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Effects of Asymmetric Valve Timing with Constant NVO Duration on HCCI Engine Combustion Characteristics

Khashayar Ebrahimi*, Alex Schramm, Charles Robert Koch

Mechanical Engineering Department, University of Alberta, Edmonton, Canada T6G 2G8

1. Abstract

Homogeneous Charge Compression Ignition (HCCI) engine combustion characteristics are investigated by changing the amount of trapped residual gas and compression ratio cycle-by-cycle by keeping the Negative Valve Overlap (NVO) duration constant and only varying the Exhaust Valve Closing (EVC) and Intake Valve Opening (IVO) timings. Three different NVO durations are tested. Rate of heat release, which is calculated from the in-cylinder pressure trace, and the exhaust gas emission measurements information are used to examine the HCCI engine combustion features. Combustion timing and burn duration are significantly affected by the level of trapped residual gas with this valve timing strategy. The measurements indicate that fuel efficiency, output torque and Indicated Mean Effective Pressure (IMEP) are improved when IVO and EVC timings are advanced simultaneously with constant NVO duration. CO concentration is reduced with the retarded EVC and IVO timings while CO_2 concentration reaches its minimum with symmetric NVO.

2. Introduction

In HCCI engines, well premixed air fuel mixture is compressed to the point of auto-ignition. HCCI combustion can greatly reduces NO_X emissions and improves thermal efficiency. However, HCCI engines produce more unburned hydrocarbons since combustion occurs at low temperatures and the engine operating range is narrow due to knock at high loads and misfire at low loads [1]. Combustion timing and load control are difficult in HCCI engines [2]. There are several ways to achieve desired HCCI combustion timing. Preheating the charge with a heater in the intake is one way to ensure combustion happens at the right time. Variable Valve Timing (VVT) is another fast, feasible and effective way to have controlled combustion in HCCI engines [3]. Different VVT strategies have been investigated in HCCI engines. In one strategy, exhaust gas is reinducted from exhaust port using delayed EVC timing which is known as re-breathing technique [1]. Exhaust retention is another technique that employs early EVC followed by late IVO [4]. In this technique, EVC happens before TDC and trapped residual gasses are compressed first and then expanded after TDC. IVO happens after TDC to minimize back-flow to the intake manifold. This strategy is known as NVO retention [3]. The main advantage of this technique is that high temperature of trapped residual gases helps fuel decomposition and reformation during compression.

Mixture temperature and composition at IVC has important effects on HCCI combustion characteristics. Fully flexible VVT system allows to cycle by cycle control over mixture condition at IVC. Studies show that HCCI combustion characteristics i.e. thermal efficiency, fuel efficiency, load and emissions are strongly depend on mixture temperature and composition at the beginning of compression stroke [1, 3, 5, 6, 7]. In [5], an experimental study is done with NVO retention and re-breathing valve strategies. They report that re-breathing technique results in higher thermal efficiencies and NO_X emissions reduction at the same load compared to NVO retention and this strategy also increases the HCCI operating range. The effects of NVO fuel injection is investigated in [7] and it is found that the thermal effects of NVO play an important role in HCCI combustion. The effects of NVO duration and exhaust valve lift on HCCI combustion show that combustion phasing is advanced with early EVC and higher exhaust valve lift but late EVC improves fuel efficiency [8]. Effects of IVC timing on HCCI combustion characteristics show that early IVC improves indicated thermal efficiency [9]. It is found that NVO with n-heptane as an additive expands the HCCI operating range while keeping NO_X emissions very low. NVO duration is decreased by adding n-heptane as additive to gasoline as the main fuel [10]. NVO pilot injection approach is used to stabilize HCCI combustion at low loads [11]. NVO in combination with stratified charge provides a useful technique to improve

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*Corresponding author: ebrahimi@ualberta.ca

