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Research Article

USING THREE-INPUT THREE-OUTPUT TO COTROL A BLENDED FUEL HCCI ENGINE

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ABSTRACT
Main challenges in development of Homogeneous Charge Compression Ignition (HCCI) engines are simultaneous control of three parameters; combustion phasing, power output and emissions. It is obvious that emissions are directly related to exhaust gas temperature (T_{exh}). Consequently controlling exhaust gas temperature can lead to emissions control. In the present work, a physic based control model is developed to control the engine power output, combustion phasing and exhaust gas temperature. Furthermore a dynamic control model has been developed to predict combustion phasing, Indicated Mean Effective Pressure (IMEP) and T_{exh} in HCCI engine doing full cycle. The results of developed model are validated for the two set of transient experimental data available for a single cylinder Ricardo engine. The mentioned model well predicts the crank angle at which 50% of in cylinder fuel mass is burned (CA50), IMEP and T_{exh} . A three-input three-output controller is then designed to track CA50, IMEP and T_{exh} by adjusting the fuel rate, fuel equivalence ratio (ϕ) and Octane Number (ON). The performance of the developed controller is tested for a HCCI engine model to evaluate the tracking and disturbance rejection capabilities. Results show that the mentioned controller is capable to accurately track CA50, IMEP and T_{exh} while can reject the disturbances due to engine speed and intake manifold temperature variations.

Keywords: *HCCI Engine Control, Three Input Three Output Controller, IMEP & Emissions Control*

INTRODUCTION
Homogeneous charge compression ignition (HCCI) has benefits of both Otto and diesel cycles. The main advantages of HCCI combustion are no throttling losses, lower combustion temperature and then reduced Nitrogen Oxides (NOx) and particulate matter emissions (Zhao, 2007). On the other hand, lower combustion temperature in HCCI engines increases the unburned hydrocarbon (HC) and carbon monoxide (CO) emissions (Shahbakhti *et al.,* 2010). The combustion in HCCI engine is controlled by auto-ignition of mixture having certain charge properties. Studies show that mixture properties significantly influence combustion phasing, power output and emissions (Delmar, 2003; Verheul *et al.,* 2004). It is known that some engine variables have more effect on the HCCI engine outputs. Experimental studies reveal that emissions are directly related to exhaust gas temperature (Shahbakhti *et al.,* 2010). They show that higher HC and CO emissions are observed at lower T_{exh} and high combustion temperature results in high NOx emission but low CO and HC emissions. It means that the HCCI engines emission problems is related to exhaust gas temperature.
The combustion initiation in a HCCI engine is the most significant parameter that should be controlled. Due to very high sensitivity of initiation of combustion to variations of charge properties CA50 control is the most challenging issue in HCCI engines (Lu *et al.,* 2005; Shahbakhti *et al.,* 2008).
The combustion initiation in HCCI engine is achieved by modifying engine charge properties during intake and compression stroke as main strategy to control CA50. These are several accepted methods to control the combustion phasing in HCCI engine: controlling the amount of residual gas trapped in the cylinder due to internal EGR (Shaver, 2006; shaver 2009), controlling effective compression ratio by means of variable valve timing or actuation (Bengtsoon *et al.,* 2007; Ravi *et al.,* 2010), controlling and regulating the intake manifold charge temperature prior to intake stroke (Widd *et al.,* 2012), controlling the blended fuel octane number (Audet *et al.,* 2009; Bidarvatan *et al.,* 2012; Bidarvatan *et al.,* 2013).
After controlling of combustion phasing which is the prime parameter, power output is the second most important parameter that should be controlled. Several studies has been carried out to control the

combustion phasing and power output simultaneously (Ravi *et al.*, 2010; Bidarvatan *et al.*, 2013). In the previous study (Bidarvatan *et al.*, 2013) ϕ has been considered as the input to control IMEP in an HCCI engine. But ϕ is a qualitative parameter and it is not an appropriate parameter to control IMEP. In a conventional SI engine the load or power output is controlled by amount of premixed charge where as in CI engine this is done by means of variation of fuel. The working principle of HCCI engine is the same as conventional reciprocating engines. Therefore, in order to control the HCCI power output; fuel intake or charge rate or both has to be controlled.

In present study fuel rate is taken as the main input parameter to control the IMEP. Consequently the airflow rate has been adjusted at the same time to keep phi constant, since fuel rate variation influences the phi for a constant airflow rate and therefore affects CA50. When there is a demand to change IMEP; to control CA50 an appropriate phi is selected from CA50-phi map. In fact, work output demand and selected phi from the map determine the fuel and airflow rate respectively.

Experimental study (Shahbakhti *et al.*, 2010) shows that exhaust gas temperature is a very good indicator of emissions composition and content so the T_{exh} control can lead to emissions control. In this study T_{exh} is representative of emissions. Experimental studies show that T_{exh} in the HCCI mode depends widely on the timing of initiation of combustion. Apart from CA50 which is influenced by T_{exh} there are other secondary factors such as heat loss, energy input and Burn Duration (BD) that should be taken into account. Also previous study shows that intake pressure and fuel ON could be the primary variables in which the location of CA50 is influenced by.

In present work fuel ON is taken as variable input that can easily be controlled to influence the T_{exh} sub-controller. The designed controller has three sub-controllers: CA50, IMEP and T_{exh} and three inputs: ϕ, FR and ON. The problem is the influences of any input variations on the other outputs. For instance, when the exhaust temperature varies its sub-controller changes the ON to regulate T_{exh} to achieve desired emission level. It is obvious that any ON variations affect the CA50. CA50 sub-controller compensates its advances or retards by ϕ variations. On the other hand for any change in CA50 its sub-controller adjust it by ϕ. Undoubtedly, equivalence ratio variations affect the exhaust gas temperature after that T_{exh} sub-controller regulates it by ON. These behaviors also are seen for IMEP variations. In fact, the influence of any input is considered as disturbance for other sub-controllers. Unlike a CI engine in present controller, the emissions can be removed in power demand phase. When there is a demand to change engine power in a CI engine, more fuel is injected into the cylinder therefore equivalence ratio increases and causes more emissions. In present controller, fuel and airflow rates vary at the same time to keep phi constant then this strategy removes the emissions in power demand phase in HCCI engines. In conventional engines, there is no system to control the emissions. Present work shows that a sub-controller can control the emissions. In brief, three main parameters of the HCCI engine can be controlled.

