

Study of the Combustion Characteristics of a HCCI Engine Coupled with Oxy-Fuel Combustion Mode

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ABSTRACT

The present work proposed to implement oxy-fuel combustion mode into a homogeneous charge compression ignition engine to reduce complexity in engine emissions after-treatment and lower carbon dioxide emission. The combination of oxy-fuel combustion mode with homogeneous charge compression ignition engine can be further optimized by the utilization of direct high temperature and pressure water injection to improve cycle performance. A retrofitted conventional diesel engine coupled with port fuel injection and direct water injection is utilized in this study. A self-designed oxygen and carbon dioxide mixture intake system with flexible oxygen fraction adjustment ability is implemented in the test bench to simulate the adoption of exhaust gas recirculation. Water injection system is directly installed in the combustion chamber with a modified high speed solenoid diesel injector. The combustion characteristics of homogeneous charge compression ignition coupled with oxy-fuel combustion under different oxygen fractions, engine loads and speeds are studied in this work. The experimental results indicate that the minimum applicable oxygen fraction in oxy-fuel combustion with homogeneous charge compression ignition is around 85% limited by cyclic variation performance, and pure oxygen can be utilized under suitable fuel injection quantity without abnormal combustion such as knocking. As the exhaust gas recirculation ratio is improved, the start of combustion is postponed and combustion stability is deteriorated. The potential of utilizing water injection to control abnormal combustion while maintaining system thermal efficiency identical is also illustrated, the feasibility of implementing oxy-fuel combustion into homogeneous charge compression ignition engine is proved.

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INTRODUCTION

As air pollution and energy problem are attracting more and more concerns around the world, especially in the metropolises, the demand for a high efficiency and low emission power source is becoming more and more urgent. Scientists and engineers have proposed numbers of energy utilization inventions to solve these problems, and oxy-fuel combustion is considered as one of the most promising technological solutions for high efficiency and low emission power generation [1, 2, 3]. The oxy-fuel combustion utilizes oxygen instead of air as oxidant to eliminate the generation of nitrogen oxides during combustion process which saves huge amount of costs in nitrogen oxides after-treatment. Most of the researches regarding oxy-fuel combustion are focusing on solid fuel such as pulverized coal, and now the application of liquefied and gaseous fuel in oxy-fuel combustion are starting to draw attention from researchers and scientists [4-5]. The oxy-fuel combustion with coal was firstly proposed by Abraham et al in 1982 aiming to utilize the high concentration carbon dioxide in exhaust gases for enhanced oil recovery (EOR) [6]. Recently, the development of oxy-fuel combustion in power station has been focusing on greenhouse gases recovery and lowering cost in exhausted gases after-treatment [7-8]. After decades of research and development, the oxy-fuel combustion technology is now a maturing solution in large power station which burns solid fuel such as pulverized coal with the capability of

capturing high concentration carbon dioxide for EOR application. Recently, Mohammad Asadi et al reported to utilize a nanostructured electrocatalysts to convert carbon dioxide into ionic liquid which can be further used in producing liquid fuel, the technology in taking advantage of carbon dioxide emissions is also presenting a positive effect on the utilization of high concentration carbon dioxide capture in oxy-fuel combustion [9].

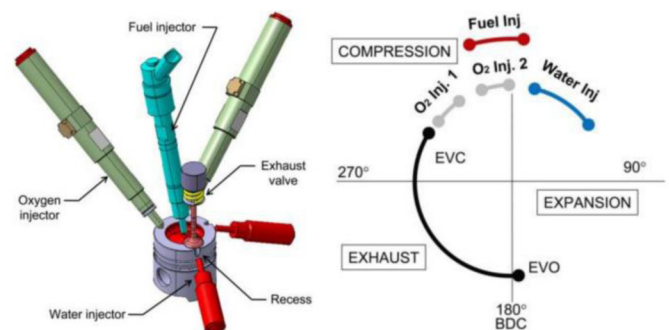


Figure 1. Schematic of combustion chamber layout and engine working process proposed by Azmi Osman [11]

