EFFECT OF DUAL-CORE SPARK DISCHARGE ON IGNITION PROBABILITY AND ENGINE POWER

Nguyen Minh Tien*, Bui Van Hung, Nguyen Xuan Bao, Truong Thi Hoa

The University of Danang - University of Technology and Education

*Corresponding author: nmtien@ute.udn.vn

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Abstract - This report presents the experimental study of developing a dual-core spark discharge (2C-SD) model for clean combustion. We first studied ignition probability (P_{ig}) of lean methane/air at an equivalence ratio of 0.5 using 2C-SD with different spark-gaps (d_{gap} = 1.0mm and 2.0mm) in a constant volume combustion chamber. We then applied 2C-SD to the engine driving a 2.5-kW generator. The results indicated that P_{ig} is 30% and 45% at d_{gap}=1.0mm and 2.0mm, respectively, while P_{ig} is 0 when using conventional single spark discharge (CSSD). Compared to CSSD, when using 2C-SD the engine power could be improved by 4%-9.7%, depending on the throttle openings. We expect the larger volume of the initial flame kernel by 2C-SD could enhance P_{ig} and quickly reach the critical flame radius before self-sustained propagating. The faster initial flame speed is essential for achieving the optimal combustion phasing, resulting in a higher power.

Key words - Dual-core spark discharge; Lean methane/air combustion; Ignition probability; Constant volume combustion chamber; Internal combustion engine

1. Introduction

Recently, lean-burn combustion has drawn significant attention due to its advantages for enhancing the thermal efficiency of internal combustion engines (ICE) [1, 2]. The advantages include (1) lower pumping loss due to wide-open throttle, (2) reduction of heat losses to cooling by low combustion temperature [1], and (3) increased specific heat ratio [3]. However, slow burn and misfire are the biggest challenges of the lean-burn concept to attain an optimal combustion phasing, generally occurring at 15^0 after top dead center (ATDC), resulting in unexpected thermal efficiency. How to avoid the misfire and accelerate the initial flame kernel development is vital in improving the thermal efficiency of fueled-lean ICEs.

As for successful flame development, many researchers investigated a critical flame radius (R_c) [4-6] for self-sustained propagation. As long as the heat release from chemical reactions is larger than the heat dissipation rate and the heat loss, the flame kernel could pass its critical radius and propagate steadily. Hence, a robust and healthy embryonic kernel initiated by an effective and reliable ignition energy system is essential for successful flame development.

Available data indicated that the ignition system should be improved as long as in-chamber turbulent levels are intensified to promote the flame propagation speed of lean mixtures [2, 7-10]. This is probably because the high turbulent dissipation rate by increasing turbulence renders ignition more difficult [9, 10]. The conventional ignition system could be improved by adjusting the spark gap [11], using multi-coil discharge [12], and increasing discharge current [13]. Research in novel ignition systems such as nanosecond repetitive pulse [14], microwave [15], and laser [16] revealed the promising potential for enhancing the ignition, and so does the engine thermal efficiency under lean conditions. However, the hardware complexity and compatibility are the obstacles to applying the common spark ignition (SI) engines. Improving the ignition system is thus still an open issue.

Badawy et al. [17] conducted experimental optical and thermal tests in a constant volume combustion chamber and a single cylinder gasoline direct injection engine to understand the effect of spark gap on flame kernel development, engine performance, and emissions. They reported that the flame kernel area increases as the spark gap increases. In addition, the engine output increases slightly, and the combustion process becomes more stable due to the reduction in cyclic variation as the spark gap increases. Moreover, using a larger spark gap (i.e., 1.4 mm) the engine produced minimum hydrocarbon emissions and particulate number concentration. NO_x emissions increased as the spark gap increased due to the higher combustion temperature. Recently, Zheng et al. [18] have developed an innovative three-core ignition system based on the motivation to enlarge the ignition kernel volume in the early stage. After testing a three-core ignition system on a single-cylinder engine operated at lean conditions, they reported that the engine stability could be improved. Furthermore, in-chamber pressure and heat release rate were increased, suggesting the higher indicated thermal efficiency. Zheng et al. [18] also found a decrease in hydrocarbon and carbon monoxide emissions and an increase in NO_x when applying the three-core ignition system.