Control Model Design

To predict cycle-to-cycle variation of IMEP, CA50 and T_{exh} in an HCCI engine a control model has been developed. A multi zone thermodynamic model is developed to determine thermodynamic constants and predict exhaust gas temperature. Also a physics-based Control Oriented Model (COM) is developed to simulate the behavior of HCCI engine cycles.

Multi Zone Thermo-kinetic Model

In present study, a multi zone thermo-kinetic model has been developed to investigate the effects of some parameters such as; inlet temperature and pressure, equivalence ratio, ON, Exhaust Gas Recirculation (EGR) and engine speed on the exhaust gas temperature. By means of the thermo-kinetic model thermodynamic constant parameters in various processes of the engine cycle is determined. This model is coupled to a full kinetic mechanism of Primary Reference Fuels (PRFs-iso octane and normal heptanes). The Cantera, which is an open source module, is coupled to the developed model to use the full kinetic mechanism of PRFs and determine thermodynamic constant parameters of COM. The mentioned thermo-kinetic model is validated with a large number of experimental data taken from the Ricardo engine. The engine specifications are presented in table 1.

Table 1: Single cylinder Ricardo engine specifications

Parameter	Value
Bore	80 mm
Stroke	88.90 mm
Compression ratio	10:1
Displacement volume	0.447 Lit
Number of valves	4
IVO, IVC [aBDC]	-175/+55
EVO, EVC [aBDC]	-70/-175

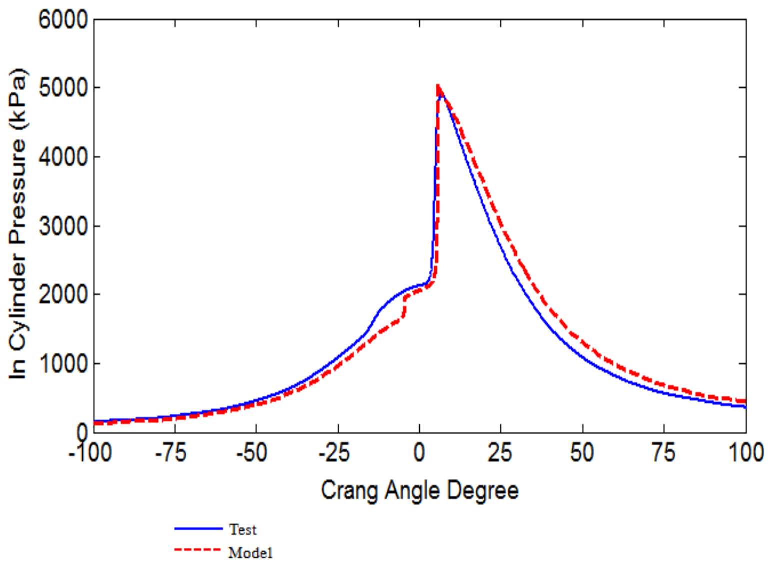

Figure 1: Comparison of pressure simulated and test No. 3

A typical predicted pressure histories derived by multi zone model and experimental results are shown in Figure 1 (Kirchen *et al.*, 2007). The simulated and experimental data are in good agreement. Also due to the effects of bulk temperature of zones on each other maximum pressure in multi zone model is smaller than that the one in single zone. In order to predict combustion parameters such as: BD, CA50 and P_{max} by means of simulation, the developed multi zone model should be validated. Table 2 shows experimental and simulation data for three different engine operating conditions that have been used to validate combustion parameters; Burn Duration (BD), CA50 and P_{max}. BD is defined as the crank angle duration where amount of 10% and 90% of in cylinder fuel mass is burnt. C°

$$BD = CA90 - CA10 \tag{1}$$

Table 2: Engine operating conditions

Test No.	ON (-)	N (rpm)	Phi (-)	EGR (%)	T_{man} °C	P_{man} (kPa)
1	0	800	0.63	8	106	95
2	20	1000	0.66	0	113	93
3	40	909	0.6	0	101	90

Figure 2 shows the comparison of simulated and experimental data in predicting combustion parameters: Maximum pressure, Burn Duration, combustion phasing and maximum error in predicting parameters are less than 12%.

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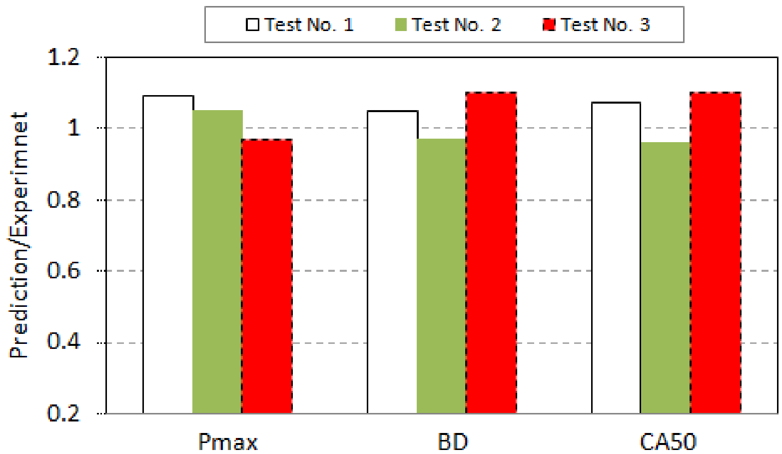

