



NUMERICAL INVESTIGATION OF PPCI STRATEGY FOR HIGH-EFFICIENCY COMBUSTION

R. Sener^{1*}, M. Yılmaz²

¹ Batman University, Automotive Engineering Department, Batman, Turkey.

² Marmara University, Mechanical Engineering Department, Istanbul, Turkey.

*ramazan.sener@batman.edu.tr

ABSTRACT

Homogeneous charge compression ignition (HCCI) is a combustion concept with significant potential due to low NO_x, soot emissions, and high efficiency. However, the PPCI strategy has potential because the HCCI engine operates in a limited load range and is difficult to control. Early direct injection during the compression process is an option within the PPCI concept. However, in this strategy, the spray angle should be applied narrower to prevent the fuel from impinging the cylinder wall. In this study, it was aimed to constitute a PPCI concept with a pre-, main- and post-injection strategy and injector with an 80-degree narrow spray angle. Two different injection strategies were proposed in order to minimize emission. These were compared with the conventional injection strategy under the same conditions. The partial premixed (PPCI) combustion process was investigated in terms of combustion efficiency, fuel consumption, and emissions. The engine emits significantly low NO_x emissions with the PPCI combustion strategy.

Keywords: HCCI, PPCI, Combustion, emission reduction.

INTRODUCTION

Homogeneous charge compression ignition (HCCI) combustion engines constitute alternative or complementary responses to the sophisticated and complex after-treatment method that seems imperative for the conventional diesel engine [1]. HCCI engines are to prepare an air/fuel mixture highly diluted by the burned gases, to ensure simultaneous ignition in the entire region of the combustion chamber, and to precisely control such combustion for the best performance in terms of efficiency and pollutant emissions [2]. Since combustion occurs uniformly throughout the bulk of the mixture, thermal NO_x and soot generation are known to be much lower than the conventional diesel combustion diffusion flame [3].

HCCI engines provide very high combustion efficiency. However, the engine is difficult to control [4]. The purpose of the partially premixed compression ignition (PPCI) engine is to obtain a homogeneous mixture and reduce NO_x and soot emissions as in the HCCI engine. The main difference with HCCI operation is that it is a mixture. PPCI engines can be controlled by fuel injection, while HCCI engines can operate within a limited load range, knock, and noise problems may be observed. In late injection, the start of combustion is delayed, with higher EGR ratios compared to pre-injection, and therefore all of the fuel can be injected before auto-ignition [5]. For this type of combustion, the air-fuel ratio can be chosen in a wider range, besides, it does not require a precise air-fuel ratio to control the start of combustion.

PPCI concept was constituted with the pre-, main- and post-injection strategy with an 80-degree narrow spray angle. Two different injection strategies have been proposed with different SOI to minimize emission. These are compared with the conventional CI strategy under the same conditions. The PPCI combustion process has been studied in terms of combustion efficiency, fuel consumption, and emissions. The engine emits significantly lower NO_x and soot emissions with the PPCI method.

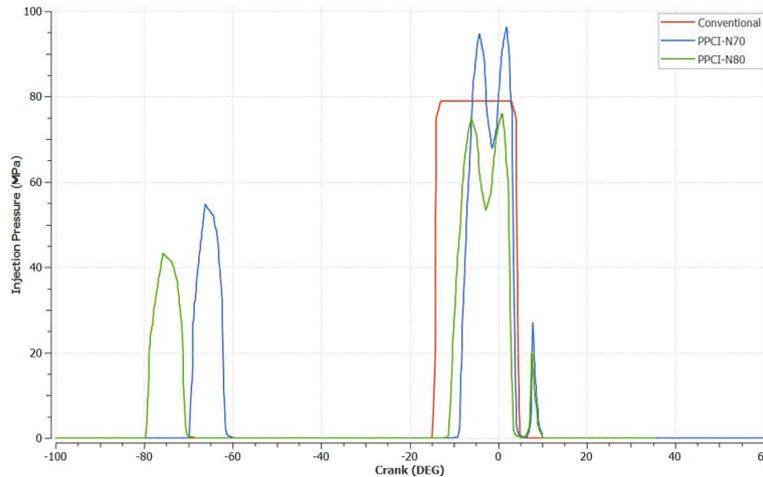
CFD MODELING

The test engine is a six-cylinder, water-cooled, turbocharged, four-stroke engine. A summary of the engine's operating parameter is listed in table 1. The engine has a bore diameter of 115-mm, a stroke of 144-mm, and displacement volume of 1496 cm³ for one-cylinder. The engine was simulated as a conventional CI engine and a PPCI engine to compare the combustion and emission.