The great potential of oxy-fuel combustion in lowering carbon dioxide and nitric oxide emissions drew attentions from modern internal combustion engine researchers and engineers. Azmi Osman

et al proposed to implement oxy-fuel combustion into ICE, water injection technology is also used to control combustion temperature and improve system thermal efficiency, theoretical thermodynamic calculations were carried out to prove the feasibility of this concept [10]. Based on his concept, Alberto conducted three dimensional CFD calculations with a more detailed engine layout and specifications as shown in Figure 1. Alberto's idea was to directly use oxidizer (eg. oxygen) and fuel (eg. hydrogen) injection into the combustion chamber; the advantage of this layout is the lowering of in-cylinder pressure during compression process and the significant decrease of negative compression work. On the other hand, the water is injected to control combustion temperature and acts as the working fluid to provide sufficient pressure to push the piston after its evaporation. The overall system efficiency is predicted to be as high as 55% [11]. Zhijun Wu et al have conducted theoretical and experimental studies of implementing oxy-fuel combustion into spark ignition (SI) engine with high temperature and pressure water injection [12, 13, 14, 15, 16, 17, 18, 19], results show that the proposed engine concept is able to reach 56% thermal efficiency in theory, the water injection process has great impact in system thermal efficiency improvement [17]. The concept of this oxy-fuel combustion coupled with spark ignition engine is derived from the high efficiency combustor developed by Clean Energy System Inc. which is often referred as internal combustion Rankine cycle (ICRC) [20-21] as shown in Figure 2, unlike traditional oxy-fuel combustion, CES combustor's control of combustion intensity mainly depends on water injection instead of using EGR, which can further extend the system overall thermal efficiency [22].

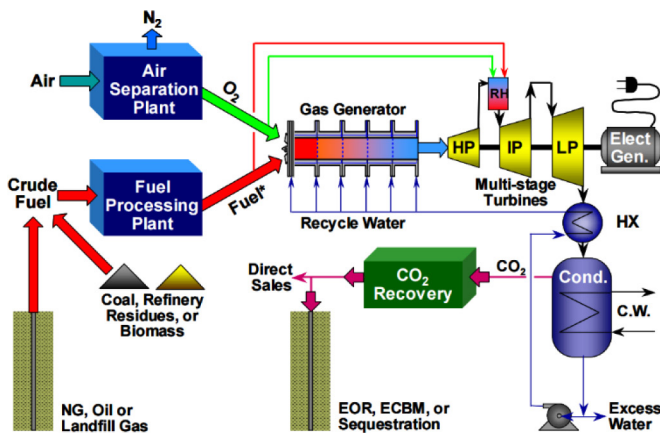


Figure 2. Schematic of CES system [20]

As discussed above, the exhausted gas recirculation (EGR) and high temperature and pressure water injection technology are the common techniques utilized in oxy-fuel combustion engines for combustion control and cycle performance optimization. Unlike the oxy-fuel technology utilized in large power plant, the oxy-fuel implemented in ICE are normally based on Otto or Diesel cycle, so the system overall thermal efficiency can be improved by increasing compression ratio. Through the experimental researches conducted by Lezhong Fu et al, the abnormal combustion phenomena such as knock and pre-ignition existing in SI engine are the main obstacles for further improving compression ratio [23]. To avoid these problems, compression ignition engine coupled with oxy-fuel combustion was proposed. As a high efficiency compression ignition concept, the feasibility of

implementing oxy-fuel combustion in a homogeneous charge compression ignition (HCCI) engine is firstly tested by the authors. n-Heptane shares similar chemical properties with the conventional diesel fuel, such as cetane number and also maintains good evaporation characteristic, which makes it a viable fuel for HCCI engine experiments [24-25].

In this study, the HCCI engine coupled with oxy-fuel combustion mode was established based on a retrofitted diesel engine, EGR and water injection strategies were tested to study their effect on combustion characteristics, the feasibility of using EGR and water injection in controlling oxy-fuel HCCI combustion is verified.