Figure 2: Comparison of simulated and experimental data in predicting parameters: P_{max}, BD and CA50

Experimental results show that three main parameters; the specific energy of fuel input (the quantitative parameter), CA50 (the position parameter) and BD (the dispersion parameter) can be selected to characterize exhaust gas temperature (Shahbakhti *et al*., 2010).

$$T_{exh} = f(BD, CA50, Q_{fuel}) \quad (2)$$

Engine speed and intake charge variables affected the exhaust gas temperature by influencing the three main mentioned parameters. Experimental results and present model show that T_{man}, P_{man} , ϕ, ON, EGR and engine speed are parameters affecting the HCCI combustion phasing and burn duration. Two correlations between BD and CA50 with relevant effective parameters is derived using a multi-zone thermodynamic model for a complete HCCI engine cycle,

$$BD = g(T_{man}, P_{man}, \phi, ON, rpm, EGR) \quad (3)$$

$$CA50 = h(T_{man}, P_{man}, \phi, ON, rpm, EGR) \quad (4)$$

In present study effects of mentioned parameters are investigated in detail and it shows that the multi zone model is capable to predict accurately and efficiently the CA50 and BD. The specific energy of fuel input q_{fuel} in terms of kJ/kg is determined as follows,

$$q_f = \frac{\phi \times LHV}{[\phi + 15]} \quad (5)$$

T_{exh} can easily be predicted using above correlations which signifies three influential parameters: q_f , CA50 and BD.

$$T_{exh} = \left[C_1 + C_2 \times q_f^{\ 1.2} + C_3 [ln(CA50)]^2\right].BD^{C_4} \quad (6)$$

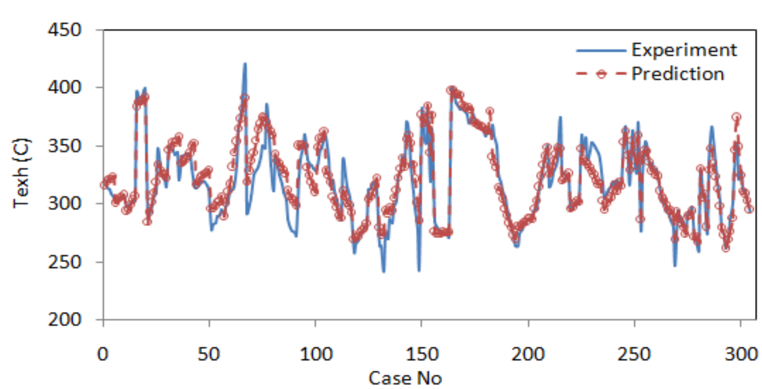

Figure 3: Comparison between predicted and experimental T_{exh}

Furthermore the Experimental data available (Shahbakhti *et al.*, 2010). is used to validate the above correlation for T_{exh} . Also constant factors are derived to be as $C_1 = 118.1$, $C_2 = 0.0151$, $C_3 = 8.9$ and $C_4 = 0.2$. In Figure 3, the predicted T_{exh} results from developed model are compared with experimental results available for HCCI engine at 304 operating conditions. The results signify accuracy of correlation. The thermodynamic constant parameters have been obtained by present model. The constant parameters: gas constant, specific heat capacity and specific heat capacity ratio are calculated for the processes of COM cycle and presented in table 3.

Table 3: Values of the COM's constant parameters

Parameter	Value
$C_{v,nc}$	0.779 kJ/kgK
$C_{v,rg}$	0.810 kJ/kgK
R_{evc}	0.286 kJ/kgK
k_c	1.361 [-]
k_e	1.272 [-]

2.1. HCCI Model

Closed cycle analysis from Intake Valve Closing (IVC) to Exhaust Valve Opening (EVO) for the single cylinder engine has been simulated based on physical governing equations.

2.1.1. *Assumption*

The three engine inputs are fuel flow rate (FR), ϕ and octane number ON also three outputs parameters are; IMEP, CA50 and T_{exh}. The physical state variables considered for HCCI engine modeling are as following;

- CA50
- Temperature at the Start Of Combustion (SOC),
- Pressure at SOC,
- Temperature of the trapped residual gases at EVC
- IMEP

2.1.2. *Thermodynamic Processes within Cycle*

- *Intake stroke thermodynamic states*

Combustion phasing strongly influenced by intake charge specification therefore the effective parameters should be considered in physical-based model. Temperature and pressure of the mixture could be derived using following empirical correlations (Bidarvatan *et al.*, 2013).

$$P_{ivc,k+1} = \left(\frac{N_k^{C_1} \phi_k^{C_2}}{T_{man,k}^{C_3}} \right) P_{man,k} \tag{7}$$

$$T_{ivc,k+1} = (aT_{man,k}^2 + bT_{man,k} + c) \frac{N_k^e \phi_k^f}{(1 + EGR)^g} \tag{8}$$

The fresh charge temperature is increased due to mixing with trapped residual gas;

$$T_{mix,k+1} = (1 - RGF_k) \frac{C_{v,nc}}{C_{v,t}} T_{ivc,k+1} + RGF_k \frac{C_{v,rg}}{C_{v,t}} T_{r,k} \tag{9}$$

- *Prediction of SOC and CA50*

Start of combustion (θ_{soc}) of certain cycle is calculated by dominant parameters of previous cycle. $\theta_{soc,k+1} = \frac{C_1 \times N_k}{(T_{ivc,k+1}^{0.43} \times \phi_k^{0.1})} + C_2 \times ON_k^{1.3} + C_3$ (10)

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The CA50 could be determined as follows;

$$CA50_{k+1} = \theta_{soc,k+1} + 0.5\Delta\theta_{comb,k+1} \tag{11}$$

- *Thermodynamic State of SOC*

Before the start of combustion, compression stroke can be assumed as isentropic process (Heywood, 1988) because there are no changes in chemical composition of the mixture.