HCCI combustion and extend the operating range [12]. NVO is used to extend the low load operating region of a light duty diesel engine running with gasoline partially premixed combustion [13]. A computational study to investigate the effects of NVO on HCCI combustion timing and duration in an engine fueled with ethanol shows that higher NVO duration gives earlier ignition whereas the longest combustion duration is found in the lower NVO duration [6]. HCCI combustion characteristics are improved experimentally with GDI multi-stage injection strategy and NVO [14]. The operating range of HCCI combustion is extended in both high load and low load limits with this technique. In [15], PIV technique is used to measure the in-cylinder flow field with different NVOs in an HCCI engine. It is found that with NVO, the in-cylinder flow speed can be increased. Using NVO with a stratified charge reduces the maximum pressure rise and knock intensity in HCCI engines at the expense of increased NO_X and CO emissions [16]. A computational study is done in [17] to investigate the effects of IVC timing on HCCI mixture preparation with NVO technique and the in-cylinder mixture preparation process and combustion characteristics are improved with this technique. It is found that NVO technique reduces smoke emission further compared to external EGR but it lowers the high load limits [18].

In this work, HCCI combustion is studied experimentally with fixed NVO duration while EVC and IVO timings are changed respect to TDC. EVO and IVC are kept constant as shown in Figure 1. Three different amounts of NVO are examined. With non-symmetric valve timing, it is possible to trap different amount of residual gas and change the effective compression and expansion ratios to get desirable HCCI combustion. Effects of this VVT strategy on start of combustion, burn duration, rate of heat release, IMEP, output torque and fuel efficiency are experimentally investigated.

Figure 1: VVT with constant NVO duration

3. Results

The experimental HCCI single cylinder engine used in this study is detailed in [19]. The engine has EVVT system which is fully independent and has adjustable valve timings. A schematic of the test setup is shown in Figure 2. The experimental conditions for the steady-state points used in this study are listed in Table 2. EVC and IVO timings are varied with constant NVO duration while the fueling rate is held constant. Pressure traces from 100 consecutive engine cycles with 0.1 CAD resolution are recorded at each operating point. The crank angle at which 50% of the energy is released, θ_{50}, is calculated based on Rassweiler [20]. The net heat release rate is determined using the usual heat release method [21] that applies the first law analysis on the engine charge assuming ideal gas properties.

Table 1: Single cylinder research engine specifications

Parameters	**Values**
Bore × Stroke [mm]	97 × 88.9
Compression Ratio [-]	13.9
Displacement [l]	0.653
Number of Valves [-]	4
IVO [CA deg aTDC]	-360° to -260°
IVC [CA deg aTDC]	-180°
EVO [CA deg aTDC]	180°
EVC [CA deg aTDC]	260° to 360°

Table 2: Operating conditions of the steady-state data points used in this study

Variables	**Values**
Injected fuel per cycle [kg]	8.8856×10^{-6}
Engine speed [rpm]	809
Intake manifold temperature [C]	80 - 82
Equivalence ratio [-]	0.25 - 0.45
Intake manifold pressure [kPa]	105 - 117
External EGR [%]	0
$T_{coolant}$ [C]	51

Figure 2: Combustion timing and Burn Duration versus center of NVO with asymmetric valve timing

Figure 3: λ versus center of NVO with asymmetric valve timing

Figure 4: Indicated Mean Effective Pressure (IMEP) and Fuel efficiency (BSFC) versus center of NVO with asymmetric valve timing

Figure 5: Output Torque versus center of NVO with asymmetric valve timing

Symmetric NVO effects on HCCI combustion timing are investigated in [4, 22]. At higher symmetric NVO duration, more residual is trapped resulting advanced combustion timing since the mixture temperature at the beginning of compression is increased. Higher symmetric NVO durations result in higher IMEP since combustion efficiency is improved with reduction in unburned hydrocarbons and CO concentrations. The effect of asymmetric valve timing on combustion timing for three different NVO durations is shown in Figure 2. Combustion timing advances and burn duration decreases for late EVC and IVO timings. With late EVC, less residual gas is trapped inside the cylinder. With late IVO, in-cylinder gas temperature is reduced due to expansion and more fresh charge is inducted into the cylinder due to low in-cylinder pressure at IVO and these trends are approximately shown in Figure 3. As λ decreases with late EVC and IVO timings the fuel concentration is higher for late valve timings. For 40^o CAD NVO duration, when EVC is further delayed, re-breathing occurs but combustion timing is still advanced (see Figure 2). With advanced EVC timing, more residual gas is trapped but at IVO, in-cylinder pressure is high and part of residual gas flows into the intake manifold and dilutes the fresh charge. Less fuel is trapped at the beginning of compression with early IVO and combustion timing is retarded. θ_{50} shows an approximately flat slope when the center of NVO timing is before -5 CAD aTDC for 60 and 80 NVO durations. This is very near to the symmetric valve timings. This point of -5 CAD aTDC suggests that with asymmetric NVO there is a point that any more trapped residuals has no effect. The trapped charge-residual homogeneity is improved when EVC and IVO timings are delayed simultaneously. In [23], both exhaust gas reinduction and retention strategies are modeled and show that greater trapped charge-residual inhomogeneity leads to the retarded combustion timing. Another observation in Figure 2 is, combustion duration is shorter when θ_{50} occurs before TDC, while burn duration is longer for θ_{50}s happen after or near TDC.