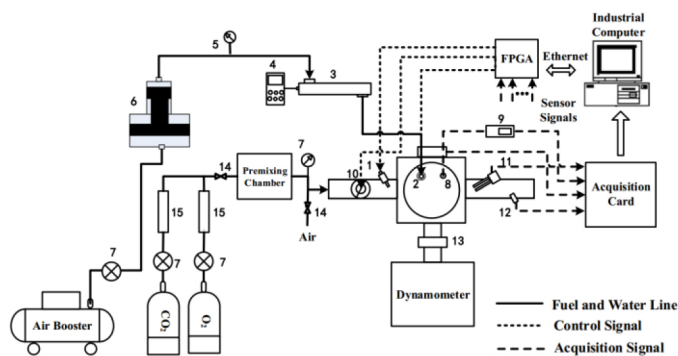
EXPERIMENTAL FACILITIES AND TEST PROCEDURE

Experimental Set-Up

The schematic of oxy-fuel combined with HCCI engine test bench is shown in Figure 3 and engine specification is illustrated in Table 1. A mechanical pump diesel engine was modified into a homogeneous charge compression ignition engine with n-heptane port injection (Figure 3, 1). The self-designed water injection system is employed to simulate the waste heat recovery process which provides sufficient energy to heat up the injected water, the high pressure and high temperature water is then directly injected into the combustion chamber at specific crank angle commanded by the control system. The water injector (Figure 3, 2) is manufactured by Wuxi fuel injection equipment research institute on the basis of traditional diesel injector, with a transient response high speed solenoid and a good endurance in high temperature injection fluid. An air-fluid booster (Figure 3, 6) is used as the water pump to ensure high enough injection pressure which provides the possibility to inject large amounts of water in a very short time. The initial high pressure air is generated by air booster with an output range from 1 to 8 bar and the boost ratio of air-fluid booster is 1:60 which result in the water injection pressure range from 60 to 480 bar. The oxygen and carbon dioxide mixture is used to simulate the EGR under real conditions. The oxygen and carbon dioxide are provided by high pressure gas cylinders, their mass flow rate is controlled by flow-meters (Figure 3, 15) separately to simulate different EGR rates. More importantly, special designed heating belts are utilized at the outlets of gas cylinders to avoid potential frosting due to the temperature drop in the gas pipes.

Table 1. Engine Specification

Displaced volume	808 mL
Stroke	114 mm
Bore	95 mm
Connecting Rod	255 mm
Compression ratio	17:1
Number of Valves	2
Exhaust Valve Open	225° BTDC (exchange)
Exhaust Valve Close	15° ATDC (exchange)
Inlet Valve Open	15° BTDC (exchange)
Inlet Valve Close	22° ATDC (exchange)



1.Intake Manifold Injector; 2.Direct Water Injector; 3.High Pressure Water Rail; 4.Rail Temperature Controller; 5.Rail Pressure Gauge; 6.Air-Water Booster; 7. Pressure Reduction Valve; 8. Pressure Transducer; 9. Charge Amplifier; 10.Electronic Throttle Valve; 11.Emission Analyzer; 12.Thermocouple; 13.Coupling; 14.Ball Valve; 15.Flowmeter

Figure 3. Schematic of oxy-fuel combined HCCI test bench

To maintain a stable water injection pressure, a self-designed water injection rail with built-in heater (Figure 3, 3) was carefully manufactured. The heater is used to simulate the waste heat recovery with a capability to heat the water in the rail up to 180°C. To monitor and control the temperature in the rail, a thermocouple was installed near to water outflow nozzle. More importantly, a thermocouple was installed inside the heater to control its surface temperature accurately during heating process which are useful in avoiding sub-cooled boiling near its surface. The schematic of the water rail is illustrated in Figure 4 below.

