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CFD Investigation into Effects of Intake Temperature on OxyFuel – HCCI Ignition and Combustion

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Abstract **-** A CFD model which is accompanied with detailed chemistry and has been firstly validated with experimental data achieved from a HSDI (High Speed Direct Injection) diesel engine has been applied to analyze the effects of intake oxygen temperature on engine performance characteristics under oxyfuel combustion condition. The simulation has been carried out at five different intake charge temperatures (140°C, 160°C, 180°C, 200°C, and 220°C). It was found that the implementation of oxyfuel HCCI combustion must be accompanied by an accurate intake temperature adjustment. Increasing intake charge temperature results in advancing the start of combustion along with a shorter main combustion stage which results in a reduction of IMEP and an increase of ISFC while decreasing intake charge temperature affects the combustion stability and leads to incomplete combustion.

Keywords**:** Intake Oxygen, HCCI Combustion, Diesel Engine, CFD Modeling, Engine Performance

1. Introduction

In recent years, oxyfuel combustion have been proposed as an effective method to support CCS (Carbon Capture and Storage) for hydrocarbon fuel combustion systems [1-2]. In oxyfuel combustion, the combustion uses pure oxygen as oxidizer instead of air. Because there is no nitrogen in the intake charge, NO_x emissions will be eliminated. Therefore, the resultants of the combustion reaction are only carbon dioxide and water vapor. Most of the previous and ongoing studies have been focused on application of oxyfuel or oxygen enriched combustion technologies on gas turbines and coal-fired power plants [3-4]. Internal combustion (IC) engines, as the main power producer on transportation sector, also utilize the thermal energy released from fuel combustion, as well as causing substantial carbon dioxide emissions. Therefore, the utilization of oxyfuel or oxygen-enriched combustion and CCS technology in IC engines has recently achieved a lot of attentions. Studies on oxygen-enriched combustion found that a slight increase of oxygen makes a remarkable decrease in smoke emissions as well as a decrease in CO and UHC (unburned hydrocarbon) emissions, however, the nitrogen oxide (NO_x) emission has an obvious increase [5]. Different techniques such as exhaust gas recirculation (EGR) and optimized injection strategies have been applied to decrease NO_x and particulates [6]. In recent reported researches, oxyfuel and nitrogen-free combustion draws attentions and much higher oxygen level is tested in real IC engine to achieve zero NO_x emission and higher engine efficiency [7-8].

Homogeneous Charge Compression Ignition (HCCI) is a low temperature combustion regime being considered for IC engines. The combustion duration in HCCI mode is shorter than traditional spark and compression ignition engines, because the auto-ignition occurs nearly simultaneously across the entire combustion chamber. At high load, the rapid energy release causes a large pressure rise, which generates pressure oscillations in the combustion chamber [9-10]. In addition, HCCI combustion usually suffers from the lack of proper combustion phasing control, since the combustion process is essentially decoupled from fuel injection [11-12]. The initiation of HCCI combustion is governed principally by the chemical kinetics: the high propensity of diesel fuel to auto ignite combined with the high compression of diesel engines, results in combustion starting before the top-dead-center (pre-TDC), very high pressure rise rates, short combustion durations, and minimal control over the timing of the combustion event [13-14].

The current CFD study has been performed as a part of a European project named RIVER (funded by the Interreg North-West Europe) [15] to explore the effects of different intake charge temperature on oxyfuel combustion in a HSDI Diesel engine under HCCI combustion. A CFD model with detailed fuel chemistry has developed and the predictive ability of this model has been firstly assessed against the experimental data. It is to be shown that such a model can capture the main combustion phase of an HCCI engine under oxyfuel combustion. Then, the effects of intake temperature charge temperature on different engine parameters have been considered.

2. CFD Model Description

The diesel engine used for the model validation is a High-Speed Direct Injection (HSDI) Ford Puma common-rail diesel engine. The engine specifications are given in Table 1. The fuel delivery system was an electronically controlled, common rail fuel injection system. The experimental test was done on a single cylinder of this engine at 1500 rev/min and 6.8 bar IMEP (Indicated Mean Effective Pressure) [16]. Cylinder pressure was measured with a flush-mounted AVL GU13P pressure transducer in conjunction with a Kistler 5010B charge amplifier. Acquired cylinder pressure traces were averaged for 200 cycles at 0.1°CA (crank angle degree) resolution. A schematic view of the engine setup is given in Figure 1 [16].