Figure 6: CO and CO_2 concentration versus center of NVO with asymmetric valve timing

Figure 7: O_2 and unburned hydrocarbon concentrations versus center of NVO with asymmetric valve timing

Figure 8: Exhaust gas temperature versus center of NVO with asymmetric valve timing

Figure 9: Rate of Heat Release for different asymmetric constant NVO duration

Figure 10: Pressure traces for different asymmetric constant NVO duration

The effects of asymmetric NVO timings on IMEP and fuel efficiency (BSFC) is shown in Figure 4. When θ_{50} advances before TDC (see Figure 2), IMEP begins to decrease and BSFC begins to increase. The reason is major part of energy is released before TDC during compression which reduces IMEP and thus fuel efficiency. Unlike symmetric NVO, increasing NVO duration does not improve IMEP (60 CAD NVO duration gives higher IMEPs with asymmetric valve timings as shown in Figure 4). Output torque decreases when both EVC and IVO timings are delayed since combustion occurs before TDC and energy is released during compression stroke (see Figure 5). However combustion is more complete with retarded EVC and IVO timings since more CO is converted to CO_2 as shown in Figure 6. CO_2 and CO are inversely related, with a maximum and minimum, respectively, at an EVC of 35 CAD bTDC. Figure 7 confirms that combustion is more complete with late EVC and IVO timings. As shown in this Figure, unburned hydrocarbon concentrations are reduced when EVC and IVO timings are delayed which means that combustion is more complete. O_2 and unburned hydrocarbon concentrations are high with symmetric NVO and it reduces with asymmetric NVO timings. Figure 8, shows effect of asymmetric NVO timings on exhaust gas temperature. As shown in this Figure, with late EVC and IVO timings exhaust gas temperature is increased which means that combustion efficiency is high. Higher residual gas temperatures with late EVC and IVO timings, helps to advance combustion timing even with less trapped residuals. Exhaust temperature for all three NVO durations shows a local minimum at -5 CAD aTDC, which indicates that combustion temperatures are lowest near symmetric NVO timings. A heat exchanger or simple heat recovery system could be used in the exhaust side to heat up the intake air flow in stationary or automotive applications.

Figure 9 and 10 shows the early and late as well as symmetric EVC and IVO timings heat release curves and pressure traces for 80^o CAD NVO duration. As the EVC and IVO timings are retarded, the timing of occurrence of heat release by LTR and HTR advances and the burn duration decreases. LTR happens in the range from 700K to 800K and HTR about 1100 K for n-heptane [1]. Both LTR and HTR reactions largely depend on temperature and trapped fuel concentration at IVC. The maximum value of the rate of heat release by HTR increases by later EVC and IVO timings and the maximum in-cylinder pressure and rate of pressure rise are increased (see Figure 10). With advanced asymmetric valve timing, combustion timing is retarded and rate of pressure rise is reduced and the knock limit can be extended in high loads. Similar behavior was seen for other NVO durations.

5. Summary and Conclusions

Effects of non-symmetric valve timing with constant NVO durations on HCCI combustion characteristics are studied on an experimental HCCI engine fueled with n-heptane. EVC and IVO timings are changed while all other engine parameters are kept constant. With late EVC and IVO timings, combustion timing is advanced, burn duration is decreased, combustion efficiency is improved and exhaust gas temperature is increased. However, IMEP and fuel efficiency are decreased since major part of fuel energy is released during compression stroke. High load knock limit can be extended and rate of pressure rise can be reduced with retarded EVC and IVO timings. Further studies regarding asymmetric valve timing effects on HCCI combustion with other NVO durations are needed.

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