Cycle-to-cycle variation of a HCCI engine operated with n-heptane

Li, H.; Neill, W.; Chippior, Wallace

Cycle-to-Cycle Variation of a HCCI Engine Operated with n-Heptane

H.L. Li[1], W. S. Neill, W. Chippior
National Research Council, Ottawa, ON, K1A 0R6, Canada,

J. D. Taylor
National Renewable Energy Laboratory, Golden, CO, USA

Introduction

Homogeneous Charge Compression Ignition (HCCI) is an advanced combustion technology being increasingly considered for future internal combustion (I.C.) engines. In principle, HCCI involves the combustion of a homogeneous mixture of fuel, air and diluents at low to moderate temperatures and high pressure. It has been demonstrated that HCCI has several desirable combustion characteristics including diesel-like fuel conversion efficiency and extremely low NO_x and soot emissions. However, as reported previously in the literature, HCCI combustion leads to higher HC and CO emissions, as well as higher cycle-to-cycle variations in indicated mean effective pressure (imep). These make it difficult to operate a HCCI engine under low load conditions.

Cycle-to-cycle variation in the combustion process has long been a topic of concern to researchers because it adversely affects engine performance, producing losses in power and efficiency as well as increasing noise [1, 2]. Severe cyclic variation is always accompanied with high emissions of unburned hydrocarbons (UHC) and CO. Traditionally, the coefficient of variation in imep (COV_{imep}) is employed to describe engine performance stability. COV_{Pmax} is used to indicate the combustion stability and noise. Previous researchers have suggested that HCCI engines should have less cycle-to-cycle variation than S.I. engines [3, 4]. Such a statement is based mainly on HCCI engine's kinetically controlled combustion characteristics, including the initiation of combustion without an external ignition source and rapid heat release without involving the turbulence controlled flame propagation processes [5]. These were shown to be the main contributors to the cyclic variation of S.I. engines [6]. However, the research results reported in the literature for HCCI engines have not been consistent with the hypothesis of lower cyclic variation.

Cyclic variations of the HCCI engines have been experimentally examined by a number of researchers. Compared to traditional S.I. engines, the initiation of HCCI combustion and the following heat release process are controlled by the chemical reaction rates, which depend on the temperature, pressure and mixture properties including fuel composition, air/fuel ratio and EGR rate. Numerous factors that influence the mode and extent of cycle-to-cycle variation have been identified. These include fluctuations in the following parameters and factors: (1) intake temperature and pressure; (2) intake air/fuel ratio or fuel flow rate; (3) coolant and lubrication oil temperatures; (4)the presence of diluents as a result of either external or internal EGR; (5) thermal and mixture composition stratification as results of in-homogeneity; (6) the intensity of intake charge motion and bulk turbulence; (7) the completeness of combustion in the preceding cycle; and (8) fuel mixing system and homogeneous mixture formation strategies. This paper presents cyclic variation data obtained under stable and well controlled operating conditions. The results obtained reflect the cyclic variation characteristics of HCCI engines and help to understand this phenomenon.

---

[1] Corresponding author: email: hailin.li@nrc-cnrc.gc.ca, phone: (613) 949-4177, Fax: (613)957-7869

