A Diagnosis Technique for the Identification of Misfire in a Converted-diesel HCCI Engine

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Abstract: The homogeneous charge compression ignition (HCCI) and the exploitation of ethanol as alternative fuel is one way to explore new frontier of internal combustion engines and towards maintaining its sustainability. Misfire and partial burning can cause several serious problems in the HCCI engines fuelled with ethanol. Novel methods for identification of misfire play important roles in HCCI engine operation and exhaust after-treatment system. In this study, a 0.3 liter single-cylinder direct-injection diesel engine was modified to operate on HCCI. The diagnosis technique is introduced for misfire identification. An artificial neural network (ANN) model were designed based on in-cylinder pressures at 0, 5, 10, 15 and 20 CAD aTDC as main inputs to predict indicated mean effective pressure (IMEP). The model was tested with the experimental data, indicating an average error less than 0.1 bar between predicted and measured IMEP and the results indicated that the model can predict IMEP as well as misfire.

Key–Words: HCCI engine, Ethanol, Misfire detection, Artificial neural network.

1 Introduction

One promising combustion concepts for internal combustion engines (ICEs) is homogeneous charge compression ignition (HCCI) which reduces fuel consumption, nitrogen oxides (NOx) and particulate matter (PM) engine-out emissions. The characteristic of HCCI engine is similar to spark ignition (SI) for its mixture homogeneity and compression ignition (CI) for high compression ignition feature [1]. These are the benefits of HCCI engine that can be fuel economy compared with diesel, higher thermal efficiency due to fast heat release with reduced heat transfer losses and operating on high dilute mixture that causes a lower combustion flame temperature that results in operating with ultra low NOx and PM [2]. In addition to HCCI benefits, a number of major challenges and obstacles associated with it, including production high unburned hydrocarbon (HC) and carbon monoxide (CO) emissions [3], control of combustion timing [4] and a weak cold-start capability. Misfire and knock are the two limiting factors for operation of ethanol fuelled HCCI engines.

Delayed combustion which was acquired by decreasing intake temperatures makes unstable combustion with misfire and partial burn in HCCI engine [5]. Misfire is lack of combustion which makes raw fuel inters into the exhaust system and has a cooling effect on exhaust after-treatment systems [6] that result in production high HC and CO [7]. In case of in-cylinder misfire occurrence, pollutant levels may be produced by engine which go above the emission standard. Real time performance monitoring of the exhaust gas emission control system and engine misfires detection are very essential due to onboard diagnosis (OBDII) system rules. Thus, engine diagnostic systems should be developed for monitoring and detecting misfire continuously. For several decades, fault diagnosis system has developed for ICES which can have the huge economic benefit.

Many researchers focused on setting up the systems for misfires recognition. In-cylinder pressure is an obvious parameter and provides consistent quantity for misfire recognition [8]. Failure in combustion makes engine to run like motoring that in this case IMEP becomes negative [9, 10]. Another way that is suitable alternative to in-cylinder pressure is using ionization current measurement that misfire can detect depends on ions concentration in the electrodes gap [11]. Lack of combustion causes fluctuation in engine speed which can be recognized by using crankshaft position sensor [12, 13]. During misfire event, oxygen concentration becomes high in exhaust manifold, thus measuring exhaust gas temperature and oxygen concentration is another way to misfire detection [14]. In this article, in-cylinder pressure data were used to detect misfire. The data for the whole in-cylinder pressure trace is needed for determining IMEP. But, the new ANN model from this work requires only five values of the pressure data to predict IMEP, compared to a large amount of data required. The new ANN model stemming from our work is intended for HCCI misfire detection.

To the best of the authors' knowledge, this study is the first study undertaken to develop a misfire detection technique for HCCI engines. The paper is presented as follows. Section 2 describes the engine experimental set-up for this study. In section 3,the effect of misfire on HCCI engine operation is investigated and new ANN model is developed with experimental data. Finally, the summary and conclusions from this work are presented in Section 4.

2 Experimental Engine Setup

A single-cylinder, four-stroke, naturally-aspirated, air-cooled, direct injection diesel engine was modified for HCCI operation using ethanol fuel. The specifications of this engine are listed in Table 1.