Table 1. Main characteristics of the test engine

Displacement volume	1496 cm ³
Bore	115 mm
Stroke	144 mm
Con. rod length	231 mm
Compression ratio	17.6
Injector hole diameter	0.171 mm x 8
Spray angle	149 deg. for CI
	80 deg. for PPCI
SOI	15° bTDC for CI
	80° and 70 bTDC for PPCI

There are two possible approaches to achieving very low emissions. The first relies on early injections for mixture formation before the combustion described as HCCI combustion. The second depends on late injections and charge-air characteristics to raise the fuel-air mixture to a fully pre-mixed condition before auto-ignition defined as PPCI combustion [6]. It was used the second approach to achieve ultra-low emissions in this study. PPCI strategy with early injection as 80° and 70° bTDC (PPCI N80 and PPCI N70) compared to the conventional diesel engine. The total injected fuel mass was the same in these three cases. Fig. 1 shows the injection rates for the modeled strategies.

**Figure 1.** Injection timings and injection pressure curve of the modeled strategies.

The numerical simulations were performed using Converge commercial CFD code [7]. The modified cut-cell Cartesian grid method has been used for meshing. The domain is re-meshed at each time-step for moving boundaries. The adaptive mesh refinement (AMR) is used to refine the grid based on fluctuating and moving conditions such as temperature or velocity.

The Renormalization Group (RNG) k - ϵ model [8] has been preferred to calculate in-cylinder turbulent flow for solution accuracy, simplicity, and effectiveness [9,10]. A detailed chemistry solver (SAGE) coupled with detailed chemical kinetics mechanisms was selected for the combustion process inside the cylinder [7]. The SAGE combustion model calculates the rates of reaction and species concentrations within each cell and each time step using CHEMKIN-formatted input files. The model uses a reduced reaction mechanism for n-heptane (C_7H_{16}) to represent diesel fuel. This mechanism has 42 species and 168 reversible reactions performing hydrocarbon combustion and NO formation. Sub-models of the simulation are listed in table 2. Surfaces of the engine were prepared as a full engine (fig. 2).

Table 2. CFD simulation Sub-models.

Turbulence model	RNG k- ϵ
Combustion model	SAGE
Evaporation model	Frossling
Collision model	NTC
Spray-wall interaction model	Rebound/Slide
Spray Breakup model	KH + RT
NOx model	Extended Zeldovich
Soot model	Hiroyasu

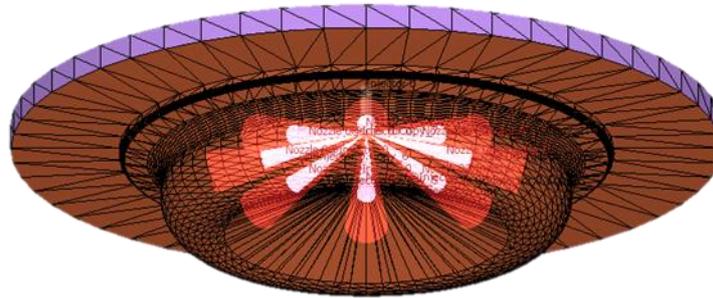


Figure 2. The surface of the CFD model of the test engine for CI and PPCI strategy.

