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Partial-burn crankangle limit criteria comparison on an experimental HCCI engine

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1. Abstract

Misfire and partial-burn criteria are defined using crank angle based engine parameters and investigated on an experimental Homogeneous charge compression ignition (HCCI) single-cylinder engine at 59 operating conditions. The best criteria to distinguish between normal, partial burn and misfire operating conditions for this engine are: the standard deviation of CA10 (Crank angle at which 10 percent of fuel mass has burned) and burn duration. The partial burn limit for five different blends of isooctane and n-heptane fuels is presented. Increasing the manifold pressure at each specific fuel octane number results in a lower equivalence ratio partial burn limit for the engine operating points tested.

2. Introduction

HCCI combustion has potential for improved fuel economy, very low oxides of nitrogen (NOx) and low particulate emissions. HCCI is considered as a high-efficiency alternative to spark-ignited (SI) gasoline operation and as a low-emissions alternative to traditional diesel compression ignition (CI) combustion. However, the practical application of HCCI requires overcoming several technical hurdles. HCCI misfire or partial-burn is undesirable because it results in increased exhaust emissions and reduces engine power output.

A misfire event is a lack of combustion which results in a momentary lack of torque. Misfire leads to a sudden engine speed decrease [1] and is undesirable since it can lead to speed and torque fluctuations, increased exhaust emissions [2], and unburned fuel in the exhaust that will eventually damage the catalytic converter [3]. In particular, there is a high risk of misfire in HCCI operation, which can have a much more destructive consequence on the engine's performance and emissions than SI combustion [4]. At a fixed fuel octane and engine speed, HCCI operation is limited by three boundaries: misfire, partial burn, and knock limit [4]. To reduce HCCI engine knock at high loads, combustion-phasing retard [5, 6] has been used. Combustion-phasing retard can help to reduce knock since the autoignition occurs during the expansion stroke and the effect of the naturally occurring thermal stratification produced by heat transfer are enhanced prolonging the duration of the staged autoignition event which lowers the peak heat-release rate [6, 7, 8]. To mitigate excessive pressure rise rate, precise control of the combustion phasing is often required. Beyond a certain combustion phasing, if the combustion is retarded too much, CO and HC emissions increase and combustion becomes unstable [9] resulting in partial-burn or misfire cycles. This happens because the charge cooling effect due to piston expansion overcomes the exothermic reactions of the combustion event preventing the charge from undergoing strong combustion. These factors limit the extent of combustion-phasing retard to reduce the pressure-rise rates but the exact combustion-retard limits and the behavior of the combustion for these conditions are not well known [10].

The acceptable combustion phasing range decreases with increasing fueling. At a sufficiently high fueling rate, the acceptable combustion phasing is highly constrained by the knock and misfire limits, and this operating condition represents the highest possible engine power output for a given intake pressure [11, 12]. On the other hand, as the cylinder charge is made leaner (with excess air) or more dilute (with a higher burned gas fraction from residual gases or exhaust gas recycle) the cycle-by-cycle combustion variations increase until some cycles have partial burning. Further leaning or more charge dilution results in reaching the misfire limit as a portion of the cycles fail to ignite. Such operation is undesirable from the point of efficiency, HC emissions, torque variations and roughness [13].

It is difficult to describe the dynamics of HCCI near the misfire operating region and thus to control HCCI effectively to avoid misfires [14]. The understanding of the HCCI engine behavior in case of misfire and delayed combustion is an important first step to provide a control strategy to avoid misfire and expand HCCI operation as close as possible to this region. Techniques for misfire recognition, which are mainly based on the analysis of in-cylinder pressure,

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ionization current and crankshaft angular speed are detailed in [15]. Cost effective methods of misfire detection use existing crankshaft sensors and are based on crankshaft speed fluctuation [16, 17, 18, 19]. Here, equivalent methods to detect misfire in terms of crank-angle based parameters and cylinder pressure are proposed. In the next section of this paper, the single cylinder experimental setup used to collect the data is briefly described. Then, the procedure to find a partial burn and misfire limit in HCCI engine is outlined. Different partial burn limits of HCCI engine for five different fuel octanes are illustrated in the next section. Finally, the crank angle based parameters fluctuations for data points in three different regions of normal, partial burn and misfire are investigated in order to choose the proper parameters to be used as a feedback signal in future HCCI closed loop control.