Experiment Set-up and Procedure

A Co-operative Fuel Research (CFR), single-cylinder, variable compression ratio, four-stroke engine was used for this research. The engine was modified from the standard CFR configuration by the addition of a port fuel injection system and other hardware needed to control critical engine parameters such as intake temperature, air/fuel ratio, recirculation of exhaust gas, and intake and exhaust pressure. A port fuel injector for flexible fuel vehicles was modified to provide air-assisted atomization of liquid fuels. The airflow rate to the engine was measured using a mass flow meter (Sierra, model 780 Series Flat-Trak^{TM}). A Coriolis-effect mass flow meter (Micro Motion, Model D6) was used to measure the fuel flow rate. The engine was coupled to an eddy current dynamometer/ variable speed AC motor combination for starting the engine, measuring engine load, and maintaining engine speed when HCCI combustion was unstable. The cylinder pressure was measured with a high frequency-response piezoelectric pressure transducer (Kistler Corp., model 6121) mounted flush with the cylinder surface using the detonation transducer access port. An encoder fitted to the cam shaft provided a TTL signal with a resolution of 0.1°camshaft (0.2°crankshaft), which was used as the data acquisition clocking pulses to acquire the cylinder pressure data. In this research, pure n-heptane was used as a surrogate for diesel fuel. The fuel was injected into the intake manifold at 25°CA ATDC during the intake stroke. The injection process lasts about 10~30°CA depending on fuel flow rate and is finished well before intake valve closure.

For these experiments, the coolant and lubrication oil temperatures were controlled at 82ºC. At each operating condition, the engine was run for at least 5 minutes or until engine operation stabilized before sampling experimental data. Engine performance data and key operating parameters were sampled for approximately 4 minutes at a frequency of 1 Hz. During the same time period, cylinder pressure traces for 500 engine working cycles were measured, saved and processed. The averaged cylinder pressure trace was analyzed to obtain the heat release and a complete set of combustion parameters. Individual cycles were analyzed to quantify statistical variation in imep and Pmax.

Results and Discussions

Figure 1 shows the effect of air/fuel ratio on the cyclic variation, represented by COV_{imep} and COV_{Pmax}. Relatively higher COV_{imep} was observed when engine knock occurred. The oscillation of the cylinder pressure contributes to this phenomenon and may not reflect the real cyclic variation of the engine power as the pressure in the combustion chamber is not uniform. It is also noted that the value of COV_{Pmax} is usually smaller than that of COV_{imep}. The relatively low imep and high peak pressure of HCCI engines contribute to this phenomenon. Increasing the air/fuel ratio gradually suppresses engine knock and reduces the cyclic variation. Relatively stable HCCI combustion can be obtained for a wide range of air/fuel ratios with minimum COV_{imep} obtained at an air/fuel ratio of 48. Upon further increasing the air/fuel ratio, HCCI combustion becomes gradually more unstable as indicated by increased COV_{Pmax} and COV_{imep}. Leaning the operating mixture still further, the COV_{imep} continue to increase while COV_{Pmax} stay approximately constant and then decrease quickly. This is due to an overly retarded combustion phasing, where peak pressure is due to the compression process only.

Figure 2 shows the effect of compression ratio on cyclic variations of imep and peak pressure. The COV_{imep} was equal or higher than COV_{Pmax} for all compression ratios. Comparable COV_{imep} and COV_{Pmax} values were only observed for lower compression ratios which had unstable combustion. Slightly higher COV_{imep} values were observed at higher compression ratios. Decreasing compression ratio enhances the combustion stability. The minimum COV_{imep} was observed at a compression ratio of 11. In comparison, the value of COV_{Pmax} is approximately constant over a range of compression ratios greater than 11. As the equivalence ratio is decreased below 11, the value of COV_{imep} increases dramatically while COV_{Pmax} increases initially and then quickly decreases.

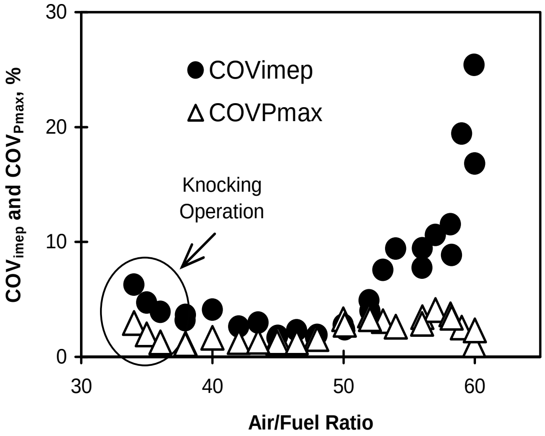

Figure 1 Variations of COV_{Pmax} and COV_{imep} versus air/fuel ratio. CR=10, $T_{in,air}$=30 ºC, P_{in}=95 kPa, N=900 rpm.