RESULTS AND DISCUSSION

Different injection strategies of PPCI strategy were modeled as PPCI N80 (80° bTDC early injection and 80° narrow spray angle) and PPCI N70 (70° bTDC early injection and 80° narrow spray angle) and conventional diesel using the CFD code. The results of these strategies were compared by means of combustion, turbulence, and emissions. According to the modeling studies, the crank angle at which 50% of the fuel is burned occurred near to the TDC since the injection was started very early in the PPCI method. The IMEP value decreased by 4% for the PPCI N80, as the start of combustion was earlier than conventional diesel (fig. 3). The maximum in-cylinder pressure has increased however the maximum and mean temperatures inside the cylinder have decreased with the PPCI strategy (fig. 4a and 4b). While the turbulent kinetic energy increases with the PPCI method around the TDC, it became lower around the 20-120° aTDC (fig. 4c). Heat release Rate was more with the PPCI method in the premixed combustion zone and it occurred earlier. In the mixing-controlled combustion zone, heat release was lower in the PPCI method (fig. 4d). In the cylinder, the fuel mixed better with the air with early injection strategy, high temperatures occurred in the region close to the piston (fig. 5).

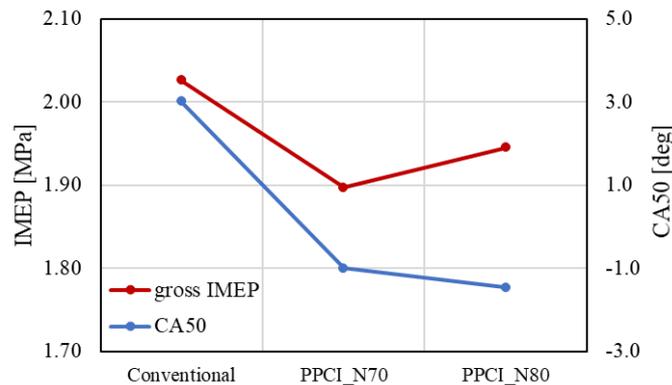


Figure 3. IMEP and CA50 results of the test engine for CI and PPCI strategy.

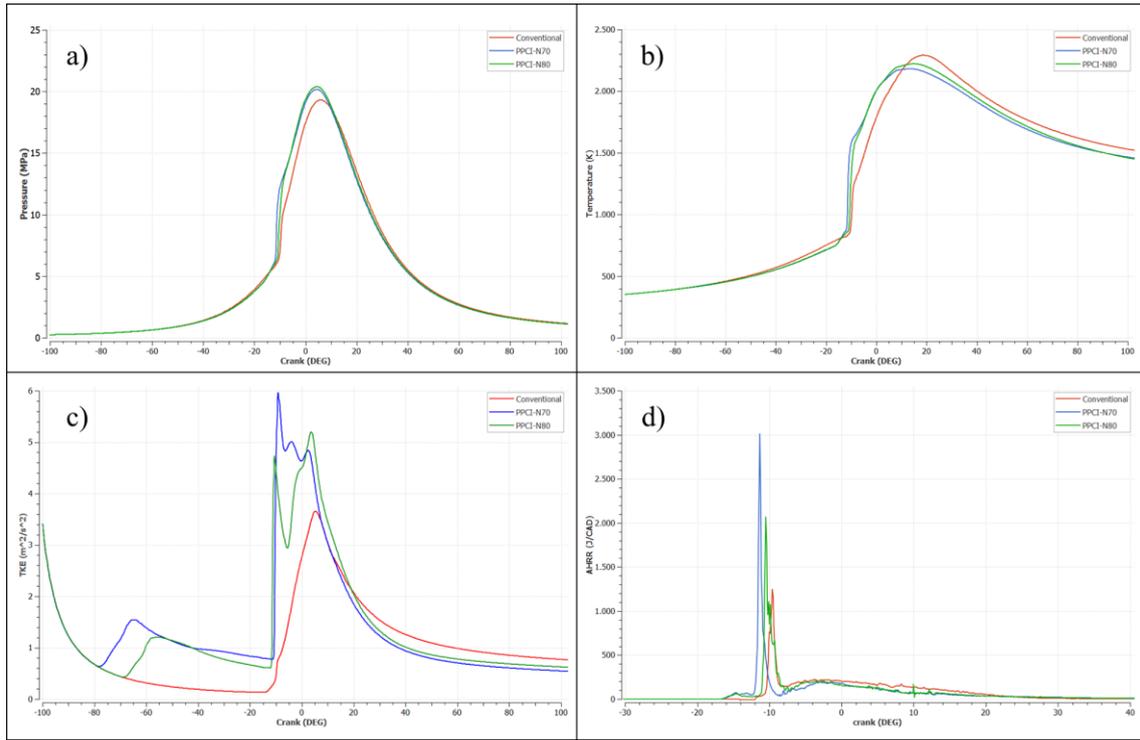


Figure 4. In-cylinder pressure, temperature, AHRR, and TKE curves of the test engine for CI and PPCI strategy.