Table 1: Yanmar L70AE engine model specifications.

Parameter (units)	Value
Bore (mm)	78
Stroke (mm)	62
Compression ratio	19.5
Displacement (lit)	0.296
Number of valves	2
Intake valve opening (CAD aBDC)	155
Intake valve closing (CAD aBDC)	59
Exhaust valve opening (CAD aBDC)	-59
Exhaust valve closing (CAD aBDC)	-155

2.1 Instrumentation

Schematic of the engine setup is shown in Fig. 1. A 30 kW Magtrol eddy-current brake dynamometer was used to adjust the engine speed and load. In addition, a Crompton Parkinson AC electric drive motor with 22kW power was coupled to a Yanmar engine for engine motoring. The engine is first run in diesel mode and is then switched to HCCI once the condition is ready. To facilitate HCCI operation, a fuel premixing and heating system was added to the intake manifold. The preheating system used a 3 kW electric heater which was placed upstream of the intake manifold. A DEWE-5000 data acquisition system and DEWECa software were used for data logging.

A water cooled piezoelectric pressure transducer (Kistler 601 A) was placed inside the engine cylinder head to measure in-cylinder pressure with 0.2° CAD resolution. A crank angle encoder (Kistler 2613B) was coupled to the crankshaft to measure crank angle degree (CAD). Exhaust and intake temperatures were measured with a K-type thermocouple with an accuracy of ±1.5°C.

2.2 Misfire definition

In this study, a cycle is considered a misfire cycle when its IMEP is negative [9, 10]. A cycle is considered a partial-burn cycle if its heat release is reduced by 10% or more compared to a well-burning cycle. Fig. 2 shows operating regions, normal, partial burn and misfire, for 25 cycles. Also in-cylinder pressures at 0, 5, 10, 15 and 20 CAD aTDC (P_0, P_5, P_{10}, P_{15} and P_{20}) are presented.

2.3 Misfire generation

It is very practical to generate misfire by skipping spark [15] or cutting fuel [16] in ICE misfire detection studies. However, misfires can be produced with different mechanisms in an HCCI engine. In this work, three types of misfires are generated:

I) Low temperature (Fig. 2),

II) High dilution (ultra lean air-fuel mixture),

III) Fuel cut off (artificial misfire, Fig. 3).

By reducing the intake temperature (T_{in}), the reactivity of air-fuel mixture significantly decreases. Since, HCCI is very sensitive to the temperature of the air-fuel mixture, misfires will occur once the T_{in} is not sufficient to support a normal/partial burn HCCI combustion.

Misfires type-II are generated with decreasing equivalence ratio (Φ) due to reduction in amount of heat released from the air-fuel mixture.