This report presents the experimental study of a new prototype of dual-core spark discharge (2C-SD) capable of generating two discharge channels simultaneously at the same dimension as the conventional single spark discharge (CSSD). The 2C-SD was tested on a constant volume combustion chamber (CVCC) and single-cylinder gasoline engine to investigate its effect on (1) ignition probability (P_{ig}) of very lean methane/air mixture at an equivalence ratio (ϕ) of 0.5, and (2) gasoline engine power.

2. Experimental Setups

2.1. Dual-core spark plug discharge

The 2C-SD prototype has been developed based on the traditional idea of multi-ground electrodes with a copper core (MGE1). Figure 1(a) presents a 3-D prototype in the dimension of M14×1.25 with two copper cores at the center. The spark plug was connected to a regular dual-coil car ignition. Hence, replacing the conventional single spark plug on the SI engine is very convenient. The preliminary result in Figure 1(b) indicates two discharge kernels simultaneously, which seldom occurs when using the commercial MGE1. We expect that the multi-discharge kernels by 2C-SD could initiate a larger volume of the flame kernel that is much strong enough and becomes self-sustained propagation as fast as possible under lean conditions.

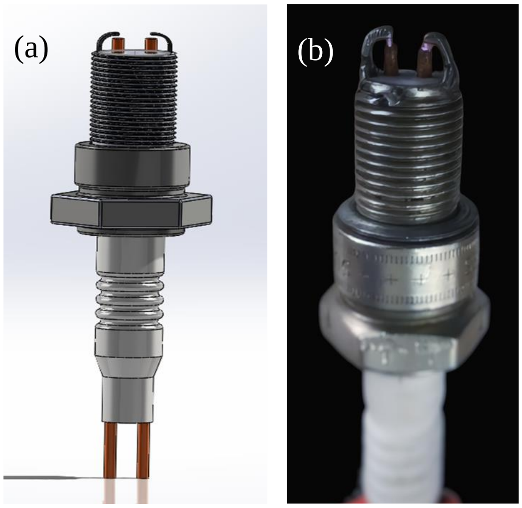

Figure 1. *(a) 3D model design of dual-core spark plug. (b) Preliminary design and its functional test, showing two discharge channels simultaneously*

2.2. Constant volume combustion vessel system

Experiments of very lean methane/air mixture at $\phi = 0.5$ are conducted in a cylindrical constant volume combustion chamber (CVCC) at the atmospheric condition. The readers are directed to Refs. [19-21] for more detail on the facility. A simplified sketch of such facility is included in Figure 2 alongside the ignition circuit for completeness. The 2C-SD was connected to the dual-core car ignition coil which is controlled by a 5-V signal. The spark gap between electrodes (d_{gap}) was varied at 1.0 mm and 2.0 mm to study the effect of d_{gap} on P_{ig}.

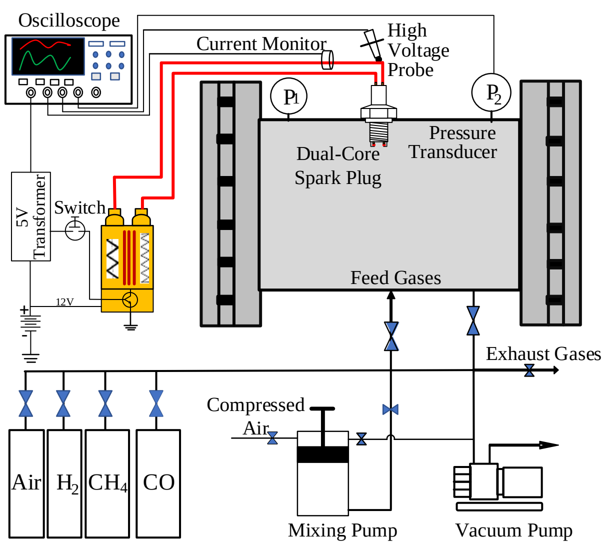

Figure 2. *The simplified sketch of a constant volume combustion chamber alongside the ignition circuit*