3. Engine Setup

A single cylinder Ricardo Hydra Mark 3 block fitted with a VVT Mercedes E550 cylinder head is used [20] and is shown schematically in Figure 1. The engine with specifications given in Table 1 [21] is outfitted with a Kistler piezo-electric pressure transducer. This engine represents a typical spark ignition engine. The intake air is heated with a temperature controlled 600W electric heater, while the intake pressure is adjusted with an externally driven supercharger. N-heptane and iso-octane are individually port injected to set octane values with two injectors driven by a dSpace-MicroAutobox ECU.

Cylinder pressure is recorded 3600 times per crank revolution, and then analyzed for the pertinent combustion metrics, such as IMEP (Indicated Mean Effective Pressure), CA50 and burn duration. All other parameters are logged at 100 Hz using A&D Baseline DAC. The operating points span the range between normal operating condition to the misfire condition. All of the engine operating points are at steady-state operating conditions (inputs to engine and engine speed held constant). The tests operating conditions are listed in Table 2.

Table 1: Configuration of the Ricardo single-cylinder engine

Parameters	Values
Bore × stroke [mm]	97 × 88.9
Compression Ratio	12
Displacement [L]	0.653
Connecting Rod Length [mm]	159
Valves	4
Valve Lift [mm]	9.3

Table 2: Engine operating conditions

Parameter	Range
Manifold Pressure [kPa]	90-120
Manifold Temperature [°C]	85-102
External EGR [%]	0
Fuel Octane Number [PRF]	0,10,20,30,40
Engine Speed [RPM]	1024
Equivalence Ratio [-]	0.30-0.54

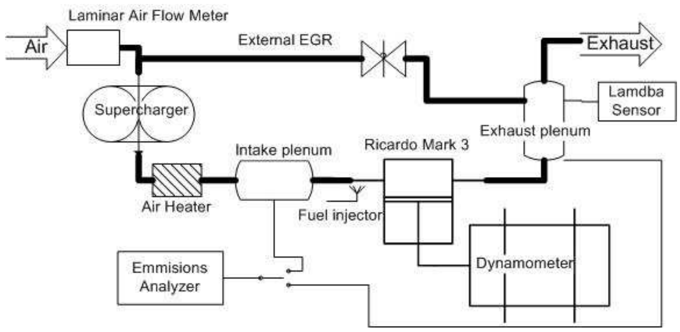

Figure 1: Schematic of the experimental setup

4. Results and Discussion

<u>Determination of Misfire Limit Criteria</u>
A cycle is defined to be a partial burn cycle if its total heat release is reduced by 10% or more compared to the previous cycle [10]. An experimental operating point is considered a partial burn point if more than 20% of the cycles are partial burn cycles. Operating points with more than 30% partial burn cycles are considered to be misfire points. The process to identify partial or misfire operating points is shown in Figure 2.

All operating points are partial burn, misfire or normal with none of the operating points used in this paper near the knock limit. Using the above criteria, 59 HCCI engine operating points are analyzed to categorize them into the different combustion regions: 30 are found to be partial burn, 11 misfire and 18 points are normal combustion. Consecutive cycle total heat release for a partial burn and misfire operating point are shown in Figure 3 and Figure 4 for two operating points. The number of cycles with more than 10 percent reduction in total heat release compared to the previous cycle

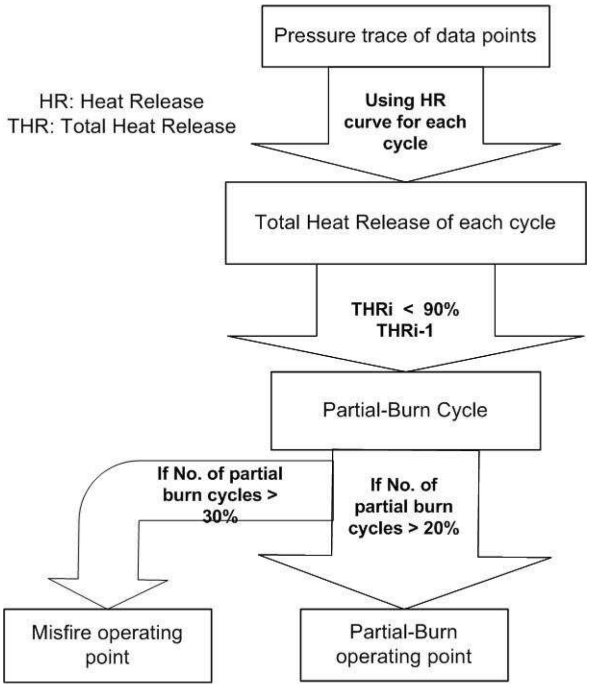

Figure 2: Flowchart: Procedure to determine the status of HCCI operating condition

are 21 and 38 percent for Figure 3 and Figure 4 respectively. In the misfire case, Figure 4, the number of cycles with reduction in total heat release is substantially higher compared to the partial burn point case of Figure 3, causing a torque reduction.