The computational mesh was created using AVL ESE Diesel Tool [17]. As diesel is used as fuel for this numerical research, a reduced chemical mechanism with 349 reactions and 76 species is employed to study the oxyfuel combustion under HCCI combustion mode [18]. The computational grid at top dead center (TDC) is shown in Figure 2.

A summary of the parameter settings for this model is provided in Table 2. The Nordin model has applied to take parcels collision into account . The $\mathrm{K}-\zeta-\mathrm{F}$ approach has applied to take account of turbulent effects. One of the main advantages of this model is it's robustness to be used for computations involving grids with moving boundaries and highly compressed flows as it is the case in IC-engines [17].

As can be seen in Figure 3, the present model is seen to perform well, particularly to capture the phasing of the main combustion stage (MSC) under HCCI regime. This confirms that the chemistry scheme employed can be used to simulate the HCCI combustion process.

Table 1: Engine Specification [26]

Model	Ford Puma DuraTorq
Type	4 Cylinder, 4 stroke diesel engine
Combustion chamber	Bowl in piston
Valves per cylinder	4
Bore [mm] × stroke [mm]	86 × 86
Squish Height [mm]	0.86
Comperation ratio	18.2:1
Displacement [cm^3]	1998
Connecting rod length [mm]	155
Peak cylinder pressure [MPa]	18
Injection system	Common rail DI [up to 180 MPa]
Injector	Solenoid with 6 holes
Injector hole diameter [mm]	0.159
Injection angle	154°

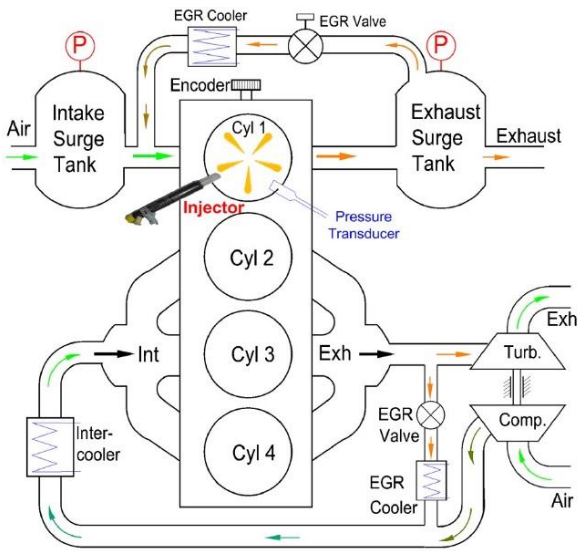

Figure 1: Schematic view of the engine laboratory setup [26]

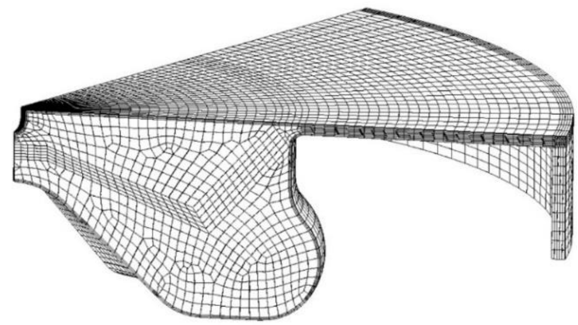

Figure 2: Computational grids at TDC

Table 2: Parameter Setting for KH-RT breakup model

Model constant	Value
KH-WAVE model constant to adjust stable droplet radius (C1)	0.61
KH-WAVE model constant to adjust break-up time (C2)	12
Type constant to adjust break-up length (C3)	10
RT model constant to adjust wave length (C4)	5.33
RT model constant to adjust break-up time (C5)	1
Constant for child droplet parcel number adjustment (C6)	0.3
Constant for child droplet parcel mass adjustment (C7)	0.05
Constant to adjust droplet normal velocity (C8)	0.188

3. Results and Discussion

This section describes the CFD investigations performed to analyze the effects of the intake charge temperature on the oxyfuel HCCI combustion characteristics. While studying the influence of intake temperature, intake pressure has set to 2.2 bar. Investigations have conducted using four different diluent strategies based on the volume fraction of O_2 and a diluent gas (CO_2). Variation in diluent ratio has achieved by adding different percentage of CO_2 for a range from 79% to 85% v/v.