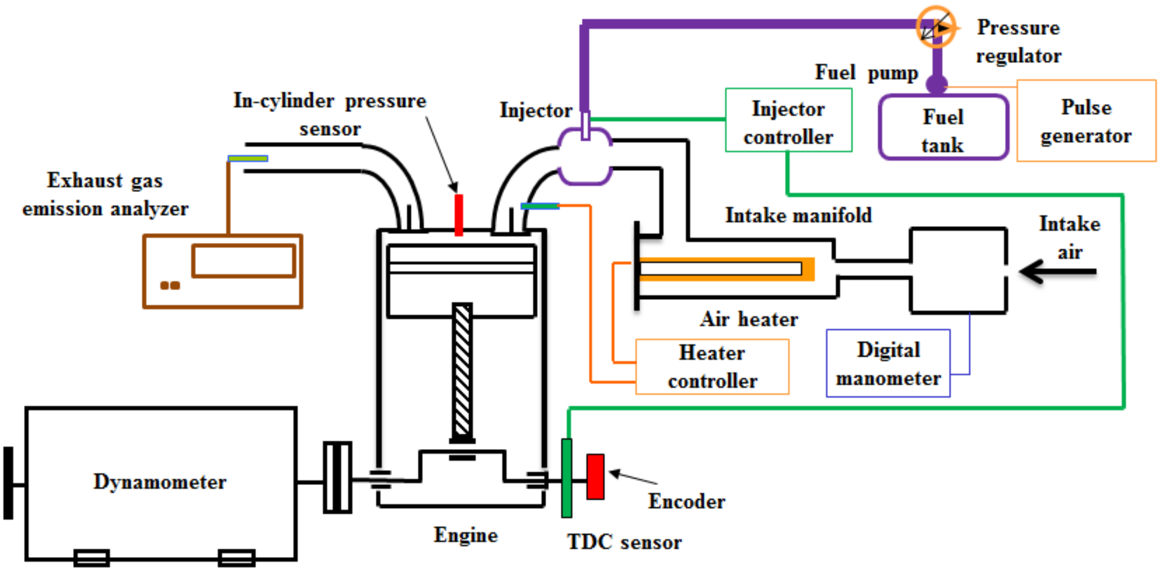

Fig. 1: Schematic of the experimental setup used to collect HCCI data.

For category (III), here, an electric circuit pulse generator was designed to periodically turn the fuel pump relay on-off, thus misfire could be generated artificially by reducing the quantity of injected fuel.

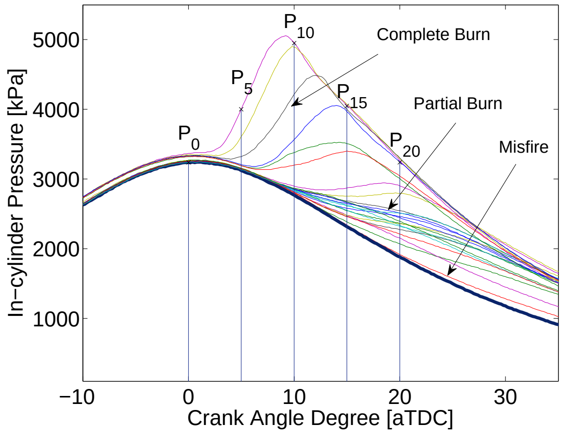

Fig. 2: In-cylinder pressure trace versus crank angle degree for complete burn, partial burn and misfire cycles.

3 Experimental Results and Discussion

In this section, the collected experimental data is analyzed to understand how misfire affects HCCI engine parameters. In particular, the relation between misfire and IMEP which will be used later to design an ANN model to predict IMEP as well as misfire.

3.1 Misfire in HCCI engine

Misfires can be produced by air-fuel ratio fluctuation, causing cycle variability in an engine. In this study, artificial misfires are generated by employing one pulse generator which controled fuel pump relay to adjust the quality of injected fuel. Fig. 3(a) shows the normal and misfire cycles index, in which zero and one represent normal (non-misfire) and misfire cycles respectively. Fig. 3(b) indicates that the variation of and maximum in-cylinder pressure (P_{max}) follow the same trend of misfire. Fig. 3(c) shows engine speed fluctuations during misfire due to lack of engine torque during misfire cycles.

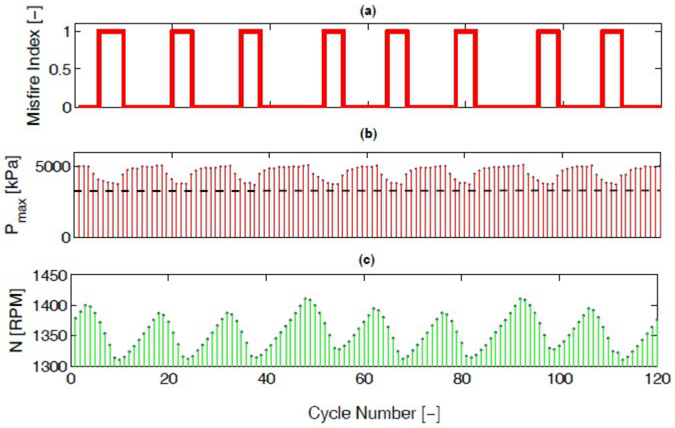

Fig. 3: Variation of maximum in-cylinder pressure and engine speed during 120 consecutive cycles with periodic artificial misfire. (N=1400 RPM, Φ=0.25→0→0.25 and T_{in}=145°C)

Fig. 4 (a) shows the effect of T_{in} on in-cylinder pressure profile. As T_{in} decreases, P_{max} also decreases which result in unstable combustion for too low T_{in}. An internal combustion engine gains its energy from the heat released during the combustion of air-fuel mixture.