Therefore, temperature and pressure of the mixture is predicted by poly-tropic relation $(PV^{k_c} = const.)$ where k_c is the specific heat capacity ratio;

$$T_{soc,k+1} = T_{mix,k+1}\left(\frac{V_{ivc}}{V_{soc,k+1}}\right)^{k_C - 1} \tag{12}$$

$$P_{soc,k+1} = P_{mix,k+1}\left(\frac{V_{ivc}}{V_{soc,k+1}}\right)^{k_C} \tag{13}$$

Where V_{ivc} and V_{soc} are in cylinder volumes at θ_{ivc} and θ_{soc} respectively which is calculated by slider crank mechanism (Heywood, 1988).

- *Thermodynamic State of EOC*

In cylinder gas temperature at the end of combustion is;

$$T_{eoc,k+1} = T_{soc,k+1} + \Delta T_{comb} \tag{14}$$

$$\Delta T_{comb} = \frac{LHV_{fuel} \times \overline{CoC}}{(1 + RGF_k)(AFR_{st} / \phi_k)\overline{C}_v} \tag{15}$$

Where AFR_{st} and $\overline{CoC}$ are the stoichiometric air-fuel ratio and the average completion of combustion respectively and LHV_{fuel} is the lower heating value of PRFs. Pressure at end of combustion using ideal gas law:

$$P_{eoc,k+1} = P_{soc,k+1}\left(\frac{V_{soc,k+1}}{V_{eoc,k+1}}\right)\left(\frac{T_{eoc,k+1}}{T_{soc,k+1}}\right) \tag{16}$$

- *Expansion Stroke*

The expansion of burned mixture is assumed to be isentropic processes:

$$T_{evo,k+1} = T_{eoc,k+1}\left(\frac{V_{eoc,k+1}}{V_{evo}}\right)^{ke-1} \tag{17}$$

$$P_{evo,k+1} = P_{eoc,k+1}\left(\frac{V_{eoc,k+1}}{V_{evo}}\right)^{ke} \tag{18}$$

where k_e is specific heat capacity and is obtained by the multi-zone model.

- *Exhaust Stroke*

During thermodynamic state of exhaust stroke; in-cylinder trapped residual gas temperature and its fraction could be coupled thermally for two consecutive engine cycles.

The residual gas of pervious cycle is mixed with fresh charge of a coming cycle and transfer parameters influences previous cycle. The residual gas temperature at EVC is determined by poly-tropic relation.

$$T_{r,k+1} = T_{evo,k+1}\left(\frac{V_{evo,k+1}}{V_{evc}}\right)^{ke-1} \tag{19}$$

- *Prediction of IMEP*

IMEP of any cycle is calculated by relevant parameters of previous cycle (Nazoktabar *et al.*, 2012).

$$IMEP_{k+1} = FR_k^{C_4}(C_1 \phi_k T_{ivc,k+1} + C_2 \phi_k + C_3) \tag{20}$$

- *Prediction of T_{exh}*

As mentioned before the exhaust gas temperature is correlated using relevant parameters and is determined as following:

$$(T_{exh})_{k+1} = f(T_{ivc,k+1}, P_{ivc,k+1}, \phi_k, ON_k, N_k, EGR_k) \quad (21)$$

2.2. Control Oriented Model

According to governing equations of the physical processes of present model, for any cycle the state variables and outputs are obtained as a function of model states (X) and input (u) of two successive cycles.

$$X_{k+1} = f(X_{k+1}, u_{i,k}) \quad (22)$$

$$y_k = g(X_k, u_{i,k}), i = 1,2\&3 \quad (23)$$

Where the state, input, output (y) and disturbance vectors (W) of the model are stated as follows:

$$X = [CA50\ T_{SOC}\ P_{SOC}\ T_{evc}\ \ IMEP]^T$$
$$y = [IMEP\ \ CA50\ \ T_{exh}]^T$$
$$u = [FR\ \phi\ \ ON]^T$$
$$W = [rpm\ T_{man}]^T \quad (24)$$

Temperature of residual gas is derived from two consecutive cycles of engine model.

2.3. Validation of Control Oriented Model

The COM is validated using experimental data available from Ricardo engine tests (Shahbakhti *et al.*, 2009).

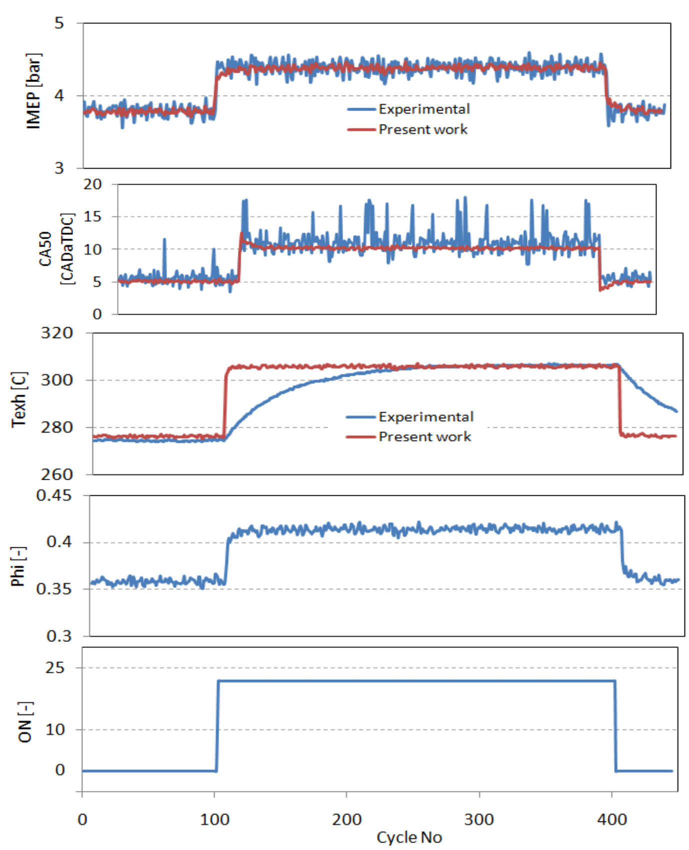

Figure 4: COM test results validation for a step change in ϕ and ON for 445 engine cycle

