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Effect of Direct Water Injection Pressure on Cycle Performance and Emissions Characteristics within a Compression Ignition Internal Combustion Rankine cycle Engine

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ABSTRACT

Internal combustion Rankine cycle (ICRC) with oxy-fuel is a novel concept to achieve zero carbon emission in theory due to the carbon dioxide capture system, and nitrogen oxides can be completely eliminated as intake of air is replaced by oxygen. In previous studies, traditional compression ignition engine coupled with ICRC system (CI-ICRC) shows great potential in brake thermal efficiency (BTE), emission characteristics and cycle performance through direct water injection (DWI). Since the CI-ICRC has been proved a feasible way to realize high efficiency and low emissions, a self-designed CI-ICRC prototype engines was established, series of experiments have been conducted focusing on the optimization of CI-ICRC engine including oxygen content, DWI temperature, DWI timing, etc. In this study, to further determine optimum DWI strategy, the effect of DWI pressure on cycle performance and emissions characteristics has been investigate. According to experimental results, under 320℃A DWI timing and constant mass of injected water, higher DWI pressure with shorter DWI pulse width reduces the direct impact of vapor on combustion so that shorter ignition delay and less HC emissions are obtained. With the increase of DWI pressure, the cycle performance and BTE of CI-ICRC prototype engine is improved due to the better atomization of water. The optimum BTE achieved within the prototype engine is 46.6%, with coefficient of variation close to 1% under 35MPa DWI pressure. But the NO_X and soot emissions slightly increased as elevating DWI pressure. The experimental results can also be utilized in providing reference information for DWI utilization within other novel internal combustion engine concepts.

Keywords: Internal combustion Rankine cycle; oxy-fuel; direct water injection pressure; thermal efficiency

NONMENCLATURE

Abbreviations	
ICE	Internal combustion engine
BEV	Battery electric vehicle
FCV	Fuel cell vehicle
TTW	Tank-to-wheel
ICEV	Internal combustion engine vehicle
LDV	Light duty vehicle
HEV	Hybrid electric vehicle
WTT	Well-to-tank
EGR	Exhaust gas recirculation
WHR	Waste heat recovery
HEI	High energy ignition
VCR	Variable compression ratio
VVA	Variable valve actuation
ICRC	Internal combustion Rankine cycle
DWI	Direct water injection
CR	Compression ratio
HCCI	Homogeneous charge compression ignition
OF	Oxygen fraction
FPGA	Field programmable gateway array
TTL	Transistor-transistor logic
CoV	Coefficient of variation
IMEP	Indicated mean effective pressure

PM	Particulate matter
BTE	Brake thermal efficiency

1. INTRODUCTION

The internal combustion engines (ICEs) accounts for a large part of transportation, but facing great challenges due to increasingly stringent emission legislation, especially in light duty vehicles (LDVs), the rise of battery electric vehicles (BEVs) has brought a huge impact on ICEs [1]. BEVs show great superiority in tank-to-wheel (TTW) efficiency and in-use emissions [2]. However, the driving range of BEVs is limited compared with internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs) due to the advantages of liquid fuels with high energy density, easy transportation and storage. Additionally, the electric generation in China is highly dependent on coal-based thermal power generation, which increases well-to-tank (WTT) emissions for BEVs [3]. In order to meet the emission requirements and energy demand, the development of after-treatment technology makes the cost of ICEs more expensive [4]. Therefore, new technologies of ICEs are needed to improve TTW efficiency and address emission problems such as lean burn, high energy ignition (HEI), exhaust gas recirculation (EGR), turbocharging, variable valve actuation (VVA), variable compression ratio (VCR), etc[5-8]. These technologies do effectively reduce NOx emissions, but still fail to meet zero carbon emissions under the target of carbon neutral. To achieve ultra-high efficiency and zero emissions simultaneously, carbon-neutral fuels can be used or novel ICE concepts need to be proposed.