The effect of different diluent strategies on in-cylinder cylinder pressure, and in-cylinder temperature are shown in Figure 4 and Figure 5, respectively, under a constant intake temperature and intake pressure. As illustrated in Figure 4 and Figure 5, the increase of intake oxygen content from 15% to 21% results in a significant increase of peak in-cylinder pressure and peak in-cylinder temperature. Applying oxyfuel HCCI combustion leads to acceleration of the combustion process which results in a shorter ignition delay period and higher rate of heat released. Subsequently, the in-cylinder temperature and in-cylinder pressure have increased.

According to Figure 6, the increase of intake temperature from 140℃ to 220℃ under constant inlet pressure results in a reduction of IMEP at all diluent strategies considered. It can be concluded that increasing intake temperature results in advancing the start of combustion along with a shorter main combustion stage (MCS) which mainly occurred in the compression stroke. Therefore, some portion of produced power has wasted and the total output work has decreased in the power stroke. Consequently, the IMEP has been negatively affected by increasing the intake temperature. Based on the CFD results, further reduction of intake temperature charge, lower than 140℃, leads to deteriorating the combustion stability. Therefore, the implementation of oxyfuel combustion using diluent strategies must be accompanied by an appropriate intake temperature adjustment. The effect of different diluent strategies and intake temperature on ISFC is shown in Figure 7.

As can be seen in Figure 7, the increase of intake temperature under all four diluent strategies results in an increase in ISFC. These effects are more highlighted in the case of 15%v/v intake oxygen fraction, where the highest deterioration of ISFC is around 26%.

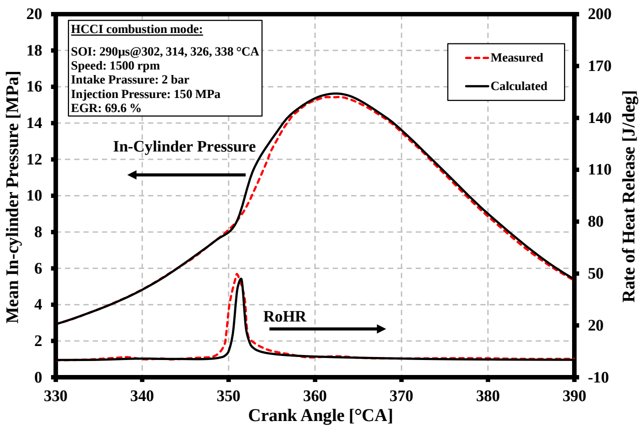

Figure 3: Comparison of calculated and measured in-cylinder pressure and rate of heat release