The partial burn and misfire criteria is used to test data on all 59 operating points to classify their operating region. Figure 5 compares the limits of misfire operating conditions for five various blends of primary reference fuels. The manifold pressure ranges from 90 and 120 kPa and is plotted on the x-axis and λ (ratio of actual air to fuel ratio to stoichiometric air to fuel ratio) on the y-axis. For this engine, HCCI misfire for each of the five octane numbers occurs in Figure 5 above the respective lines in the unstable operating condition of engine. Misfire boundary occurs because increasing the manifold pressure leads to higher gas pressure in the compression stroke directly effecting the time scales of the reactions leading to earlier autoignition [22] and cycle-to-cycle variation of the phasing of ignition increases with combustion-phasing retard for an HCCI engine [10]. Increasing manifold pressure extends the misfire limit for leaner mixtures autoigniton inside the cylinder as seen in Figure 5. Increasing the fuel octane number (higher amount of iso-octane in the mixture of iso-octane and n-heptane fuel) reduce the misfire limit (Figure 5) due to the autoignition

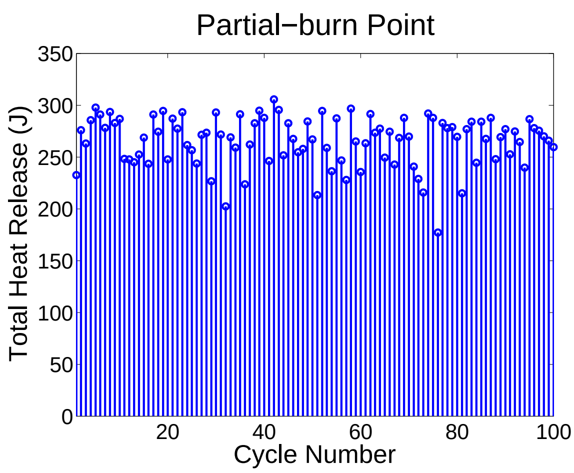

Figure 3: Partialburn Conditions: speed 1024 rpm, Tman 87 °C, Pman 105 kPa, ON 0, λ 2.87, T 14.88 Nm

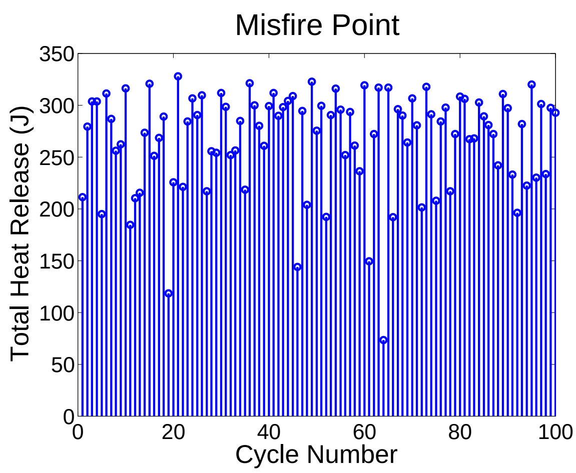

Figure 4: Misfire Conditions: speed 1024 rpm, Tman 95 °C, Pman 115 kPa, ON 20, λ 2.90, T 8.68 Nm

properties of the fuel [13]. This restricts the higher octane number fuels for HCCI operation for this engine. Stable operation with octane numbers 30 and 40 is not maintained at intake manifold pressures of 90 and 95 kPa.