Internal Combustion Rankine Cycle (ICRC) using oxy-fuel combustion is proposed by Robert W. Bilger [9], which is a novel concept to realize zero carbon emission in theory. The schematic diagram is shown in Figure 1. Firstly, oxygen is used instead of air as intake with hydrocarbon fuel, so the combustion product is only water and carbon dioxide, the NOx emissions are completely eliminated. Then the H_2O and CO_2 can be easily separated by a condenser, the cooling water will be heated through waste heat recovery (WHR) and injected into the combustion chamber near top death center to complete a Rankin Cycle, the CO_2 separated from the exhaust is converted into dry ice by a heat exchanger and captured, which is the essential point for the ICRC engines to achieve zero emissions. Furthermore, the injected high temperature and high pressure water will vaporize in the cylinder, on the one hand decreasing in-cylinder temperature so as to optimize the process of oxy-fuel combustion, on the other hand the generated steam will provide extra power for the engine, which leads to better thermal efficiency. Thus, a novel engine with ultra-high efficiency and zero emissions is obtained.

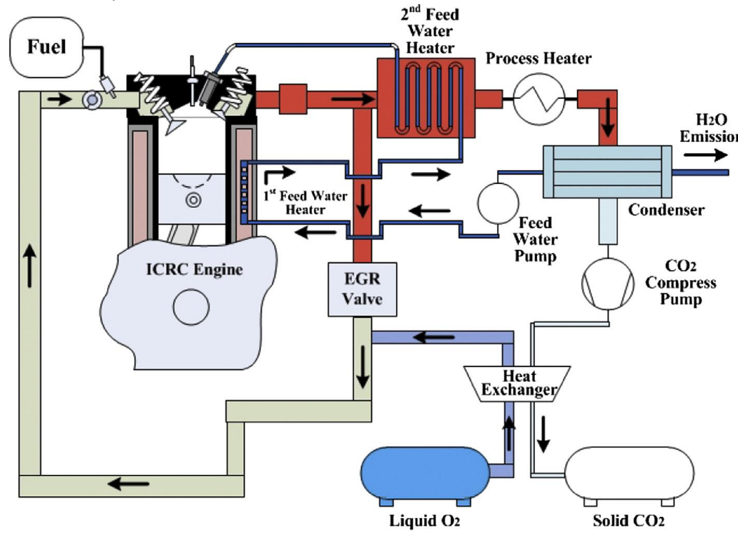

Figure. 1 Schematic diagram of ICRC engine system. [10]

To investigate the potential of ICRC engine thermal efficiency, a thermodynamic model was established and conducting experiments[10], the calculation results show that thermal efficiency rises as improving water injection temperature and reaches 67% at most, and the experimental results indicates that thermal efficiency is higher ,up to 41.5% under higher engine load condition which determines the exhaust gas temperature. Besides, a test bench based on spark ignition (SI) engines was erected to valid the feasibility of ICRC system [11], the influence of DWI on cycle performance of SI-ICRC was investigate in the reference [12], the results note that the DWI temperature shows significant impact on thermal efficiency. Thus, the experiments for the influence of DWI temperature on SI-ICRC engine was conducted [13], but DWI temperature is limited by exhaust gas temperature which determined by engine load, therefore, the experiments was conducted aiming at the influence of engine load on SI-ICRC engine [14], the results indicate that higher engine load leads to higher exhaust gas temperature, resulting in better thermal efficiency. Additionally, a numeric analysis was established to investigate thermal efficiency boundary of ICRC engine under different exhaust gas temperature, engine speed, engine load and compression ratio (CR) [15], the results show that thermal efficiency can reaches 56% under 2000rpm engine speed and 9.2 compression ratio, besides, DWI reduces the in-cylinder temperature of next cycle so that the larger CR can be utilized, the maximum thermal efficiency increases from 56% to 62% as elevating the CR to 14, even considering the energy consumption of CO_2 capture system it still reaches to 58%. In theory, the NOx emissions can be completely eliminated in ICRC concept, however, the experimental results were not that case which measures slightly NO_X emission as presence of N_2 within the engine crankcase [16]. The thermal efficiency of SI engine can be enhanced through increasing CR which limited by the intensive knock tendency, but the DWI shows great effectiveness in knock control in ICRC concept [17].