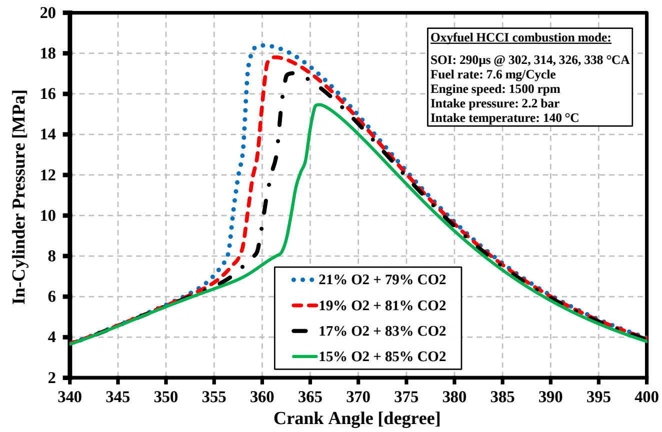

Figure 4: Effects of diluent strategies on in-cylinder pressure

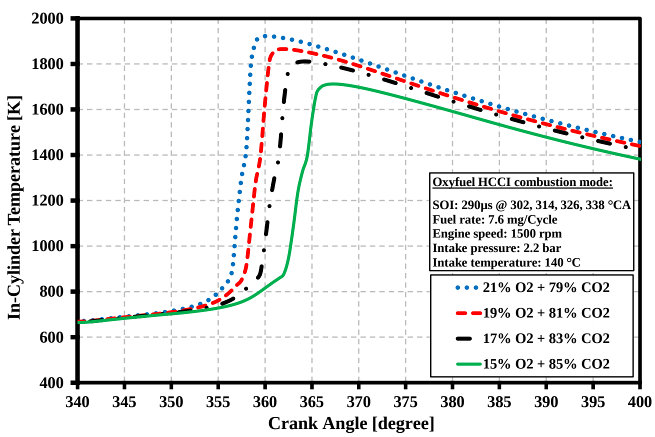

Figure 5: Effects of diluent strategies on in-cylinder temperature

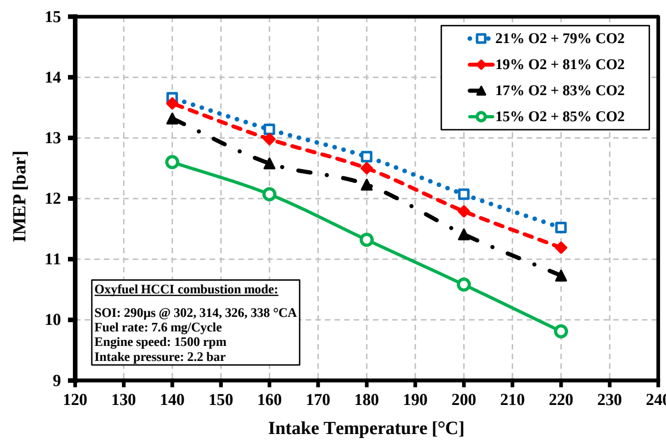

Figure 6: Influence of diluent strategies and intake T on IMEP

Effects of intake temperature on exhaust CO_2 for different diluent strategies is shown in Figure 8. As can be seen in Figure 8, with increasing the intake temperature from 140°C to 220°C for under all diluent strategies, the amount of exhaust CO_2 have decreased uniformly. This effect can be also attributed to the increase of burning rate of the injected fuel mass with increasing intake oxygen fraction due to higher oxygen availability during the premixed and diffusion combustion which results in lower exhaust CO_2.

It should be pointed out that the amount of PM emissions for all studied cases was at ultra-low level while NOx emissions was completely eliminated using oxyfuel HCCI combustion mode.

4. Conclusions

The effects of intake oxygen temperature have been computationally investigated under HCCI combustion mode. Simulation were carried out on a Ford Puma common-rail diesel engine. A reduced chemical mechanism with 349 reactions and 76 species has employed for HCCI combustion modeling. Variation in diluent ratio has achieved by adding different percentage of CO_2 for a range from 79% to 85% v/v. The research is yet to enter the experimental testing stage. Results show that intake temperature is one of the most important engine parameters in controlling the oxyfuel HCCI combustion process. The implementation of oxyfuel combustion using diluent strategies must be accompanied by an appropriate intake temperature adjustment. Nevertheless, CFD results and preliminary simulation data discussed in this paper paper that have suggested that the oxyfuel HCCI combustion has a great potential to bring the PM emissions to a very ultra-low level while the NOx emission can be completely eliminated.

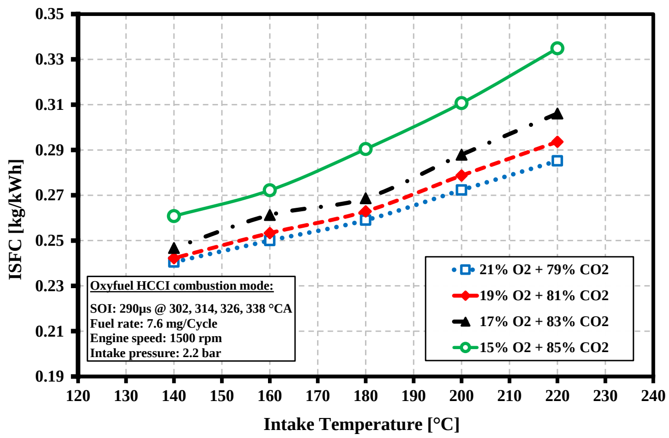

Figure 7: Influence of diluent strategies and intake T on ISFC

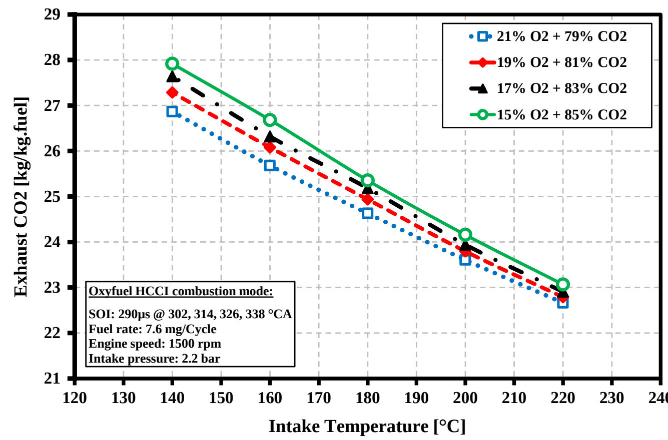

Figure 8: Effects of intake temperature on exhaust CO_2

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