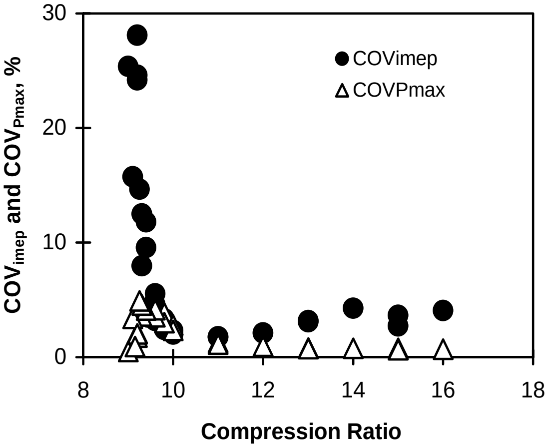

Figure 2 Variations of COV_{Pmax} and COV_{imep} versus compression ratio. AFR=50, $T_{in,air}$=30 ºC, P_{in}=95kPa, N=900 rpm.

Figure 3 shows the effect of EGR on cyclic variations of imep and Pmax. The engine was knocking slightly with zero EGR applied as shown by the relatively high COV_{imep} value. The application of EGR suppresses engine knock and reduces the COV_{imep} slightly. In comparison, introducing EGR has a weaker effect on COV_{Pmax}. With EGR rate greater than 50%, both COV_{Pmax} and COV_{imep} increased significantly.

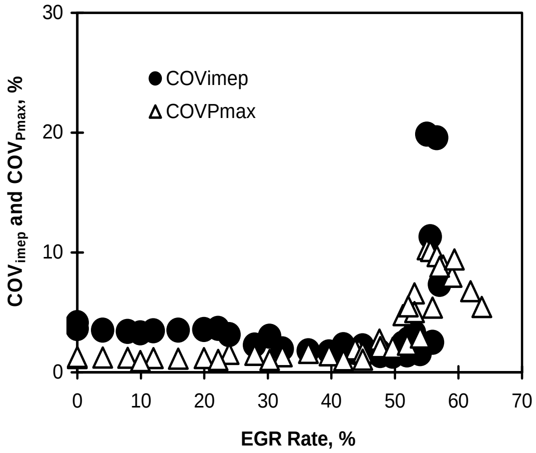

Figure 3 Variations of COV_{Pmax} and COV_{imep} versus EGR rates, CR=10, $T_{in,air}$=40 ºC, P_{in}=95kPa, $\dot{m}_{fuel}$ =0.395 kg/h

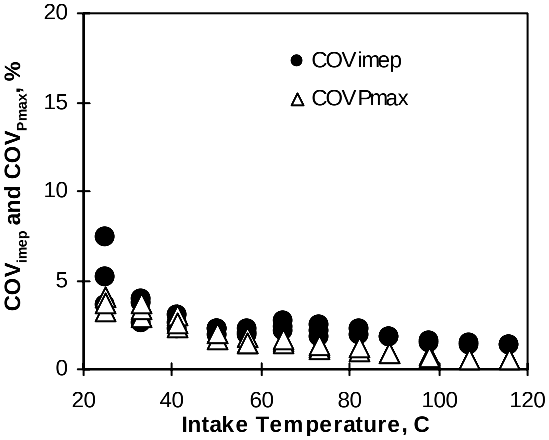

Figure 4 Variations of COV_{Pmax} and COV_{imep} versus engine speed, CR=10, AFR=50, P_{in}=95 kPa, N=900 rpm.

The effect of intake temperature on cyclic variation is shown in Fig. 4. The engine shows high cycle-to-cycle variation with lower intake temperatures under the described operating conditions.