In order to further improve thermal efficiency based on ICRC system and narrow the efficiency gap between theory and experiment, the compression ignition (CI) mode coupled with ICRC was tested. Firstly, the effect of oxygen content on auto-ignition characteristic within homogeneous charge compression ignition internal combustion Rankine cycle (HCCI-ICRC) was investigate experimentally [18], and DWI was proved to be more potential than EGR in controlling combustion process without obvious deterioration in cycle performance [19]. While the results of simulation of heterogeneous charge compression ignition oxy-fuel combustion coupled with DWI shows higher efficiency potential than HCCI-ICRC and SI-ICRC [20]. Therefore, further experiments was conducted to verify the feasibility of diffusion oxy-fuel combustion can be obtained under the intake oxygen fraction (OF, $\mathrm{OF} = V_{O_2}/(V_{O_2} + V_{CO_2})$) 50% to 65% [21], and the DWI temperature was determined to achieve higher BTE [22].

In this study, aiming at determining optimum DWI strategy within CI-ICRC engine, which shows better potential in realizing high efficiency and ultra-low emissions. The effect of DWI pressure on combustion process, BTE, emissions, etc. based on oxy-fuel diesel engine was investigated experimentally.

2. EXPERIMENTAL SETUP

In this paper, a self-designed CI-ICRC prototype engine test bench was built and the schematic diagram is shown in Figure 2. The prototype engine was modified from a two-cylinder diesel engine, the detailed modification information is described in [22] and the engine specifications are given in Table 1. The fuel will be pressurized to 180MPa in the fuel supply system, then injected directly into cylinder by a designed common rail fuel injection system [19]. The purpose of intake of O_2 and CO_2 is simulating EGR and controlling oxygen fraction. As described in [21], for achieving the stability of diffusion oxy-fuel combustion, the intake system keeps the OF at 50% to 65% by altering the volumetric flowmeter. The air intake valve only opens before conducting experiments to warm up the engine. For realizing a constant and stable supply of high temperature and high pressure water injection during the experiments, a water supply system was designed as described in the reference [23]. The water is pressurized to specific pressure then heated in water rail. For simulating WHR, electronic heater is implemented in this experiment, which is able to heat the high pressure water up to 453K at most in the water rail. In this study, the emissions of HC, CO, NO_X and soot are presented and analyzed are measured.The CI-ICRC prototype engine controller is established based on Commercial NI compactRIO platform, which is used for capturing signals (emissions, exhaust gas temperature, in-cylinder pressure, etc) and controlling (fuel injection, water injection, intake, etc.). The detailed information of controller and the type of sensors are introduced in [22].

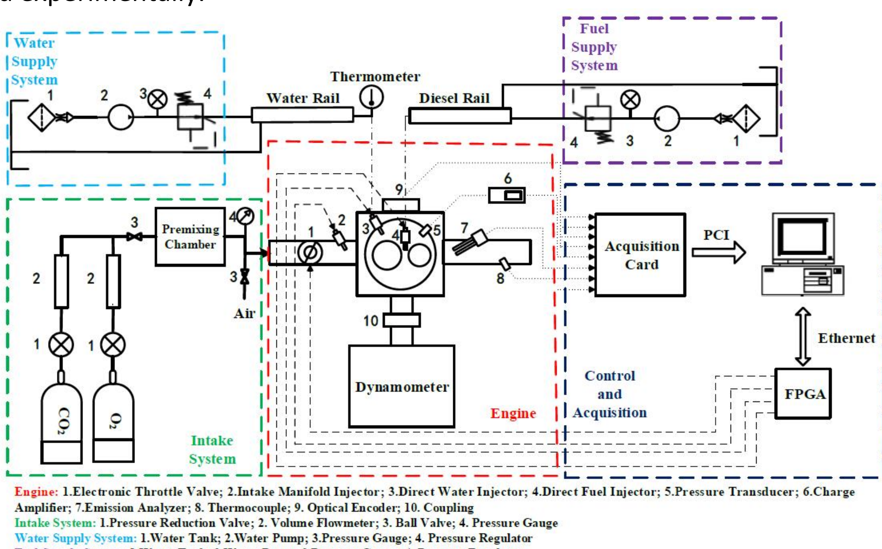

Figure. 2 Schematic diagram of CI-ICRC engine test bench.