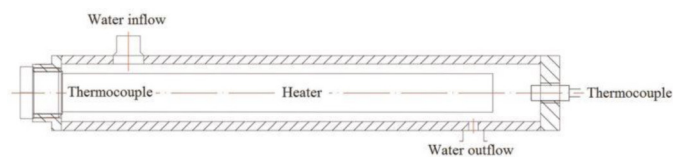


Figure 4. Schematic of high pressure and high temperature water rail

The piezoelectric pressure transducer (Figure 3, 8) is installed in cylinder head to monitor in-cylinder pressure during engine operation. Optical encoder (Figure 3, 13) is equipped on the crankshaft to track engine position, a TTL signal with a resolution 0.5°CA is generated and captured by data acquisition card to provide reference for the acquisition frequency. Cylinder pressure, intake pressure, intake temperature, exhaust temperature, fuel injection timing and duration, water injection timing and duration, exhaust emissions are all acquired by corresponding sensors and collected by NI PCI-6250 acquisition card.

NI compactRIO system is utilized to act as the controller platform for oxy-fuel combined HCCI engine test bench as shown in Figure 5. The compactRIO consists of three parts which are real-time controller, FPGA backboard and C-series modules respectively. The host computer is connected to compactRIO through 1000M Ethernet. Different modules were selected to control specific actuators or acquire data from specific sensors. In terms of oxy-fuel combined HCCI engine test bench, the Driven DI module is utilized to control direct water

injection with the capability of 5 pulses per cycle. The n-heptane port injector is control by NI 9401 TTL output module with International Rectifier AUIPS 1042G driven circuit. Electronic throttle is adjusted through PWM generated by NI 9478 module with a self-designed PID control strategy. Engine position signal generated by optical encoder is read by NI 9401 TTL input module to provide sufficient information for engine position tracking. Other Analog signals such as in-cylinder pressure, intake/exhaust temperature, intake mass flow rate, etc. are acquired by NI 9205 analog input module.

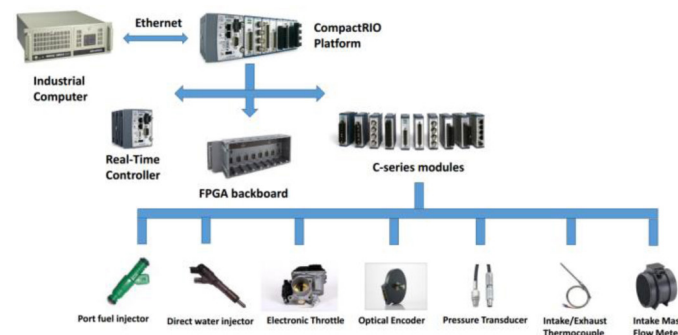


Figure 5. Schematic of cRIO control platform for oxy-fuel combined HCCI test bench

Test Procedure

The engine is first started with air intake and switched to oxy-fuel combustion mode until engine coolant reaches 85°C. There have been no measurements carried out before engine reached a steady state. n-Heptane is selected to be used as the fuel for homogeneous charge compression ignition. n-Heptane shares similar chemistry properties with the diesel fuel such as cetane number, auto ignition temperature, on the other hand, some physical properties of n-heptane are very suitable for its application in homogeneous charge compression ignition such as evaporation temperature. The adjustment of oxygen fraction is realized by controlling the mass flow-meter installed at the outlets of oxygen and carbon dioxide gas cylinders manually. The homogeneous charge compression ignition under different oxygen fraction were studied in this paper to investigate the feasibility of implementing oxy-fuel combustion mode in high efficiency HCCI engine, and high temperature and pressure water injection technologies were tested to explore the possibility in mitigating knock and improve cycle performance, some related engine operation conditions are illustrated in Table 2 below.

Table 2. Engine operation conditions.

Oxygen fraction	70%, 85%, 100%, 21% (air)
n-Heptane injection duration	6, 7 ms
Engine speed	800, 1200 rpm
Throttle angle position	100%
Water injection duration	1,2,3ms
Water injection timing	0 °CA ATDC
Water injection pressure	35MPa
Water injection temperature	120°C