Higher intake charge temperature helps to advance the combustion phasing and improve combustion stability. As shown in Fig. 5, boosting the intake pressure helps to stabilize HCCI combustion up to a certain point. Boosting the intake pressure further has little effect on the COV_{imep}.

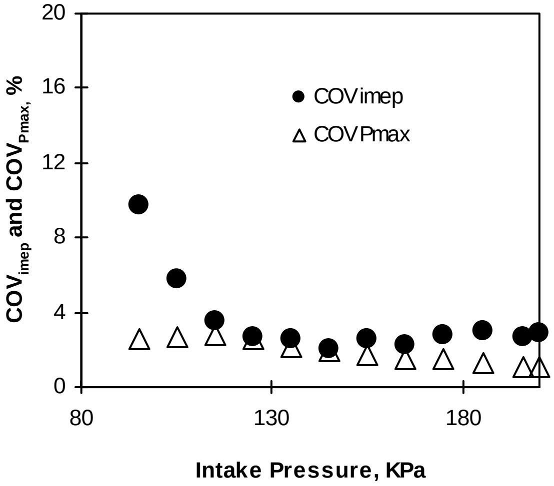

Figure 5 Variations of COV_{Pmax} and COV_{imep} versus intake pressure, CR=10, AFR=50, P_{in}=95 kPa, N=900 rpm.

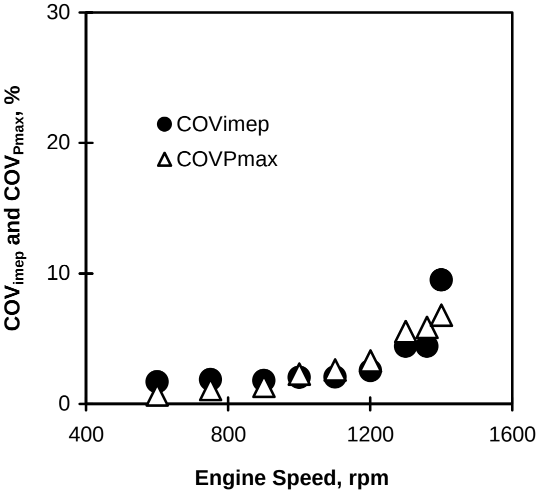

Figure 6 Variations of COV_{Pmax} and COV_{imep} versus engine speed. AFR=50, $T_{in,air}$=30 °C, P_{in}=95 kPa

Engine speed affects the time available for chemical reactions to occur. This could be very important with fuels that exhibit negative temperature coefficient (NTC) combustion [7]. As shown in Fig. 6, unstable combustion was observed at high engine speeds due to the reduced residence time for chemical reaction, which retards the combustion phasing as reported earlier [7].

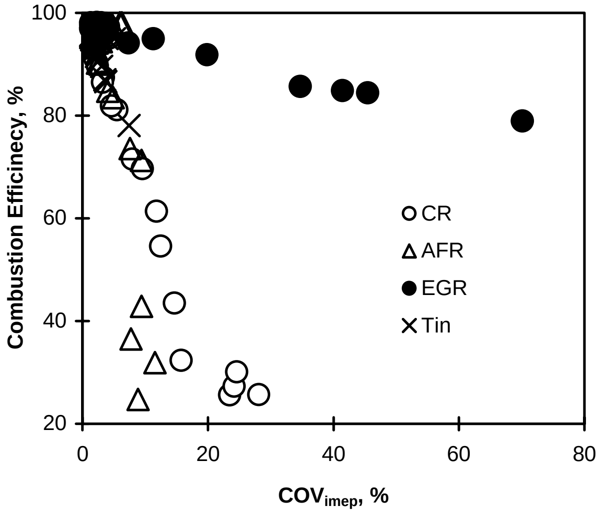

Figure 7 Variation of combustion efficiency versus COV_{imep}.