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Table. 1 Engine specifications

Bore	95 mm
Stroke	114 mm
Connecting rod	180 mm
Compression ratio	17:1
Displacement	808 ml
Fuel injection system	Direct injection
Water injection system	Direct injection
Cooling system	Water cooling
Intake system	Naturally aspirated

Table. 2 Experimental conditions

Engine speed	800 r·min^{-1}
Fuel injection pressure	120 MPa
Fuel injection quantity	30 mg/cycle
Fuel injection timing	10°CA BTDC
Coolant temperature	365 K
Intake OF	55%
Water injection pressure	30MPa, 35MPa
Water injection duration	2.3 ms, 2 ms
Water injection temperature	433 K
Water injection timing	320℃A

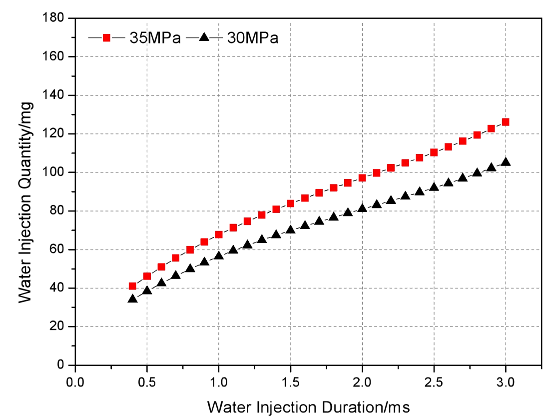


Figure. 3 Relationship between water injection duration and water injection quantity

3. RESULT AND DISCUSSION

According to the experimental results of SI-ICRC engine, the increase of DWI pressure can shorten the injecting pulse width when the quantity of injected water remains constant, thus the controllability of DWI process is improved, which indicates that higher DWI pressure can separate the DWI process from the combustion process. Furthermore, the higher DWI pressure can also promote the atomization and evaporation capacity of injected water, increasing the working fluid in the cylinder. In this work, by adjusting the inlet gas pressure of the gas-liquid booster pump in the designed water injection system, the DWI pressure is set to 30MPa and 35MPa with 2.3ms and 2ms pulse width respectively, so as to further compare the effect of DWI pressure on cycle performance and emissions characteristics of CI-ICRC engine utilizing oxy-fuel diffusion combustion. Critical parameters (including in-cylinder pressure, heat release rate, combustion characteristics and thermal efficiency, etc.) are measured and calculated experimentally, the detailed experimental results are discussed below.

3.1 Effect of DWI pressure on in-cylinder pressure within CI-ICRC

Figure 4 shows the evolution of in-cylinder pressure with crank angle (CA) under different DWI pressure. It is obvious that variation in DWI pressure leads to different peak value and phase position of in-cylinder pressure. The phase position of peak value retards to 370.5℃A under 30MPa DWI pressure compared with the 368℃A under 35MPa DWI pressure. It is observed that both water cycles decrease the maximum in-cylinder pressure, but the maximum in-cylinder pressure is 6.67MPa under 30MPa DWI pressure while it increases to 7.36MPa under 35MPa DWI pressure. Analysis suggests that in order to maintain the same quantity of injected water, the DWI pulse width is extended to 2.3ms under 30MPa DWI pressure, as described above that the DWI timing and fuel injection timing are 320℃A and 350℃A, the longer DWI pulse width delays the end of the DWI process, which leads to a further approach to the fuel injection timing, increasing the impact of water vapor on the combustion process. Therefore, utilizing higher DWI pressure can reduce the effect of water on combustion process. It is noteworthy that although the peak value of in-cylinder pressure decreases with the reduction of DWI pressure compared with dry cycle, the increment of in-cylinder pressure during the expansion stroke is almost identical under 30MPa and 35MPa DWI pressures. This is because the quantity of injected water remains constant under two water cycles, resulting the mass of working fluid in the cylinder is the same, which leads to the same in-cylinder pressure after the evaporation of high temperature and high pressure water.