The performance validation has been carried out for transient operating conditions. The comparison is presented for step changes in ϕ and ON. The comparisons of developed COM for IMEP and CA50 with experimental data for 445 engine cycles are presented in Figure 4. There is a rather large difference between predicted and experimental exhaust gas temperature at initial step change in ϕ and ON. This difference is due to the delay response time of the thermocouple to a step change in measuring exhaust gas temperature (Dehghani *et al.,* 2013).
It is concluded that exhaust gas emissins control in an HCCI engine is far more efficient and more aplicable by predicting Texh through COM model rather than using data extrated from a thermocouple reading. Table 4 shows relevent engine operating conditions that are used to derive correlation (76) and conseqently COM.

Table 4: Engine operating conditions used for validating the COM

Parameter	Value
blending ratio of PRFs	0 to 40
Phi [-]	0.35-0.72
N [rpm]	800-1200
T_{man} [C]	60-160
P_{man} [kPa]	90-150
T_{exh} [C]	246-418

3. Controller Design
A three-input three-output controller is designed to control HCCI combustion phasing, engine power and exhaust gas temperature by adjusting fuel rate, fuel equivalence ratio and blending ratio of two PRFs. In this design, an air dynamic controller has been used to adjust ϕ based on fuel rate variation. It should be stated that the HCCI engine is not controlled by means of a throttle therefore excess air is provided by a boost pressure via a turbocharger or supercharger. In this study a discrete type of Proportional Integral Derivative (PID) controller is used for simultaneous control of IMEP, CA50 and T_{exh}. In addition, a Genetic Algorithm (GA) is used to optimize the PIDs parameters.
3.1. Controller Structure
In HCCI engine the variations of air and fuel mixture flow rate is used to adjust the output power demand (Nazoktabar *et al.,* 2012). In HCCI engine these changes has strong impact on CA50 if air fuel ratio is not adjusted accordingly. In this controller when there is a request for new IMEP setting; CA50 sub-controller selects an appropriate ϕ from CA50-ϕ map in the controller to track a desired trajectory. Based on the new ϕ from the map, air fuel ratio can be adjusted by air dynamic sub-controller. CA50-ϕ map is obtained by engine test data or by HCCI engine thermodynamic model.
For any variations of CA50 and IMEP exhaust gas temperature should be adjust based on its desired trajectory to minimize engine emissions. In T_{exh} sub-controller exhaust, gas temperature is controlled by adjusting ON. Both ON and ϕ are qualitative parameters and they affect CA50 and T_{exh} simultaneously. In fact the T_{exh} sub-controller changes the ON to control the exhaust temperature then change the CA50 position. On the other hand CA50 sub-controller compensates the ON effect on the CA50 by adjusting ϕ.
In present controller the parameter ϕ plays two distinct roles:
- To select appropriate CA50 by mapping to control according to needs of desired IMEP
- Through a PID controller to control CA50 that is to change ON together with other parameters variation

Adjustment of desired T_{exh} on the basis of minimum emissions is determined by engine test. In order to control the exhaust temperature, relationship between T_{exh} and some effective parameters such as; engine speed, ON, EGR, ϕ and intake manifold temperature - pressure should be determined. The required relation is determined by means of a multi zone thermodynamic model. Figure 5 shows the controller structure that control IMEP, CA50 and T_{exh} simultaneously. As mentioned before this controller is capable of controlling 3 outputs by adjusting 3 inputs. Fuel rate, ϕ and ON are three inputs. It should be noted that in order to control IMEP simultaneous control of fuel rate and air flow rate will be needed. So an air flow sub-controller has been considered to satisfy IMEP demand and regulate ϕ ensuring that the system stays away from sudden very lean or rich regions to ensure combustion stability.

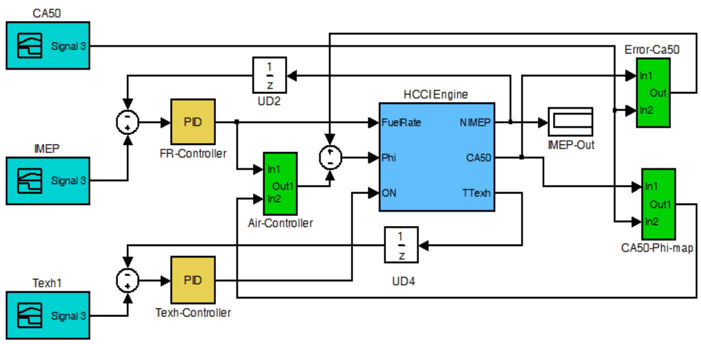

Figure 5: Brief controller layout

Based on a desired IMEP, fuel rate sub-controller changes according, therefore a constant air flow rate ϕ varies too. In order to adjust ϕ, air boost pressure controller is used to change the air flow rate. Clearly when the fuel is injected, air flow inlet does not respond immediately and therefore would be a lag which is considered by $(z/z-a)$ in z domain, a is defined as;

$$a = e^{-\tau.T} \tag{25}$$

Where τ is the time constant in which, is correlated with engine geometry and intake charge properties (Kiencke *et al.*, 2005);

$$\tau = \frac{P_{man} V_d}{k \; \dot{m}_{air} \; R T_{man}} \tag{26}$$

Where P_{man} and T_{man} are intake manifold pressure and temperature, k and R charge Ratio of specific heat capacity and gas constant, V_d volume displacement and $\dot{m}_{air}$ air mass flow rate respectively. For the present experimental setup on Ricardo engine τ varies from 0.12 to 0.18 second.

