

# Determining Appropriate Operating Conditions of a Homogeneous Charge Compression Ignition Engine

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## Abstract

**Background:** Through the last decade, an alternative combustion technology has been introduced as a homogeneous-charge compression-ignition (HCCI). **Methods:** A single-cylinder HCCI engine with compression ratio of 12.5 and iso-octane fuel is simulated using CFD and AVL Fire software, variable RPM and equivalence ratios, k-zeta-f turbulence model, eddy breakup combustion, wave atomization spray, and evaporation drops. **Results:** The engine can be coupled with a generator and adjusted to operate optimally under certain conditions and parameters for high efficiency and low emissions. The best performance of the engine is recommended at 3000 rpm and 50% load and equivalence ratio of 0.6. **Conclusion:** These figures are based on the calculation of pressure and temperature in the cylinder chamber, specific fuel consumption and mean effective pressure. The NO<sub>x</sub> emission is compared to the 6-point emission standard of Japan as well as the environmental and economic limitations.

**Keywords:** Homogeneous Charge Compression Ignition (HCCI), Optimized performance

## 1. Introduction

During last decades, an alternative combustion technology with Homogeneous Charge Compression Engines (HCCI) is known to reach higher efficiency compared with petrol engines, and their efficiency is close to that of diesel engines, and also they produce half or less of NO<sub>x</sub>. The advantages of HCCI engine motivated scientists to fix its flaws; one flaw is undesirable performance of HCCI motor in high loads and speeds. So, HCCI motor is a suitable choice for electrical hybrid vehicles. In hybrid vehicle, two or more energy sources are used to produce power, having parallel and classified combinative structures. In these vehicles, there is a need for combustion engine to work in a limited interval of speed and load. So, there is no need to fix the flaws of HCCI engine in high rounds because combustion engine is not practically placed in this field. Hybrid vehicles provide us with advantages of electrical and combustion vehicles. Hence, it is possible to design a vehicle with low pollution and suitable accelerating power through this method.

In these engines, as in spark ignition engine, fuel and air are mixed before ignition. Mixing is done in either internal system to cylinder or inside the cylinder. Spark ignition system is not used to start the ignition in this ignition method; rather the mixture of fuel and air are compressed to produce the primary energy of combustion by rising the temperature of the pre-reactions. In the final stages of compression, combustion starts in several places inside the cylinder simultaneously by auto ignition phenomenon.

Although the phenomenon of auto-ignition has along enough lifespan like gasoline engines, the first works in the field of controlled auto-ignition phenomenon, as an independent phenomenon in igniting the fuel in the engine, can be attributed<sup>1,2</sup>. The potentialities type of engine in reducing fuel consumption and emissions has led the research on the four-stroke engine type by<sup>3</sup>. Tearing continued the work and examined the effect of exhaust gas recirculation and the air-fuel ratio the efficiency of these engines<sup>4</sup>. In<sup>5</sup> showed for the first time that a 4-cylinder gasoline engine that uses the auto-ignition combustion system, using a

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higher compression ratio and intake air-heating, can operate at a limited speed and load range. The crucial works with respect to the use of controlled auto-ignition operation in four-stroke gasoline engines were performed in Europe 2000.

In 2010, the fuel consumption was studied for different forms of power transmission for HCCI engine from conventional to hybrid electric vehicle (HEV) and plug in HEV (PHEV) in two kinds of standard driving cycle and real world drive cycle (RWDC) for one complete single cylinder with the capacity of 2 liters. The results showed 10 to 15% decrease of fuel consumption for different kinds of hybrid vehicles in auto cycle and positive effect in fuel consumption when the vehicle operates engine in HCCI mode<sup>6</sup>. In 2012, the operation of HCCI technology was considered in one crossover van with hybrid powertrain. According to the hypothesis, the result showed average decrease of 2.55% of fuel consumption in US06 cycle and average decrease of 5% of fuel consumption in FTP-75 cycle relative to normal powertrain<sup>7</sup>.

Considering these results and improvement of fuel consumption in using HCCI engine in hybrid vehicle and taking the pressure and temperature of cylinder and released heat into account, its possibility is used in hybrid vehicle should be examined. In case of achieving a positive response, intervals operating better should be determined. So, an electric hybrid vehicle is considered with the engine ability of a vehicle, suitable fuel consumption and electric engine, and a HCCI is stimulated for it, using AVL Fire software and computational fluid dynamics method. Effective parameters are considered for more intervals and less pollution.

## 2. Dominant Equations and Models on Issue

We used  $k$ - $\epsilon$ - $f$  model to stimulate turbulence flow. This model was developed based on camera model<sup>8,9</sup>. A model<sup>10</sup> is used in the current study. It is assumed that when confused flames are being formed, reactants (mixture of fuel and air) contain the same eddies and are separated from combustion products having special eddies. Model in<sup>11</sup> is used to transmit heat and evaporation, suggesting that transmitted thermal energy to the drop increases its temperature and makes it vaporize<sup>11</sup>. To model distribution and emission of jet fuel droplets, wave model is used. It is supposed that there are spectra of sine waves

with swing pivot infinitesimal on the surface of jet fuel due to turbulence flow in the injector nozzlehole<sup>12</sup>. To predict the fuel droplets splashing the walls, in<sup>13</sup> the model is presented. It is supposed that when engine is working, a layer of steam is formed between droplets and the wall, and depending on the drop number ( $We$ ), the droplets return or slip on the wall<sup>13</sup>.