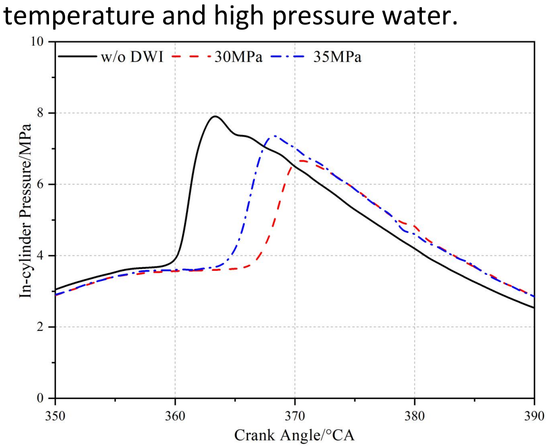
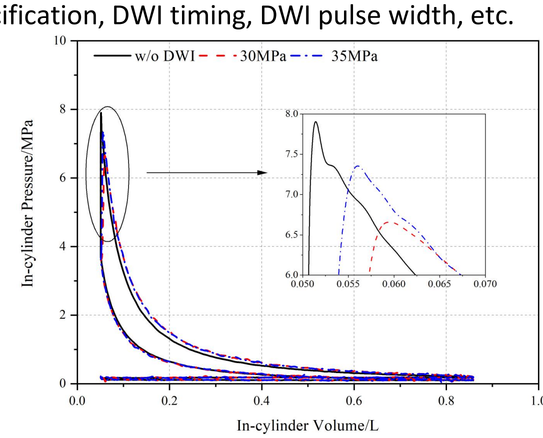
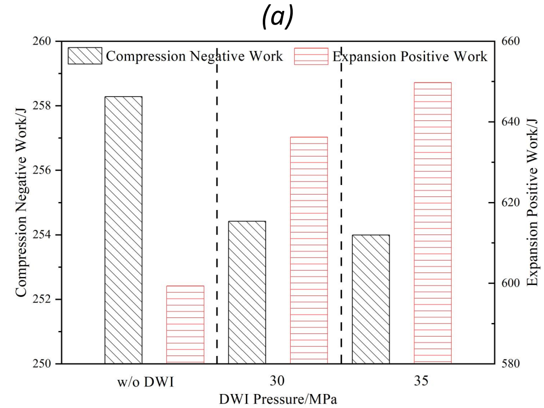


Figure. 4 In-cylinder pressure under different DWI pressure

Figure 5(a) shows the relationship between in-cylinder pressure and volume under different DWI pressure. The phenomenon shown in the P-V diagram is consistent with Figure 4, DWI reduces the maximum in-cylinder pressure and retards the phase position. Likewise, the in-cylinder pressure under two water cycles is almost identical in the expansion stroke. Figure 5(b) specifically displays the cyclic work under different DWI pressure. When the DWI pressure is 35MPa, the expansion positive work increases by 50J compared with that in dry cycle condition, while the increment is only 37J under 30MPa DWI pressure. Besides, DWI promotes the reduction of compression negative work compared with dry cycle, as shown in the figure, the compression negative work under 30MPa and 35MPa DWI pressures reduces by 4.5J and 5J respectively. From the influence of DWI pressure on the expansion positive and compression negative work, proper increase in DWI pressure has positive effect on CI-ICRC engine. However, excessively high DWI pressure causes the increase of DWI penetration distance, possibly resulting the injected water contact and adhere to the cylinder wall, which leads to the risk of oil dilution and reduction of working fluid in the cylinder. Therefore, the DWI pressure tested in this work is based on the engine specification, DWI timing, DWI pulse width, etc.



(a)



(b)

Figure. 5 Effect of DWI pressure on in-cylinder pressure and work: (a) P-V diagram; (b)cyclic work