We first vacuum the combustion chamber before injecting the appropriate mole fraction of methane and air to the desired initial pressure p_i = 1.0 bar using the partial pressure method. It notes that the nominal purity of methane is 99.9%. The methane/air mixture is then mixed well by the mixing pump before discharging a spark. The maximum ignition energy (E_{ig}) is approximately 60 mJ which is measured by the product of voltage signal $V(t)$ and current signal $I(t)$. The signal of $V(t)$ and $I(t)$ can be detected using a high voltage probe and Pearson current monitor.

The mole fraction of fuel and air is calculated by the following equations

$$CH_4 + \frac{2}{\phi}(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + \frac{7.52}{\phi} N_2 \quad (1)$$

where, mole fraction $\lambda_{CH4} = 1/(1+2\times4.76/\phi)$, $\lambda_{air} = 1 - \lambda_{CH4}$; and partial pressure $p_{CH4} = \lambda_{CH4} \times p_i$, $p_{air} = p_i - p_{CH4}$.

The experiment was repeated at least 40 trials to obtain P_{ig}, where P_{ig} is determined as the ratio of the number of successful ignition to the total number of ignition trials [22, 23]. The ignition trial is successful as the oscilloscope can track the in-chamber pressure profile during the combustion process. Otherwise, the ignition trial is unsuccessful.

2.3. Single-cylinder research engine

The ignition system with 2C-SD was evaluated on a single-cylinder gasoline engine driving a 2.5kW, one-phase generator Honda EC2500CX. Since the original conventional single spark discharge (CSSD) system on the engine is the magneto-ignition system, we added a new ignition system independently in order to apply the 2C-SD model, as indicated in Figure 3. The 2C-SD system operates based on a 5-V signal generated by a sensor (please see Figure 3b). The advanced ignition timing is 11 degrees before top dead center (BTDC) which is the same as CSSD system.

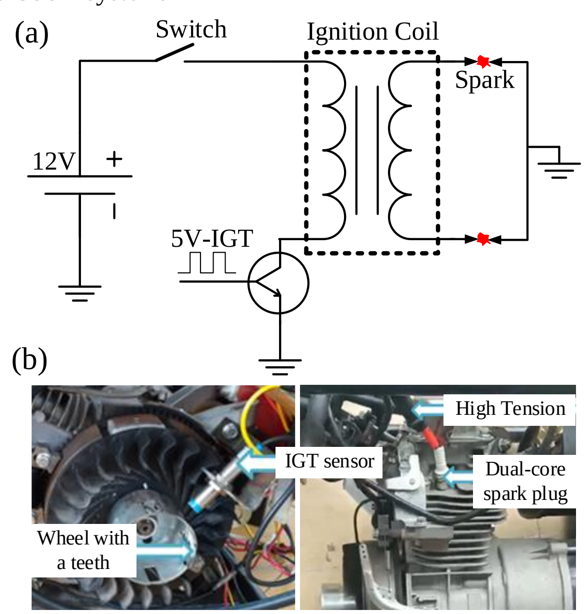

Figure 3. *(a) The 2C-SD ignition circuit and (b) its location on the engine Honda EC2500CX, 2.5 kW*

The gasoline engine used in this work is an air-cooled, carbureted fuel system, single-cylinder, natural intake, and four-stroke SI engine. The power generator has a 210/220V (50/60 Hz) AC output with a maximum output of 2.5 kW. The experiments were conducted at four different throttle opening percentages (i.e., 40%, 50%, 70%, and 85%) which were fitted with four bolts of different lengths. The external engine load was kept at 2.2kW for all experiments using the electric light bulbs. The fuel used in the engine test is commercial gasoline having a research octane number of 95 (RON95). For each combination of measured parameters, the experiment was performed at least three times (each sampling time about 12 minutes). The sampling data were collected after 10 minutes of engine running. The engine power was calculated via the power of the generator, $P_{generator} = U \times I$, where U is AC voltage, and I is current flow measured by AC clamp meter HIOKI 3280-10F.