3.2. Genetic Algorithm to tune PID Controller

In most industrial automation Proportional Integral Derivative (PID) controllers are widely used due to their simplicity, low cost and ease of design. Also in this study, GA is used to optimize parameters of the PID controller. The Matlab Genetic Algorithm Toolbox is used to optimize PID controller parameters. The parameters of GA are shown in Table 5.

Table 5: The parameters of GA

Parameter	**Value**
Number of generations	40
Selection Method	Roulette Wheel
Elitism rate	0.025
Crossover type	Arithmetic
Crossover rate	0.7
Mutation rate	0.04

The Integral of the Squared Error (ISE) has been chosen as objective function to evaluate fitness of chromosomes:

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$$IAE = \int_{\tau_1}^{\tau_2} e(t)^2 \, dt \tag{20}$$

Where $e(t)$ is the error signal in time domain;

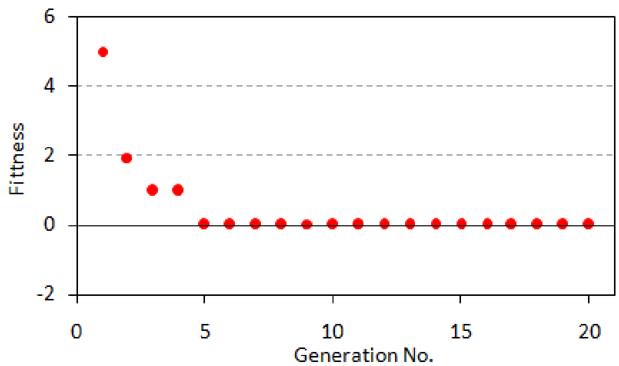

Figure 6: Fitness versus generation number

Figure 6 shows the fitness variation with generation number. It should be noted that generation numbers 1 to 5 are too large to show in the figure then the generation numbers 6 to 40 have been considered. This procedure has been done to determine parameters for all PIDs in the controller.

RESULTS AND DISCUSSION

Results

In this section, the tracking performance of the controller for step change in desired trajectory of three outputs is studied in detail.

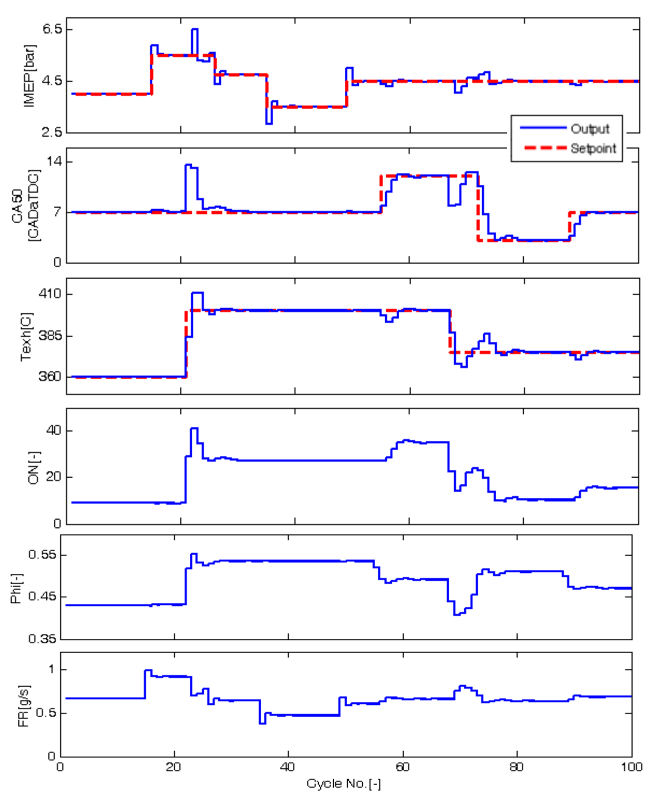

Figure 7: Single tracking performance for IMEP, CA50 and T_{exh}

The disturbance rejection properties of the controllers are shown for step changes in variable engine parameters such as; intake temperature- pressure and engine speed. The performance of the controller depends on some correlations in physical HCCI model that have been determined by test data or HCCI thermodynamic model. So the controller could accurately be tuned by the test data or HCCI thermo-kinetic models within engine operating.

Tracking Performance

Tracking performances of controller are investigated for a positive and negative step changes to meet a desired IMEP, CA50 and T_{exh}. Figure 7 show the tracking result when either IMEP or CA50 together with T_{exh} are changed. According to this figures the controller is capable of controlling T_{exh} and emissions for positive and negative step changes in desired IMEP and CA50.

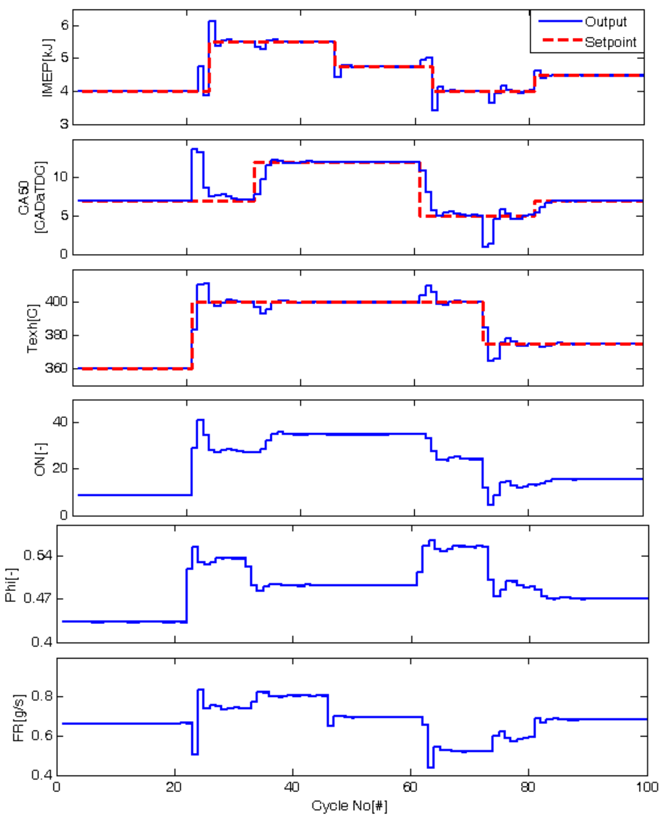

Figure 8: Simultaneous tracking performance of IMEP, CA50 and

Three simulation periods is considered to evaluate the controller tracking performance. Initially based on desired trajectory CA50 and T_{exh} are kept constant but IMEP varies in a step change. At this stage IMEP sub-controller regulates power output by adjusting FR. In this condition ON and ϕ two inputs remain constant because IMEP has less effect on CA50 and T_{exh}.