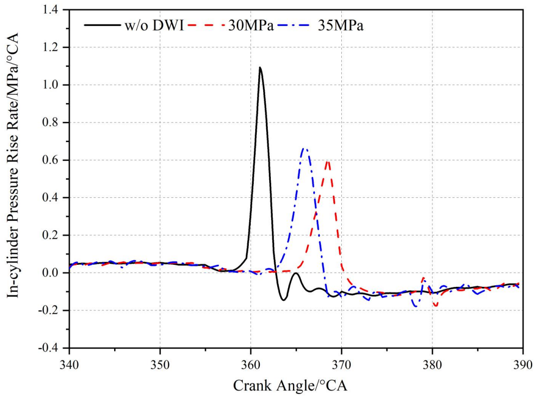


Figure. 6. In-cylinder pressure rise rate under different DWI pressure

The influence of DWI pressure on in-cylinder pressure rise rate is also analyzed and the result is shown in Figure 6. Matching the results above, the in-cylinder pressure rise rate is controlled effectively under 30MPa and 35MPa DWI pressure, indicating that the rough combustion process in the cylinder is optimized, which promotes the stability and reliability of CI-ICRC engine. Likewise, when DWI pressure is relatively low (e.g. 30MPa), due to the increase of DWI pulse width, the peak value of the in-cylinder pressure rise rate decreases and its phase is retarded.

3.2 Effect of DWI pressure on heat release process within CI-ICRC

Figure 7 illustrates the heat release rate and cumulative heat release under different DWI pressure. Figure 8 shows the phase and duration of combustion under different DWI pressure. The results shown in Figure 7 further verifies the analysis above that the negative effect of water on the combustion process in the cylinder becomes more obvious when implementing lower DWI pressure. This can be shown more explicitly in the Figure 8, the CA10 and CA50 under 30MPa DWI pressure postponed 6.5°CA and 7.5°CA respectively compared with dry cycle condition, while the difference is shortened to 4°CA and 5°CA under 35MPa DWI pressure. Meanwhile, the combustion duration under 30MPa DWI pressure is also increased by about 2°CA compared with that under 35MPa DWI pressure since the DWI process is closer to the combustion process. It is worth noting that the effect of different DWI pressures on the cumulative heat release is relatively small, from the experimental results, the cumulative heat release under 35MPa DWI pressure is increased by about 108J compared with dry cycle, while the increment is about 88J under 30MPa DWI pressure. The results indicate that improving DWI pressure appropriately can further optimize the effect of water on the work capacity of CI-ICRC engine.

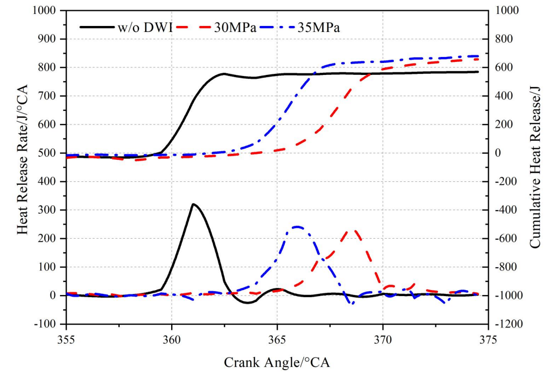


Figure. 7 Heat release rate and cumulative heat release under different DWI pressure

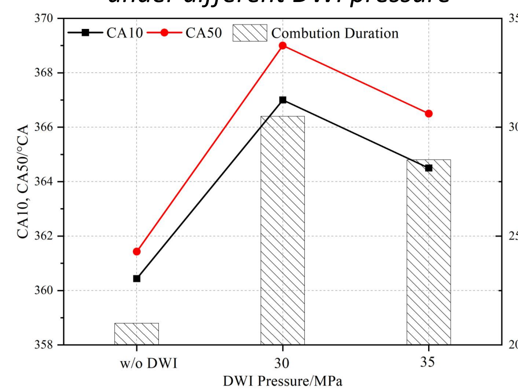


Figure. 8 Phase and duration of combustion under different DWI pressure

The cyclic fluctuation and IMEP (Indicate Mean Effective Pressure) of CI-ICRC engine under different DWI pressure are also measured and shown in Figure 9. As seen in the figure, the IMEP increases under both water cycle conditions compared with dry cycle, but the increment of IMEP under 30MPa DWI pressure reduces by about 0.05MPa compared with that under 35MPa DWI pressure, which suggesting that higher DWI pressure leads to a better performance for CI-ICRC engine. At the same time, the result of combustion cyclic fluctuation under different DWI pressure are also presented in the figure. When utilizing higher DWI pressure (e.g. 35MPa), the CoV (Coefficient of variation) is 1.2%, while the CoV is about 2.2% under 30MPa DWI pressure. But in general, the CoV is controlled within 3% after implementing DWI, indicating that the working stability of CI-ICRC engine is improved compared with dry cycle condition.