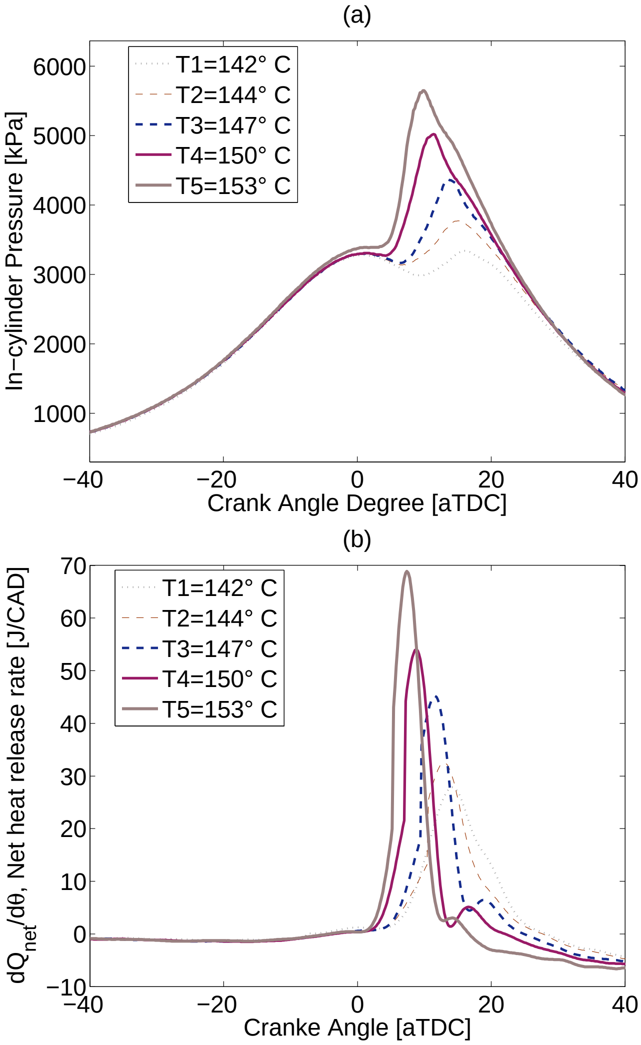

Fig. 4: Variation of in-cylinder pressure and net heat release rate versus crank angle degree. (N=1350 RPM and Φ=0.34)

Fig. 4(b) shows the net heat release rate at different T_{in} for ethanol HCCI combustion that indicates with decreasing T_{in}, net heat release rate declines due to low combustion temperature also in-cylinder gas temperature declines due to delayed combustion since the temperature of the combustion chamber decreases as the piston goes down through the expansion stroke.

3.2 Misfire identification based on ANN

Artificial neural network (ANN) is a well recognized method for modeling complex systems such as combustion systems [17]. ANN have been previously used to detect misfires in SI engines. Wu and Lee (1998) used an artificial neural network to develop a crankshaft speed fluctuation model for misfire detection in a four cylinder engine. Their results indicated that their model could detect misfires with over 98% accuracy [18]. Nareid and Lightowler (2004) used a crankshaft angular acceleration measurement to develop a hardware neural network to detect misfires [19].

P_0, P_5, P_{10}, P_{15} and P_{20} are well correlated with misfire event. Here, an ANN is designed to predict IMEP using P_0, P_5, P_{10}, P_{15} and P_{20} as the main inputs (Fig. 5) for identification misfire.

The number of hidden layers and neurons within each layer are designed by the complexity of the problem and data set. In this study, the designed ANN has two hidden layers with 10 neurons. The output of the ANN model is IMEP. ANN training is carried out through feedforward back propagation algorithm. The TRAINLM function (Levenberg-Marquardt algorithm) is used for the training and adaptation learning. Experimental data at misfiring and normal firing conditions are used for the training and testing of the ANN model.

