minor improvement need to be done on measurement apparatus prior to the experiment conducted in order to acquire a better result as compared to the other researcher.

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