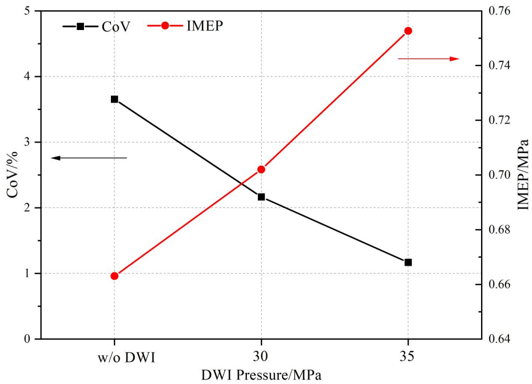


Figure. 9 Cyclic fluctuation and IMEP under different DWI pressure

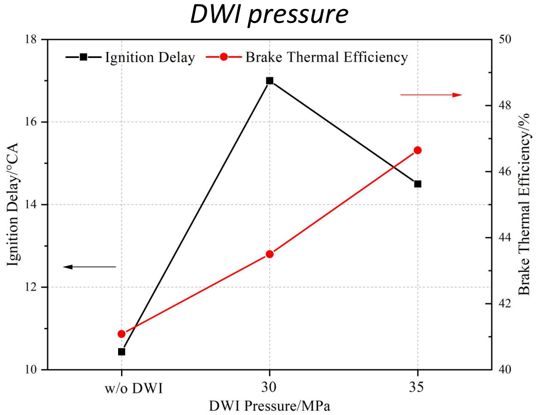


Figure. 10 Ignition delay and brake thermal efficiency under different DWI pressure

Figure10 displays the ignition delay and brake thermal efficiency under different DWI pressure. It can be seen from the figure that the increase of DWI pressure can improve the brake thermal efficiency of CI-ICRC engine. The BTE reaches 46.6% and nearly 44% under 35MPa and 30MPa DWI pressure respectively, both of which increases obviously compared with 41% under dry cycle condition. The influence of DWI pressure on ignition delay is consistent with that on combustion phase, the injected water decreases the in-cylinder temperature, resulting that the ignition delay increases to 14.5°CA under 35MPa DWI pressure. Apparently,while utilizing lower DWI pressure (e.g. 30MPa), the combustion process will be affected more significantly as previous analysis, which leads to a longer ignition delay (17°CA).

3.3 Effect of DWI pressure on emissions within CI-ICRC

This section mainly aims to analyze the variation in CI-ICRC engine emissions of carbon monoxide (CO), unburned hydrocarbon (HC), nitrogen oxides (NOX) and particulate matter (PM) under different DWI pressure, the results are shown in the Figure 11 and Figure 12. Generally, due to the negative effect of water on combustion, incomplete combustion under water cycle condition causes the higher CO and HC emissions than dry cycle, but the increment becomes lower as improving the DWI pressure. Specifically, the HC emissions under 35MPa DWI pressure is 30% less than that under 30MPa DWI pressure. On the contrary, the NOX and PM emissions are reduced after utilizing DWI, due to the influence of the lower in-cylinder temperature under 30MPa DWI pressure. Compared with 98 × 10-6 NOX emissions under 35MPa DWI pressure, the NOX emissions under 30MPa DWI pressure is further reduced to 76 × 10-6.

