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Mechanism analysis on controllable methanol quick combustion

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HIGHLIGHTS

- The great change in DMDF thermal efficiency was investigated by simulating and testing.
- Thermal efficiency is improved by methanol quickly burning to increase isochoric degree.
- Temperature and concentration of methanol/air mixture on DMDF were investigated.
- Quickly burning with controllable heat release is the key characteristics for DMDF.

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ABSTRACT

This paper explored the reason that the amount of methanol consumed is much lower than that of its theoretical value in terms of calorific value in diesel methanol dual fuel (DMDF) combustion by the means of engine bench test and modeling analysis. The results from experiments show that, the DMDF has much higher combustion rate than that of the correspondent diesel (D) mode and the accelerating effect caused by methanol changes with engine load, methanol-air mixture concentration and intake air temperature. At low load condition, the ignition delay caused by methanol is dominated while the accelerating effect is weak. However, this situation just turned upside down at high loads, to bring forth great improvement in isochoric degree. When methanol conducts quickly burning, both the combustion efficiency and the conversion efficiency from heat to work are improved, and the replacement ratio S_R becomes much lower than its theoretical value 2.16. In order to reveal the mechanism of high efficiency DMDF at various running conditions, a 3-dimensional CFD model to simulate and analysis the process of methanol burning together with diesel was built. By fixing constant operating parameters and boundary conditions, both the putting off and accelerating effects caused by methanol are enhanced with increasing methanol concentration. The putting off effect weakens with rising air temperature, while the accelerating effect becomes more effective in this process. Hence, the isochoric degree for DMDF deteriorates with rising air temperature at lean methanol mixture but improves as the concentration increases. Finally, a relational graph among isochoric degree, heat release concentration degree, methanol-air mixture concentration and temperature are derived, from which we get the understanding of controllable methanol quick combustion (CMQC) to further improve the DMDF thermal efficiency.

1. Introduction

The internal combustion engine (ICE) is the most efficient power plant up to now [1,2]. There are two main energy conversion processes happening while engine running [3], i.e. chemical energy of fuel converting to thermal one (FTT) by combustion, and the thermal energy converting to mechanical (TTM) energy by crank-link mechanism. These processes proceed simultaneously with in-cylinder combustion and the energy convection relationship in ICE is shown in Fig. 1.

The incomplete combustion loss generates in the FTT process. In the TTM process, there exists the exhaust loss, cooling loss and miscellaneous loss [4]. Then the brake thermal efficiency η_e can be drawn from the combustion efficiency η_c and heat-to-work efficiency η_w [5], as shown in Eq. (1).

$$\eta_e = \eta_c \cdot \eta_w \tag{1}$$

Abbreviations: DMDF, diesel methanol dual-fuel; D, diesel; S_R, replacement ratio; S_P, replacement rate; CMQC, controllable methanol quick combustion; ICE, internal combustion engine; FTT, fuel to thermal energy; TTM, thermal energy to mechanical energy; SI, spark ignition; CI, compression ignition; ATDC, after top dead center; TDC, top dead center; BDC, bottom dead center; IVC, intake valve close; EVO, exhaust valve open

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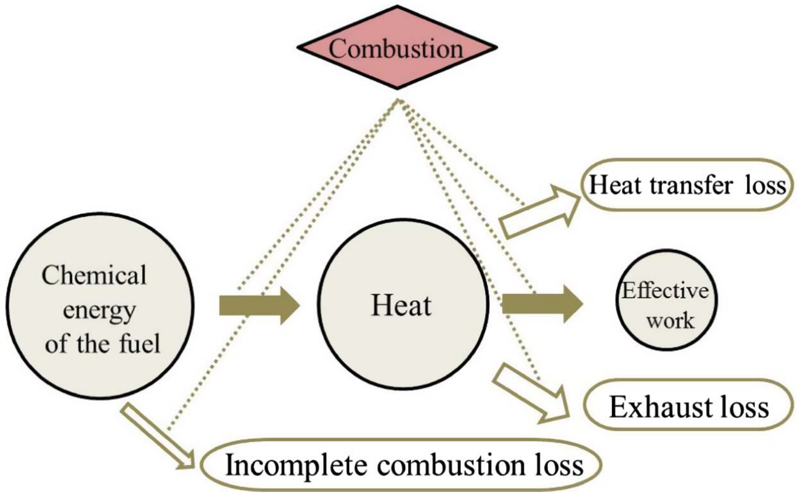

Fig. 1. Energy convection relationship in ICE.