Misfire limit for different fuels

To recognize the misfire limit using a single parameter, several techniques using IMEP (Indicated Mean Effective Pressure) have been used [4, 10, 21]. In [10] a standard deviation of IMEP more than 2% is deemed unacceptable as this corresponds to the appearance of partial burn and misfire cycles. The coefficient of variation, is used to measure cyclic variability of engine parameters [23]. *COVImep* (Coefficient of variation of IMEP) for determining cyclic variation of IMEP have been calculated for all the operating points used in this study and categorized using previously defined normal, partial burn or misfire operation. The results are shown in Figure 6 and *COVImep* clearly distinguishes three

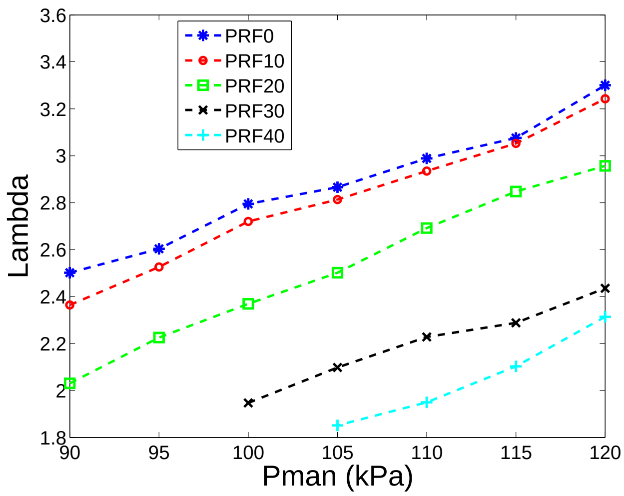

Figure 5: HCCI Misfire Boundaries as a function of λ and P_{man} for PRF0, 10, 20, 30 and 40

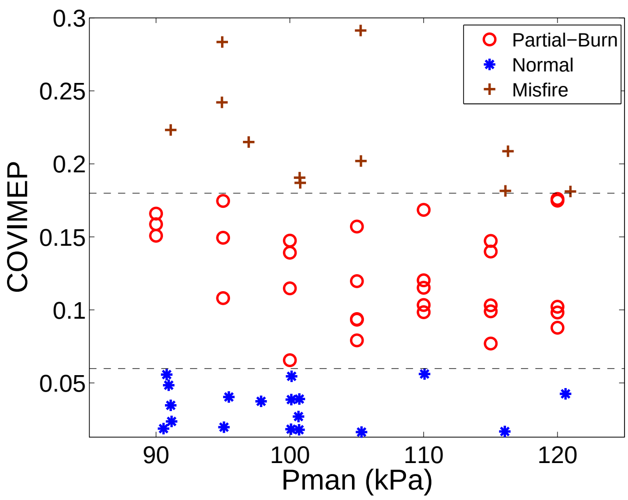

Figure 6: Trends of change in cyclic variation of Indicated Mean Effective Pressure (IMEP) with manifold pressure

different operating regions for the collected data points. The operating points with $0.06 < CovImep < 0.18$ are partial burn region while operating points with $CovImep > 0.18$ are the misfire region of this engine.

To determine the best parameter and to identify misfire conditions using an alternative to *COVImep* the crank-angle based parameters of CA1, CA10, CA50 and Burn Duration (BD) (Crank angle difference between CA10 and CA90) for all 59 operating points are shown in Figures 7 to 10. In Figures 7 and 9, no clear boundaries between the three regions of HCCI operating conditions are evident in variations of CA1 and CA50. In contrast, in Figures 8 and 10 three zones