3. Results and discussion

3.1. Ignition probability of very lean methane/air using 2C-SD at different spark gap d_{gap} = 1.0 mm & 2.0 mm

Ignition is statistical in nature. A successful ignition must include all three stages from the breakdown and the formation of flame kernel to the self-sustained propagation flame. If only the breakdown and the kernel formation occur without the development of self-sustained propagation flame, this event belongs to failure ignition (no in-chamber pressure profile observed). The ignition probability, P_{ig}, is popularly used to quantify the ignition capabilities of different types of discharge. Again, it is defined as the ratio between the number of successful ignition events and the total number of ignition trials. Based on this definition, the total ignition trials must be large enough to obtain an accuracy value of P_{ig}. Figure 4 shows the ignition probability as a function of the number of ignition trials at d_{gap} = 1.0 mm and 2.0 mm.

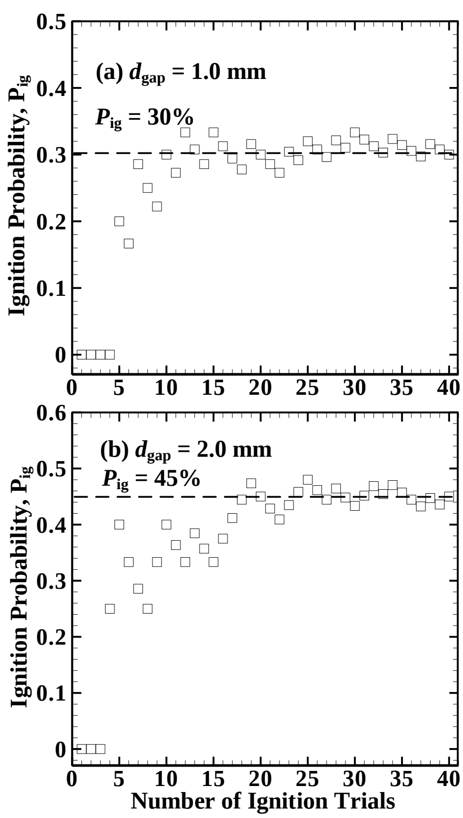

Figure 4. *Ignition probability (P_{ig}) of very lean methane/air mixture (ϕ = 0.5) using 2C-SD. (a) P_{ig} = 30% at d_{gap} = 1.0 mm; and (b) P_{ig} = 45% at d_{gap} = 2.0 mm*

It is seen that the ignition probability converges when the number of trials is above 25. In this study, 40 trials were conducted for each condition so that a reliable value of P_{ig} was obtained.

Using 2C-SD, the ignition probability of a very lean methane/air mixture approximates 30% at d_{gap} = 1.0 mm and/or 45% at d_{gap} = 2.0 mm, while P_{ig} is 0% when using CSSD at the same condition. Since the equivalence ratio ϕ = 0.5 is quite close to the lower flammability limit of the CH_4/air mixture (i.e., $\phi \approx 0.44$), hence the mixture is extremely hard to burn by using CSSD. This is probably because the initiated ignition kernel cannot reach the critical flame radius [4-6] for successful self-sustained propagation. However, 2C-SD initiates two-ignition channels simultaneously, as indicated in Figure 1(b), and thus enhances the ignition kernel to attain the critical radius before successful development.