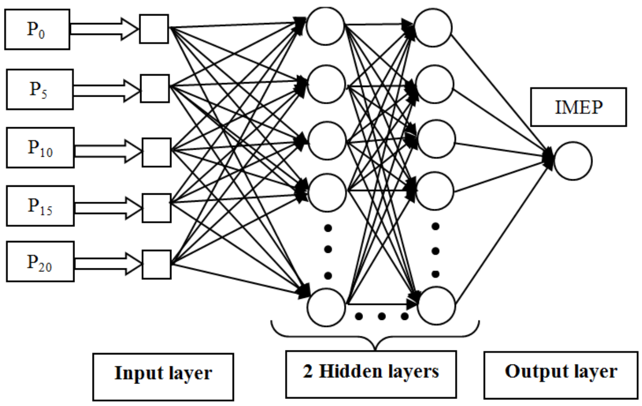

Fig. 5: Structure of the IMEP prediction ANN model.

40 different operating points are used for this study (Speed=1350 RPM, Φ=0.26-0.36 and T_{in}=140-155°C). 100 cycles (Mixed misfire and non-misfire cycles) are randomly selected and used to train and validate the ANN model.

The results in Fig. 6 indicate that the ANN model captures the trend of IMEP variations and shows good agreement with the experimental measurements. The model can predict HCCI IMEP with a correlation coefficient R^2=0.94 for the 70 testing data points which were not used for training. Comparisons of the experimental results and the model predictions demonstrate that IMEP in the ethanol HCCI engine can be accurately simulated by the designed ANN model.

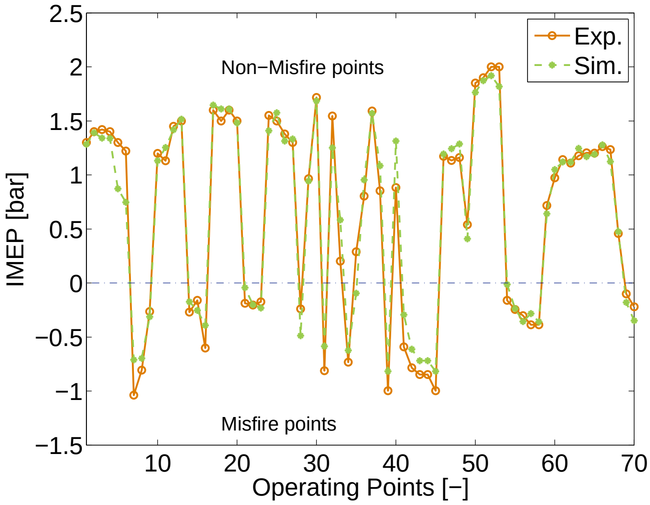

Fig. 6: Comparison between simulated (Sim.) and experimental (Exp.) IMEP for 70 testing data points at a range of HCCI operating conditions.

The points with $IMEP < 0$ are misfire which is separated from non-misfire cycle in Fig. 6 and identified in Fig. 7. The diagnosis technique for misfire identification is shown in Fig. 7 which normal and misfire cycles index, in which zero and one represent normal (non-misfire) and misfire cycles respectively.

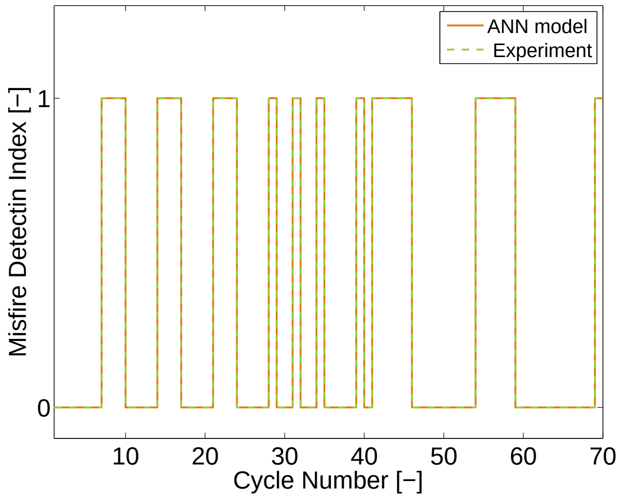

Fig. 7: Performance of the misfire detection model to identify misfire.