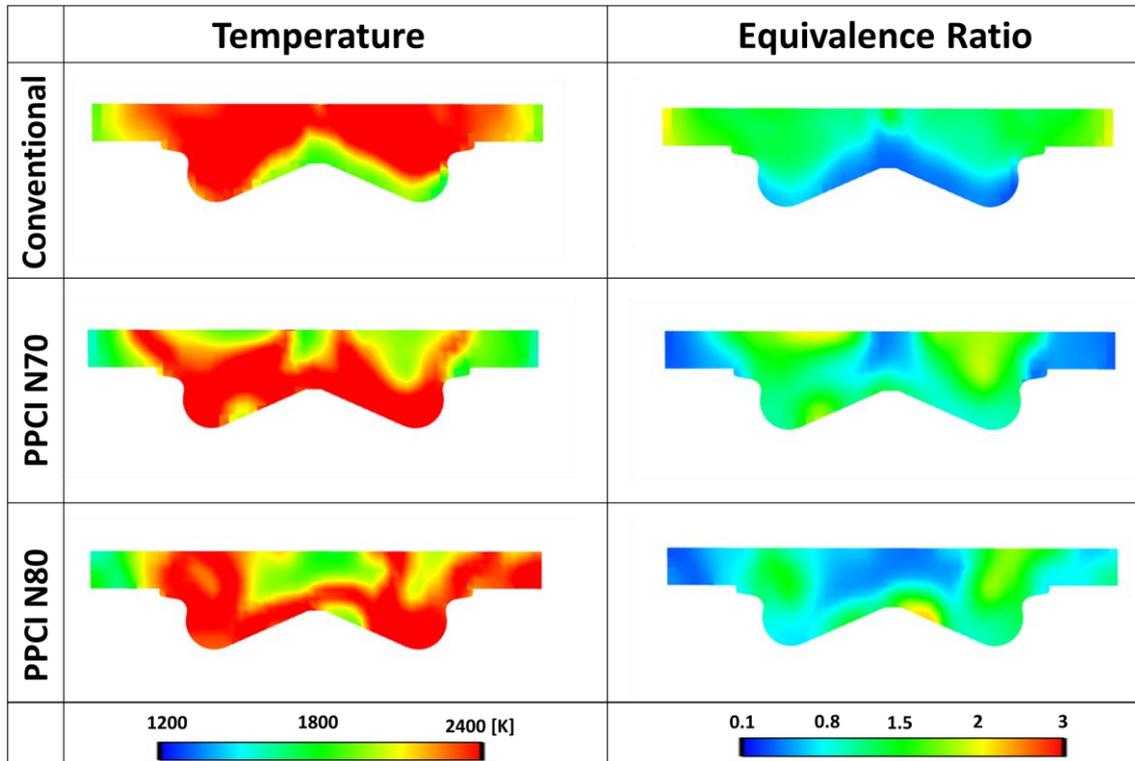


Figure 5. the in-cylinder temperature and equivalence ratio distribution of the test engine for CI and PPCI strategy at 20° aTDC