As for DMDF combustion, two parameters are defined to evaluate the utilization of methanol, that is the replacement rate S_p and replacement ratio S_R, which are defined in Eqs. (2) and (3),

$$S_P = \frac{M_d - M_{dm}}{M_d} \times 100\% \tag{2}$$

$$S_R = \frac{M_m}{M_d - M_{dm}} \tag{3}$$

M_d, M_{dm} – Mass flow rates of diesel in D and DMDF modes, kg/h.
M_m – Mass flow rate of methanol in dual-fuel mode, kg/h.

When transforming to DMDF mode, the practical S_Rs are always deviate from its theoretical value 2.16 [6,7]. Assuming a 35% η_e for D mode, then this value turns to be 27.88% and 39.75% when the S_R s are 4 and 1.3 with 30% S_P in DMDF, resulting in almost 12% η_e difference. This is a great change in engine performance and we have made a tentative exploration on it from the energy balance point of view [8]. However, quantities of all loss items are decided by the combustion process as shown in Fig. 1, and the results from theoretical cycle analysis show that, the engine can achieve higher brake thermal efficiency as the combustion approximating to constant volume heat release [9,10]. In this case, the η_c and η_w are improved simultaneously with smaller loss items. Therefore, accelerating the combustion rate while keeping the heat release phase position controllable has always been the ambition for high efficiency ICE [11,12]. Methanol has the potential to improve the isochoric degree with a flame propagation speed 1.3 times as gasoline. While, its effect on DMDF combustion phase and the influence factors are still waiting for exploration.

Similar with methanol, hydrogen is also an alternative fuel characterized with high speed flame propagation. Besides its application on SI engine [13,14], studies on CI engine fueled with hydrogen has also been conducted recently [15]. Mohammad [16] and Carmen [17] investigated the performance of diesel-hydrogen dual fuel engines. In their studies, the hydrogen was introduced from the inlet manifold which is similar with DMDF. They found the addition of hydrogen contributes to improve η_e. However, these studies concern more about the emission properties of the engine with less analysis on S_R. As for DMDF, the combustion becomes complicated due to the interaction between diesel and methanol. Fig. 2 shows the phenomenological model for DMDF proposed by Wang [18]. He found several combustion modes exist in DMDF, including diesel ignites methanol then forms flame propagation, diesel-methanol premixed combustion simultaneously and methanol multipoint auto-ignition. The addition of methanol and decline in diesel may shorten the combustion duration for all the above modes. However, high efficiency DMDF with no abnormal combustion is still a challenge which needs accurate controlling the combustion modes and phase positions by adjusting the influence factors comprehensively. Moreover, these factors have not been researched comprehensively with systematic approach.

This study aims to reveal the mechanism of high efficiency DMDF combustion and look for the boundary conditions that help to further decrease the DMDF S_R. Both the experimental and simulation were used for analysis. In the experiment, the in-cylinder combustion between the two running modes at different load, air temperature and mixture concentration conditions were compared and analyzed, and we found the CMQC was the key to achieve high efficiency DMDF combustion. Based on the data from the experiments, a three-dimensional CFD model of in-cylinder combustion was built to investigate into the effect of methanol-air mixture concentration and temperature on CMQC. By the means of modeling calculation, a relational graph of heat release concentration and isochoric degrees changing with mixture concentration and temperature was derived, which offers a reference for dual-fuel engine calibration. The results shown in this study are helpful in avoiding uneconomic running conditions while achieving high efficiency CMQC.

2. Experimental setup

In this study, the experiments were conducted on an YC4D120-30 diesel engine. Three methanol injectors were arranged at the intake manifold with 4 bar injection pressure. Table 1 shows the parameters of the dual-fuel engine.

Two groups of experiments were designed to investigate the action mechanism of CMQC, as shown in Table 2. The first group is the load characteristics test at 1660 r/min (A speed in ESC test for this engine) for both D and DMDF running modes. In this group, all the dual-fuel experiments were carried out with the achievable maximum S_P. The second group of experiments was conducted at 1660 r/min-50% load condition. This group was design to research the effect of mixture concentration and intake air temperature on CMQC. Four cylinder pressure sensors were used to monitor the combustion process. The contrast experiments between D and DMDF were conducted by keeping the same engine speed and torque. Then the diesel flow rate decreases with increasing methanol injection quantity, and we can get a desired point when it drops to be the expected value corresponding to S_P [19,20]. Boundary conditions, such as the diesel injection timing, intake air temperature, cooling water temperature and methanol temperature, were kept the same in each group of the contrast experiments. The experimental system, as well as the experimental facilities was described in detail in literature [8].