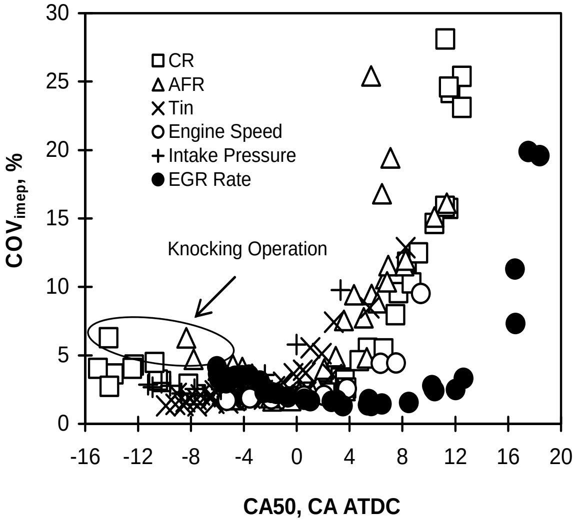

Figure 8 Variation of COV_{imep} versus combustion phase CA50

Unstable and retarded combustion has been reported to result in low combustion efficiency as the fuel does not burn completely [8]. As shown in Fig. 7, extremely high combustion efficiency (over 99%) can be obtained with stable combustion. The combustion efficiency decreases dramatically when stable combustion can not be maintained, which leads to increased COV_{imep}. Also, the deteriorations in COV_{imep} follows similar trends when the instabilities are achieved through approaches other than increasing EGR rate. In comparison, a substantial increase in the COV_{imep} can be tolerated without significantly deteriorating combustion efficiency when EGR is applied under constant fuel flow rate operation. Combustion efficiencies over 80% can still be achieved with a COV_{imep} value as high as 50%.

Unstable combustion was always observed under operation with an extremely fuel lean mixture, low intake temperature, low compression ratio, high EGR rate or high engine speed. All of these operating conditions tend to result in retarded combustion phasing [7]. It was shown that combustion and indicated thermal efficiencies are generally a function of combustion phasing notably CA50, the crank angle where 50% of the chemical energy has been released [8]. The correlation of COV_{imep} with CA50 is shown in Fig. 8. Low COV_{imep} values were observed when the combustion phasing occurred before top dead center with the exception of knocking operation. Retarding combustion phasing beyond 4°CA ATDC leads to a significant increase in COV_{imep} for all approaches examined except increasing EGR. As shown in Fig.8, the application of EGR shows superior characteristics in retarding the combustion phasing. Stable HCCI combustion can be obtained with CA50 as late as 14 °CA ATDC.

The variation of the cylinder pressure is mainly due to the variation of total energy released, combustion phasing and combustion duration. Considering the much shorter combustion duration encountered in HCCI engines [7], the variation of heat release process itself on HCCI combustion is of the smaller magnitude in comparison to S.I. engines. As shown in Fig. 9, the cyclic variation of the HCCI engine correlates well with that in total heat released. The significant variation in total energy released in different cycles contributes mainly to the cycle-to-cycle variations of the HCCI engine.

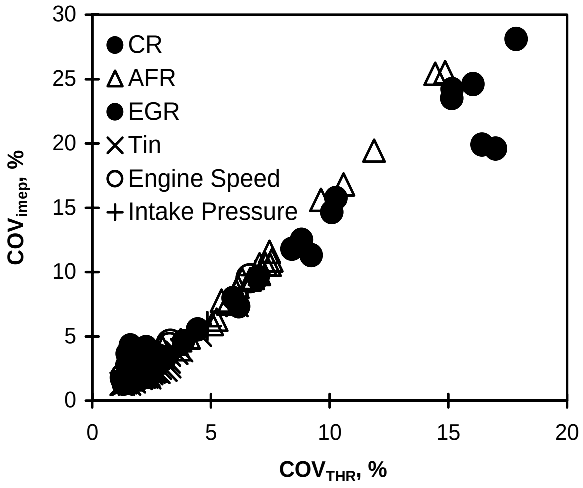

Figure 9 Variation of the COV_{imep} verses COV in Total Heat Release (COV_{THR}) each cycle