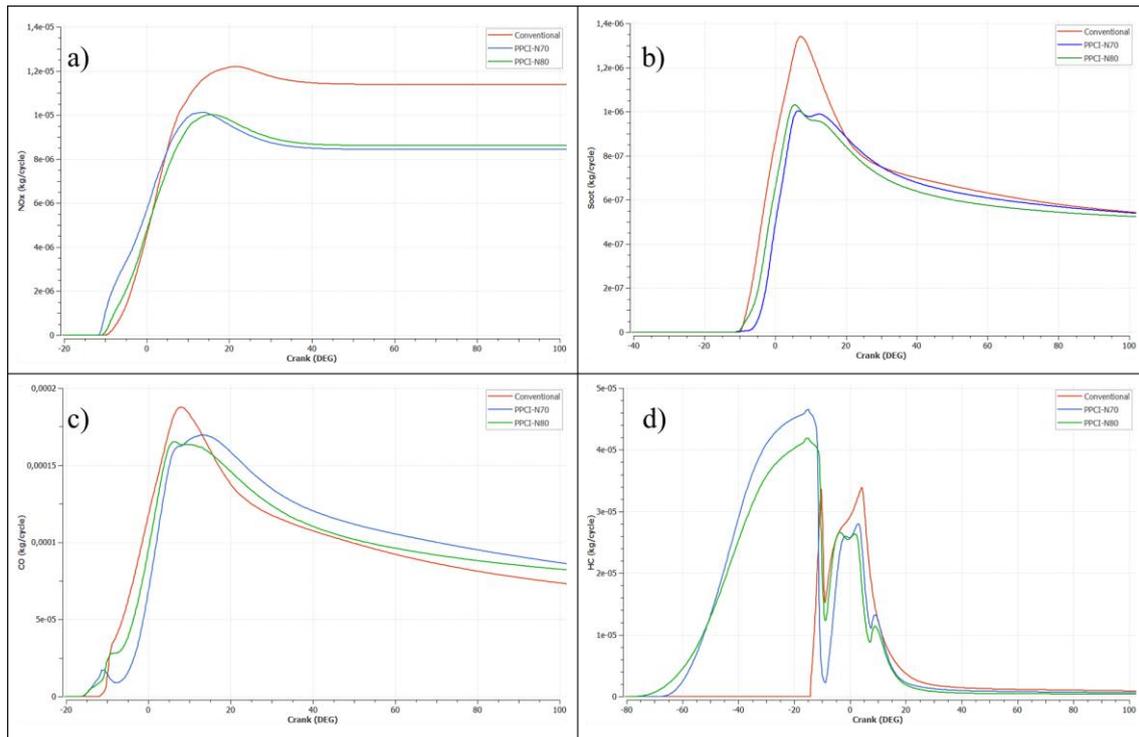


Figure 6. Exhaust emissions of the test engine for CI and PPCI strategy.

NO_x emissions were reduced by 25.91% and 24.36% for the PPCI N80 and PPCI N70, respectively, compared to the conventional diesel engine. In addition, soot emissions were decreased by 3.72% with the PPCI method. It was highlighted the importance of the method of reducing Soot-NO_x emissions together. However, CO emissions increased by 12.1% because of lower TKE values from 20° to 120° aTDC. HC emissions decreased significantly by up to 54.85%.

CONCLUDING REMARKS

The influences of different injection strategies with a narrow spray angle of 80° on the in-cylinder flow and exhaust emissions were investigated using 3D CFD commercial code in the heavy-duty engine. To eliminate the wall wetting problem and avoid out of bowl injection during the early injection for PPCI combustion, the fuel injection angle was narrowed from 149° to 80° of the conventional diesel engine. This study examined the early injection strategy and its effect on in-cylinder flow motion and exhaust emissions.

Two types of injection strategies (conventional diesel engine and early injection as 80° and 70° bTDC with split injection) were examined and the results show that the split injection strategy is very effective in reducing NO_x emissions while maintaining high thermal efficiency. NO_x emissions decreased as the injection timing was advanced 80° and 70° bTDC in a narrow-angle injection. Soot emissions were also reduced with the PPCI N80 strategy compared to the conventional diesel engine.

NOMENCLATURE

AHRR	Apparent heat release rate
AMR	Adaptive mesh refinement
aTDC	After top dead center
BDC	Bottom dead center
bTDC	Before top dead center
CA	Crank Angle
CFD	Computational Fluid Dynamics
EVO	Exhaust valve opening
HCCI	Homogeneous charge compression ignition
IVC	Intake valve closing
PM	Particulate matter

PPC	Partially premixed combustion
PPCI	Partially premixed compression ignition
PPCI N80	PPCI strategy with the narrow spray angle of 80° and SOI of 80 bTDC
PPCI N70	PPCI strategy with the narrow spray angle of 80° and SOI of 70 bTDC
RANS	Reynold Averaged Navier-Stokes
SOI	Start of injection
TDC	Top dead center
TKE	Turbulent kinetic energy

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