In the second stage simulation period immediately after a step change in T_{exh} both ON and ϕ vary simultaneously. In this condition T_{exh} sub-controller regulate exhaust gas temperature by ON. On the other hand ON variations have disturbance effects on CA50. Figure 7 shows that CA50 sub-controller can regulate combustion phasing and cancels the disturbance effects of ON variations on CA50 by adjusting ϕ. At third stage, simulation for IMEP is kept constant but both CA50 and T_{exh} varies in a step change. At first for a negative step change in T_{exh} ON decreases to regulate it. But ON variations change the CA50 position on the basis of set-point. So ϕ varies immediately and compensates ON disturbance effects on CA50.

Results shows that the controller can increase IMEP about 40% in positive step change and can decrease it around 35% in negative step change. Also CA50 can be increased more than 70% and decreased near 60% in positive and negative step change respectively.
The best way to evaluate the performance of the controller is to change the three mentioned inputs simultaneously. Figure 8 show the tracking results for simultaneous step changes in the desired IMEP, CA50 and T_{exh}. According to this figures IMEP and FR variations have less effect on the CA50 and T_{exh} but ON and T_{exh} compensate disturbance effects on each other. For a positive step change in T_{exh}, its sub-controller increase ON to regulate T_{exh} but ON variations influences CA50 then ϕ changes to regulate CA50. On the other hand for a step change in CA50, its sub-controller change ϕ to regulate combustion phasing, similar to previous condition ϕ variations affect T_{exh} in this situation T_{exh} adjust the ON to compensate ϕ effects.

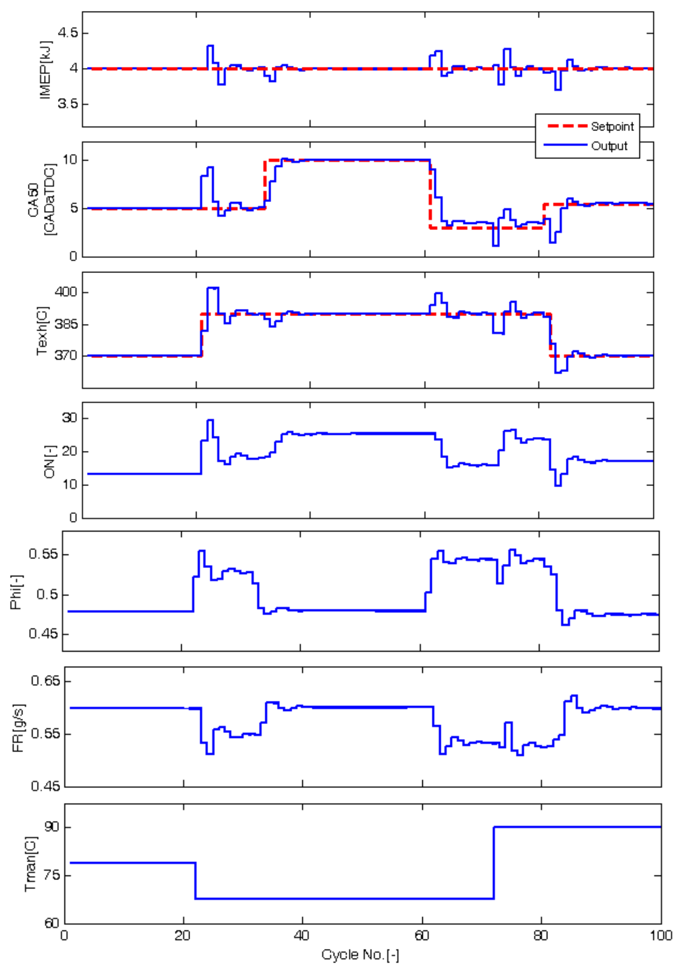

Figure 9: Disturbance rejection; intake temp. variation of (85-65-100 C)

Results show that the overshoot for CA50 sub-controller due to step change increase is about 10% and is rejected within next 3 engine cycles. The CA50 overshoot is related to the ON variations by T_{exh} sub-controller. According to figs. 7 and 8 this overshoot is damped by ϕ within only the next cycle. ON and ϕ variations affect the IMEP considerably but its sub-controller regulate IMEP by decreasing FR. For a desired step changes in CA50 its sub-controller selects an appropriate ϕ to regulate CA50 variations. Clearly, ϕ variations affect the fuel and airflow rate simultaneously and then influence the IMEP as a result. On the other hand, no overshoot is observed for CA50 despite step changes of IMEP because CA50 sub-controller immediately selects an appropriate ϕ referring to CA50-ϕ map.

Table 6 shows the performance analysis for tracking and regulation of the three IMEP, CA50 and T_{exh} sub-controllers. According to figure 8 no steady state error has been observed for tracking of the three outputs.

Table 6: Tracking performance analysis for IMEP, CA50 and Texh sub-controller

Performance	Sub-Controllers		
	Texh	**CA50**	**IMEP**
Rise Time	2cycle	1cycle	1cycle
Max. Overshoot	11C	0.2CAD	0.38bar
Steady State Error	0 C	0 CAD	0 bar
Cycles for Regulation	4cycle	4cycle	2cycle

Overshoot is observed in control of IMEP and T_{exh} but overshoot for step change in CA50 is negligible. According to these results present controller is capable of tracking IMEP, CA50 and T_{exh} within four engine cycles.