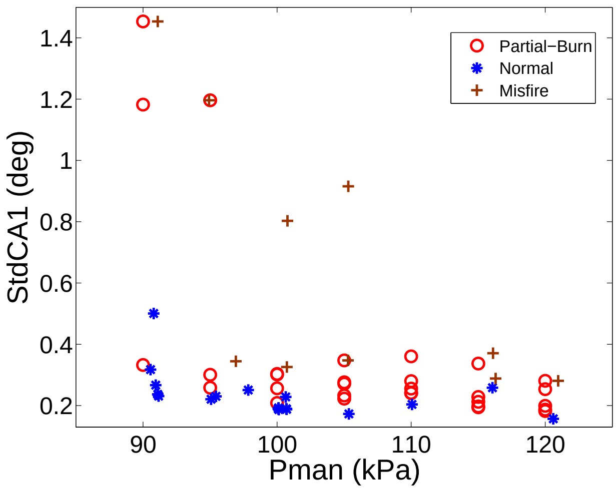

Figure 7: Trends of change in cyclic variation of CA1 with manifold pressure

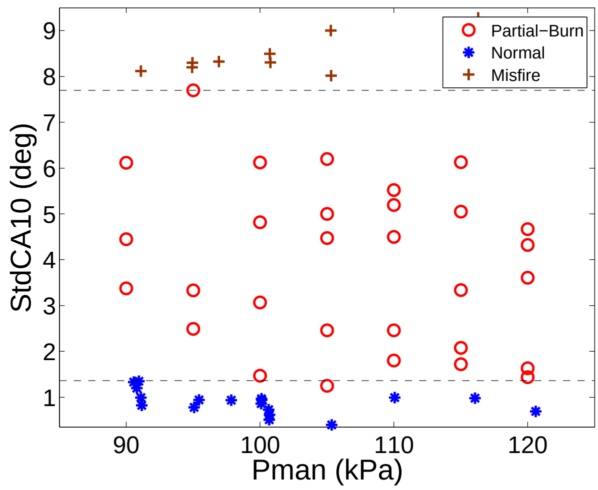

Figure 8: Trends of change in cyclic variation of CA10 with manifold pressure

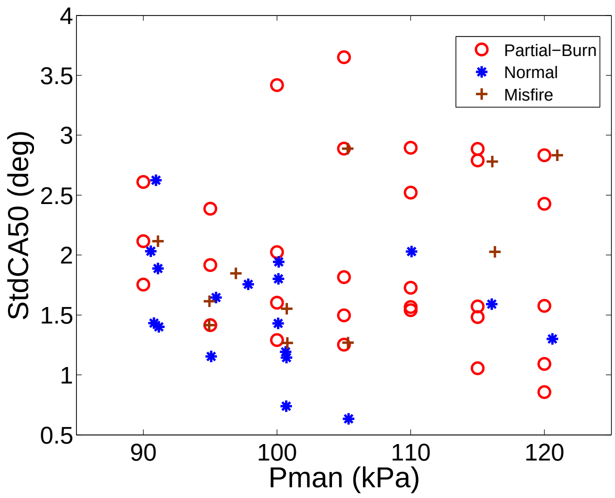

Figure 9: Trends of change in cyclic variation of CA50 with manifold pressure

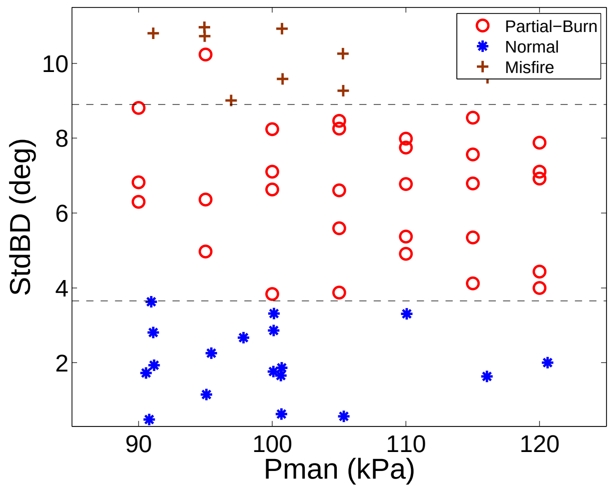

Figure 10: Trends of change in cyclic variation of Burn Duration (BD) with manifold pressure

of normal, partial burn and misfire operations are clearly visible except that a few partial burn data points are fairly close to the boundary between normal and partial burn. In Figure 8 all the data points with borders $1.3 < StdCA10 < 7.8$ fall in the partial burn region while the ones with $StdCA10 > 7.8$ in the misfire region. Figure 10 shows clear boundaries between the three different operating conditions of HCCI with the data points with $3.8 < StdBD < 9$ in the partial burn zone and data points with $StdBD > 9$ in the misfire zone. In Figure 10, StdBD has a partial burn point in the misfire region and so seems less reliable indicator compared to StdCA10 in Figure 8.

5. Conclusions

First, experimental data from HCCI engine collected at 59 operating points is used to define a criteria for misfire limit points. The criteria for characterizing HCCI engine operation as partial burn, when 20 percent of cycles are partial burn cycles, and misfire, when more than 30 percent of the cycles are partial burn is used. Then, cyclic variation of ignition timing in an HCCI engine is investigated. Examining combustion criteria it is found that CA1 and CA50 are not effective metrics for HCCI misfire recognition. However, variations of CA10 and BD are effective measures of misfire recognition and could be used as alternatives for *COVImep* to distinguish between normal, partial burn and misfire operation of an HCCI engine.

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