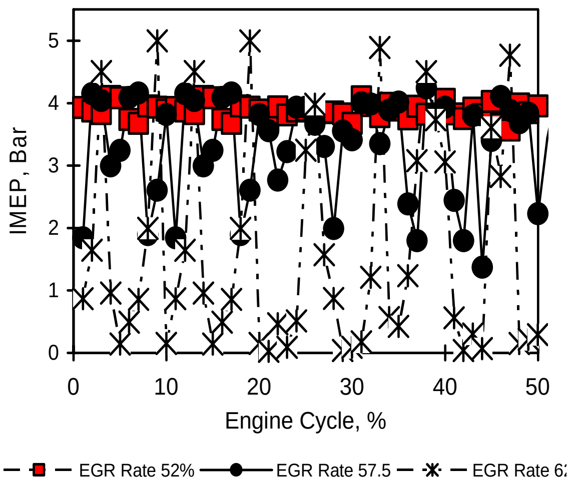

Figure 10 Imep variations with engine cycle for three different EGR Rates. CR=10, $T_{in,air}$=40ºC, P_{in}=95kPa, $\dot{m}_{fuel}$ =0.395 kg/h.

Figure 10 shows imep as a function of engine cycle for three different EGR rates. As the EGR rate increases, imep fluctuation becomes larger. It is also observed that imep show a periodic characteristic. A good combustion cycle as indicated by peak imep, is always followed by a much weaker one until the minimum imep was observed. This is due to the effect of combustion completeness of the prior cycle, which affects the mixture composition and temperature of the next cycle [9]. As shown in Fig. 10, higher EGR resulted in higher peak imep than lower EGR operation at constant fueling rates. The relative late combustion phasing, reduced heat transfer and increasingly deteriorated combustion efficiency of prior bad combustion cycle contribute to this observed phenomenon.

Conclusions

The cycle-to-cycle variations of a HCCI engine operated on n-heptane were examined over a range of intake temperature, compression and equivalence ratios, EGR rate and intake pressure. The variation of COV_{imep} with combustion phasing was examined. Based on the experimental results presented, the following conclusions can be drawn:

- For this HCCI engine, the COV_{imep} is usually higher than COV_{Pmax}. Comparable or higher COV_{Pmax} were only observed with instable combustion.
- The cyclic variation of the HCCI engine is mainly due to the variation of the total energy released in each cycle. The combustion of the current cycle is significantly affected by combustion completeness of the prior cycle.
- The cyclic variation of the HCCI engine correlates well with combustion phasing. The combustion stability deteriorates significantly with retarded combustion. Advancing the combustion phasing helps to stabilize HCCI combustion with the exception of knocking conditions
- The application of EGR was more effective than other approaches investigated in maintaining HCCI combustion stability at retarded combustion phasing. Much higher cyclic variation can be tolerated without significantly deteriorating combustion efficiency.

References

1. Patterson, D., SAE Paper 660129.
2. Heywood, J.B., 1988, McGraw Hill Press
3. Mattias, R., Franke, A., Engstrom, J., Hultgvist, A., Johnsson, B., Alden, M., SAE Paper 2000-01-2868
4. Koopmans, L., Backlund, O., and Denbratt, I., SAE Paper 2002-01-0110.
5. Dec, J.E., and Sjöberg, M. 2003, SAE Paper 2003-01-0752
6. Ozdor, N., Dulger M., and Sher, E., SAE Paper 940987.
7. Li, H.L., Guo. H.S., Neill, W.S., Chippior, W., and Taylor, J.D., ASME ICEF2006-1562
8. Li, H.L., Neill, W.S., Chippior, W., Graham, L., Connolly, T., and Taylor, J. SAE Paper 2007-01-1854
9. Wagner, R.M., Edwards, K.D., Daw, C.S., Jr., J.B.G., and Bunting, B.G., SAE Paper 2006-01-0418