Disturbance Rejection Performance

The variations in engine speed and intake temperature are used as source of disturbances to evaluate performance of the controller.

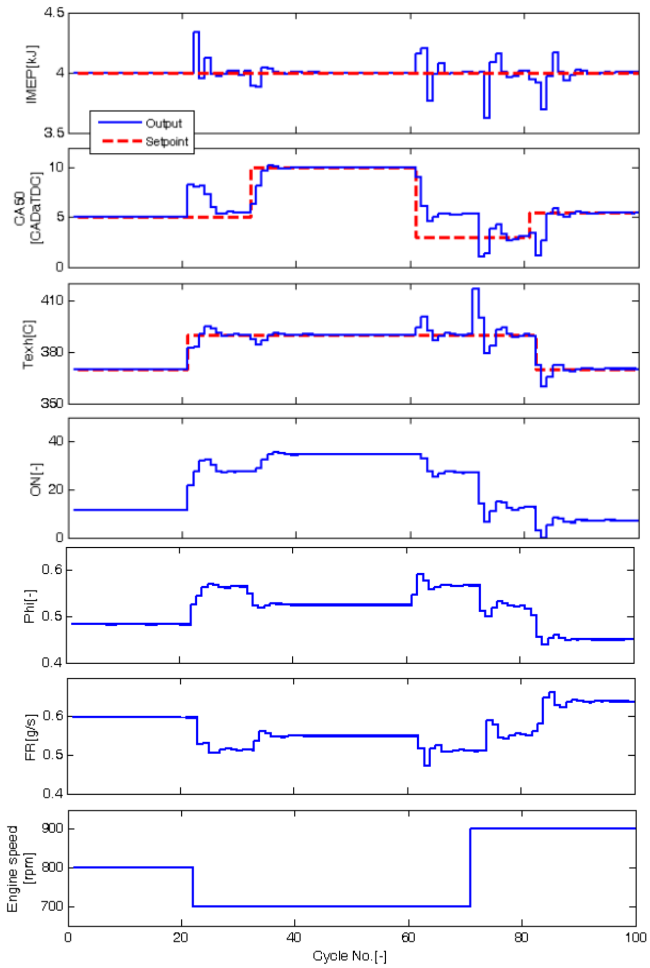

Figure 10: Disturbance rejection for speed variation (800-700-900 rpm)

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Ricardo engine experimental data (Shahbakhti *et al.*, 2010) is used to set the constant point. Figures 9 and 10 shows the performance of the step disturbances rejection of the controller.

According to these figures step change for disturbances and T_{exh} happens at the same time. In figure 9 for intake temperature variations as disturbance, T_{exh} sub-controller decreases ON in comparison to tracking performance without disturbances in figure 8. In fact the disturbance effect is compensated by ON variations.

Engine speed affects on CA50 are much more than intake temperature so the controller should change the ϕ and ON far more when there is variation in engine speed. The behavior of outputs and inputs of the two mentioned disturbances are similar. Because both disturbances have negative step change and retard the CA50.

In figure 9 for a positive step change in intake temperature CA50 advances consequently phi decreases to overcome the intake temperature effect. Variations in phi, affect the exhaust gas temperature and then ON sub-controller decreases ON to compensate T_{exh} variations.

Figure 10 shows a positive step change in engine speed effects on CA50 and T_{exh} in two consequent cycles. The CA50 and T_{exh} sub-controllers change the ϕ and ON respectively to compensate the mentioned effects. Table 7 shows the maximum absolute deviations from set value and number of engine cycles needed to minimize the output. According to two disturbance conditions the present model-based controller can stabilizes the output within 3-4 engine cycles. Maximum deviation is about 0.4, 3 and 20 for IMEP, CA50 and T_{exh} respectively.

Table 7: Performance of disturbance rejection of IMEP, CA50 and Texh sub-controller

Dist.	Control output	Max. absolute deviation	Rejection speed [cycle]
T_{man}	IMEP[bar]	0.3	2
	CA50 [aTDC]	2	3
	Texh [C]	10	3
Speed	IMEP[bar]	0.4	3
	CA50 [aTDC]	3	4
	Texh [C]	20	4

Discussion

In the present work, a physics-based COM is developed to simulate the cycle processes within any HCCI engine. The mentioned model has been setup with physical governing equations and some correlations such as; IMEP, SOC and T_{exh} which models the physical behavior of a HCCI engine. These correlations are determined by means of engine test data and HCCI thermodynamic model. The COM is validated using experimental data at steady state and transient operating conditions. Based on experimental data and multi zone model results; IMEP and T_{exh} strongly depends on fuel rate and ON respectively. Therefore Fuel rate and ON have been considered the main parameter to control the engine work output and exhaust gas temperature respectively. The COM uses sub-controllers to control simultaneously three main HCCI engine parameters such as: CA50, IMEP and T_{exh}. Three main inputs are fuel rate, phi and ON and air flow rate is the forth input that control IMEP and phi at the same time. Results show that the controller can track desired cycle-to-cycle CA50, IMEP and T_{exh}. In order to evaluate the capability of the controller simultaneous changes in desired parameters have been considered. The controller is a model-based HCCI engine controller with a feed-forward integral controller. No steady state error is observed in mode control of CA50, IMEP and T_{exh} variations. In addition, the controller is capable of regulating and tracking the desired outputs in less than 4 cycles. Physical disturbances such as; engine speed and intake manifold temperature step changes has been considered to evaluate performance of the controller. Results show that the controller is capable of rejecting the disturbances despite the desired CA50 and T_{exh} variations. In addition, the controller can reject these disturbances within 2 to 4 engine cycles, while deviations within 0.4bar, 3CAD and 20K.

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