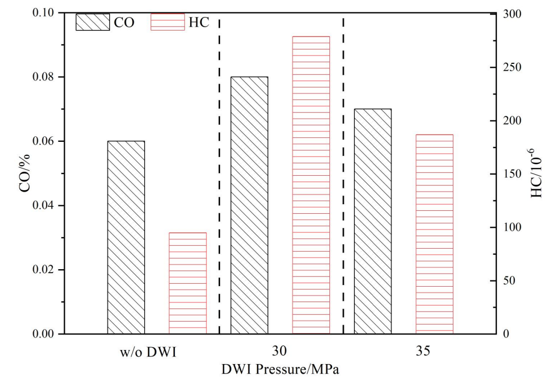


Figure. 11 Effect of DWI pressure on emissions of CO and HC

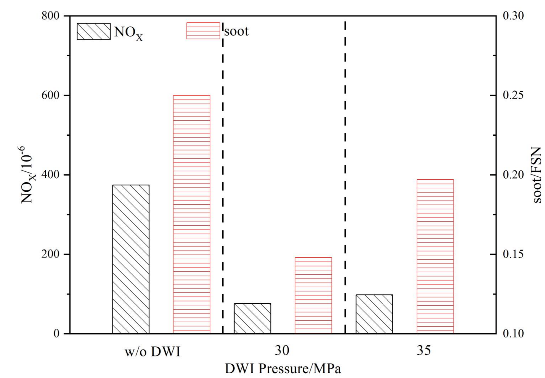


Figure. 12 Effect of DWI pressure on emissions of NOX and PM

4. CONCLUSIONS

To further optimize DWI strategy, this work conducted based on a self-designed CI-ICRC prototype test bench with oxy-fuel combustion. While maintaining constant working conditions (engine speed, DWI timing, mass of injected water, etc.), the effect of DWI pressure on cycle performance of CI-ICRC engine including in-cylinder pressure, IMEP and BTE were investigated. Besides, the emissions characteristics were also analyzed, the conclusions are as follows.

(1) From the experiments results, with the increase of DWI pressure, the performance of CI-ICRC engine is optimized and its thermal efficiency is improved, but excessively high DWI pressure will lead to the longer penetration distance, resulting the risk of oil dilution and reduction of working fluid in the cylinder. When utilizing higher DWI pressure than that in this

experiment, the optimized DWI strategy (320°CA DWI timing, 2ms and 2.3ms DWI pulse width, etc.) utilized in this work needs to be further calibrated to determine. Therefore, regarding to the cycle performance of CI-ICRC engine, the optimum DWI pressure obtained in this work is 35MPa

(2) DWI causes the increase of the expansion positive work due to the evaporation of injected water, and the increment is larger as elevating DWI pressure. When the DWI pressure is 35MPa, the expansion positive work increases by 50J compared with that in dry cycle condition. Moreover, the compression negative work reduces by 5J under 35MPa DWI pressure. The results of in-cylinder pressure rise rate indicates that DWI can optimize the drastic combustion process in the cylinder, promoting the stability and reliability of CI-ICRC engine.

(3) DWI causes the decrease of maximum heat release rate and retardation of combustion phase. Compared with dry cycle condition, the cumulative heat release under 35MPa and 30MPa DWI pressure increases by about 108J and 88J respectively, CA10 under 30MPa DWI pressure is delayed by 6.5°CA compared with dry cycle condition, while the difference is shortened to 4°CA under 35MPa DWI pressure.

(4) With DWI pressure increasing, the work capacity of CI-ICRC engine is improved. Compared with dry cycle condition, the IMEP increases under both DWI pressures, IMEP under 35MPa DWI pressure increases by about 0.05MPa than that under 30MPa DWI pressure. Besides, the higher DWI pressure contributes to a more stable operation for CI-ICRC engine, the CoV under 35MPa and 30MPa DWI pressure is 1.2% and 2.2%. The increase in DWI pressure improves the brake thermal efficiency of CI-ICRC engine, the BTE reaches 46.6% under 35MPa DWI pressure, and nearly 44% under 30MPa DWI pressure. However, DWI increases the ignition delay, and the effect becomes more obvious as lowering DWI pressure.

(5) The NO_X and PM emissions are reduced after utilizing DWI, but contrary to the effect of DWI pressure on cycle performance of CI-ICRC engine, the lower pressure of DWI, the less emissions of NO_X and PM produced by diffusion combustion. Compared with 98×10^{-6} NO_X emissions under 35MPa DWI pressure, the NO_X emissions under 30MPa DWI pressure is further reduced to 76×10^{-6}. However, DWI shows its drawback in CO and HC emissions compared with dry cycle. But the HC emissions can be reduced by 30% through utilizing 35MPa DWI pressure compared with 30MPa DWI pressure.

ACKNOWLEDGEMENT

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