How does the spark gap affect the ignition probability? As shown in Figure 4, the value of P_{ig} increases approximately 15% at d_{gap} = 2.0 mm compared to d_{gap} = 1.0 mm. This can be attributed to the quenching distance effect. It means that the heat losses to electrodes are most profound when d_{gap} is smaller than a specific value of spark gap, called quenching distance (d_q). Since the quenching distance effect, the initial spark kernel suffers large heat/radical losses to electrodes at a smaller d_{gap} making successful ignition difficult to achieve.

3.2. Evaluation of 2C-SD on a single-cylinder gasoline engine

To examine the effect of ignition methods on the engine power, 2C-SD and CSSD systems were tested on a single-cylinder gasoline engine. It should be noted that the vertical location of spark-electrode tips in the combustion chamber could affect the engine performance. Hence, the spark gap of 1.0 mm was selected for 2C-SD as the same as CSSD, although P_{ig} is even better at the larger d_{gap} = 2.0 mm. The engine power was calculated via the power of the electric generator. The engine power as a function of throttle opening percentages is presented in Figure 5. Each data point is an average value of three testing values at the same condition with its error bar. For the CSSD system, the engine power increases from 1.5 kW to 2.1 kW as increasing the throttle opening from 40% to 85%. Compared to the CSSD system, the engine power is highly enhanced by 9.7% at 50% of the throttle opening when using the 2C-SP system. This is due to the advantages of 2C-SD to the early flame kernel, as mentioned in subsection 3.1. It should be noted that the influence of 2C-SD dominates at the mid-range of the throttle opening percentage; beyond this range, its impact decreases. This behavior could be addressed by the turbulent intensity inside the cylinder, which is proportional to engine speed. The higher the turbulent intensity is, the larger the ignition energy is required due to the increase of turbulent dissipation rate as found by Shy et al. [9]. Although 2C-SD could initiate the larger kernel radius in the early stage, since the limitation of ignition energy, the weaker effect is thus found at the higher throttle openings. In short, the result indicated the applicability of the 2C-SD model on SI engines, especially when applying the lean-burn technology for higher thermal efficiency and low emissions.

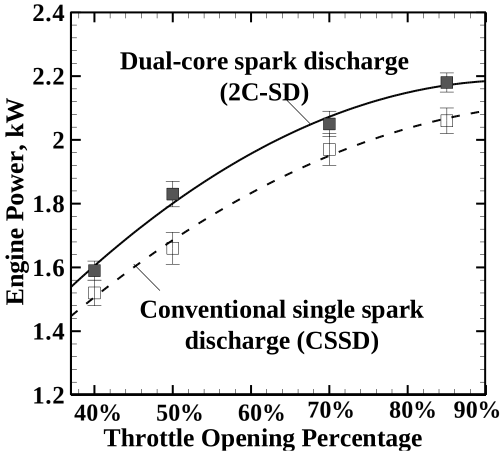

Figure 5. *Examine the effect of ignition method: 2C-SD vs. CSSD on the single-cylinder gasoline engine*

4. Conclusion

In this work, the developing dual-core spark discharge was examined in the constant volume combustion chamber and the practical gasoline engine. For the former, a very lean CH_4/air mixture at $\phi = 0.5$, near the lower flammability limit, was used to obtain the ignition probability. For the latter, both dual-core spark discharge and conventional single spark discharge were applied to the SI engine to evaluate the power output. The main results are as follows

(1) By applying the dual-core spark discharge, the ignition probability of a very lean CH_4/air mixture is 30% at d_{gap} = 1.0 mm and 45% at d_{gap} = 2.0 mm, while P_{ig} = 0 as using the conventional single spark discharge.

(2) Evaluation of dual-core spark discharge on the practical SI engine indicated that the power output could be increased up to 9.7% compared to conventional single spark discharge, suggesting the applicability of the dual-core spark discharge model on the lean-operated SI engines for high thermal efficiency and low emission.

In future work, the dual-core spark discharge will be tested on the fuel injection SI engine under lean conditions to obtain a comprehensive understanding of the advantages of the multi-core ignition method to engine performance and emissions.

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