4 Conclusion

HCCI misfire was investigated in a single-cylinder HCCI engine fuelled with ethanol. HCCI operation parameters during misfire is studied with collected experimental data from HCCI engine. The designed electric pulse generator produced artificial misfire stressfully with periodically turn the fuel pump relay on-off. Analysis of experimental data was used to design an ANN model to predict IMEP in the HCCI engine. The new ANN model from this work was verified with experimental data including with a wide range of misfire and normal cyclic data. The verification results indicated that the ANN model can predict IMEP with an average less than 0.1 bar. The diagnosis technique for misfire identification could successfully detect HCCI misfire.

References:

[1] R. Stanglmaier and C. Roberts, Homogeneous charge compression ignition (HCCI): benefits, compromises and future engine applications, *SAE Paper* 1999-01-3682; 1999.

[2] M. Christensen, B. Johansson and P.Einewall, Homogeneous charge compression ignition (HCCI) using isooctane, ethanol and natural gas a comparison with spark ignition operation. *SAE Paper* 972874; 1997.

[3] M. Shahbakhti, A. Ghazimirsaied and C.R. Koch, Experimental study of exhaust temperature variation in a homogeneous charge compression ignition engine, *J. Automobile Eng*. 224 (2010) 1177-97.

[4] M. Shahbakhti and C.R. Koch, Characterizing the cyclic variability of ignition timing in a homogeneous charge compression ignition engine fuelled with n-heptane/iso-octane blend fuels, *Int J Engine Res*. 9 (2008) 361-439 397.

[5] B. Bahri, A.A. Aziz, M. Shahbakhti and M.F. Muhamad Said, Misfire detection based on statistical analysis for an ethanol fueled HCCI engine, *IREME*. 6(2012), 1276-82.

[6] W. Ribbens and J. Park, Road Tests of a Misfire Detection System, *SAE Paper* 940975, 1994.

[7] P.Azzoni, D. Moro, C.M. Porceddu-cilione and G. Rizzoni, Misfire Detection in a High-Performance Engine by the Principal Component Analysis Approach, *SAE Paper* 960622, 1996.

[8] M. Komachiya, N. Kurihara, A. Kodama, T. Sakaguchi, T.Fumino and S.Watanabe, A Method of Misfire Detection by Superposing Outputs of Combustion Pressure Sensors, *SAE Paper* 982588, 1998.

[9] J. Heywood, *Internal combustion engine fundamentals*, McGraw Hill, New York, 1988.

[10] B. Peterson, D. L. Reuss and V. Sick .High-speed imaging analysis of misfires in a spray-guided direct injection engine. *Proc Combust Inst*, 2011;33:3089-96.

[11] K.Yoshimura, Y. Tokunaga, D. Hashimoto and H. Sakurai, Knock and Misfire Detection using Ion Current Measurement for Ultra Lean Burn Medium Speed Gas Engine, *SAE Paper* 2007-01-2078, 2007.

[12] G. Rizzoni, Fast Transforms for Rapid Isolation of Misfiring Cylinders, *SAE Paper* 871915, 1987.

[13] D. Moro, P. Azzoni and G. Minelly. Misfire pattern recognition in high-performance SI 12-cylinder engine, *SAE Paper* 980521.

[14] Y. Chung, C. Bae, S. Choi and K.Yoon, Application of a Wide Range Oxygen Sensor for the Misfire Detection , *SAE Paper* 1999-01-1485, 1999

[15] M. Tamura, H. Saito, Y. Murata, K. Kokubu and S. Morimoto, Misfire detection on internal combustion engines using exhaust gas temperature with low sampling rate, *Appl Therm Eng* 2011;31:4125-31.

[16] A.W. Osburn, T.M. Kostek and M.A. Franchek, Residual generation and statistical pattern recognition for engine misfire diagnostics, *Mech Syst Signal Pr*. 2006;20:2232-58.

[17] B. Bahri, A.A. Aziz, M. Shahbakhti, M.F. Muhamad Said, Artificial neural network model for predicting exhaust temperature of an ethanol-fuelled HCCI engine, *JSAE Paper*: 20125168, 2012.

[18] Z. Wu and A. Lee, Misfire detection using a dynamic neural network with output feedback. *SAE Paper* 980515; 1998.

[19] H. Nareid and N. Lightowler, Detection of engine misfire events using an artificial neural network. *SAE Paper* 2004-01-1363; 2004.