Thermal NO is formed behind flames and between hot burnt gases, and its two-stage mechanism was first presented in<sup>14</sup>. AVL Fire software applies discrete finite volume method to solve dominant equations on the flow based on integral expression of survival for desired control volume. The coordinate system applied is Cartesian coordinate system vector and tensor components are expressed according to Cartesian terms<sup>15</sup>.

## 3. Modeling using AVL FIRE Software

To make a three-dimensional model net, at first, two-dimensional net is produced. It is used in the loose part between piston and cylinder head from the organized network and in the piston bowl cavity from unorganized network. Since the number of injector nozzle holes is four, the built net is drawn 90 degree around the vertical axis of the cylinder, and three-dimensional nets with hexahedron structure are made. The number of net divisions in the angular direction is 27, and a network boundary layer is considered in two rows. Computational step starts from closing the intake valve and continues to opening of the exhaust valve. At this part, a single cylinder of HCCI engine with natural air taking, 0.5 liter volume, compression ratio of 12.5 1000 to 3500 RPM, and ISO octane fuel with equivalence ratio of less than 1 is simulated which is considered by Michigan University for a hybrid vehicle based on 2010 model regarding fuel consumption, as a suitable engine for a hybrid vehicle in the form of CFD in AVL Fire software. The characteristics of hybrid vehicle and main engine are presented in Tables 1 and 2<sup>16</sup>.

**Table 1.** Specification of hybrid vehicle

Architectures	Power-split
Electric machine	14 kW peak, PM
Battery	Li-ion 6 Ah 144V
Mass	1476–1580 kg
Gearbox	5-speed auto

**Table 2.** Engine Geometry for Map Generation

Engine	Naturally-Aspirated Single-Cylinder
Displacement	0.5litre
Bore * Stroke	86*86mm
Con Rod Length	175mm
Compression Ratio	12.5
Fuel	Iso-Octane

Load control is done according to equivalence ratio of 0.5 to 1 and inlet pressure, initial temperature, EGR, and Swirl of 1 bar, 380 Kelvin, 0.25, and 3000 rpm, respectively. In Table 3, the main hypotheses of modeling are presented.

**Table 3.** Main hypothesis of modeling

Load control	$0.5 < \Phi < 1$
Engine speed (rpm)	1000,1500,2000,2500,3000,3500
equivalence ratio	$\Phi < 1$
Turbulence model	k-zeta-f
Combustion model	Eddy breakup
Combustion model	HCCI
NO	Extended Zeldovich
Inlet pressure	1bar
Inlet temperature	380 k
EGR ratio	0.25
Swirl	3000 rpm

Figure 1 specifying the conditions of fuel spray in the combustion chamber and also the structure of reticulation for different mesh imprinting in each part, two-dimensional mesh is produced.

As shown in Figure 2, with the transmission of the mesh to be used in fire workflow manager, three-dimensional mesh is produced.

For equivalence ratio less than 0.5, we had abnormal combustion in this project. An example of abnormal combustion in 2000 round and ratio of 0.4 is presented in Figure 3.

For the rounds 3500, 3000, 2000, and 1500 rpm and equivalence ratios of 0.5 to 0.99, pressure was applied, which is presented in Figures 4, 5, 6, 7, and 8 respectively.

For 3500,3000, 2500, 2000, and 1500 rpm rounds and equivalence ratios of 0.5 to 0.99, temperature was applied, presented in Figures 9, 10, 11, 12, and 13 respectively.

1500 to 3000 rpm rounds were studied for equivalence ratios of 0.5 to 0.99. In Figures 14 and 15 for example, the effect of changing RPM on pressure and temperature at

equivalence ratio of 0.8 is presented.

Figure 14 shows the pressure changes in terms of crank angle with different engine speeds at  $\phi=0.8$ . Figure 15 shows temperature changes in terms of crank angle with different engine speeds at  $\phi=0.8$ . In Figure 16, the mean effective pressure for working indicator in one cycle for 1500 to 3000 rounds at different loadings is performed.

The amount of indicator special fuel consumption for different rounds and loadings is presented in Figure 17.

Changes in NOx pollutant is presented in term of RPM and equivalence ratio in Figure 18.

## 4. Discussion

Considering the fact that HCCI engine is stimulated with the purpose of being used in a hybrid vehicle in ideal situation, the condition for its best performance is suggested with respect to the results.

Also, considering the fact that equivalence ratio is about the mixing of fuel and air, decreasing this mixture and making it "poor", the combustion will be done abnormally, which in this project is observed for equivalence ratio<sup>15,16, 17</sup> less than 0.5. So, in HCCI engine, the equivalence ratio increases in a fixed round, pressure, and temperature due to fuel increase and more energy release. As high temperature and pressure may increase the probability of engine damage, equivalence ratio higher than 0.8 is not recommended because it is in this range that temperature and pressure higher than 2500 Kelvin and 80 bar are possible (except 3000 and 3500 rpm rounds). With increasing RPM, the pressure inside the cylinder decreases which is possible since for higher RPM, there will be less time for mixing fuel and air. Hence, in low RPMs, the mixture is more suitable for combustion due to homogenous mixture of fuel and air, and the pressure resulting from combustion will increase, and the combustion starts sooner due to having the mixture prepared sooner. The temperature inside the cylinder also increases in lower rounds. As a result, RPMs less than 3000 are not suitable because of putting engine in the temperature higher than 2500 Kelvin and the pressure higher than 80 bar.

In 50% to 100% of uploads, the highest amount of imep is for 3000 rounds, and for 25% uploads, the highest imep is for round 2500. Considering our previous results, round 3000 is suggested.

With increasing RPM, iSFC decreases, and with increasing of loads, it increases. The lowest iSFC is

about idle situation with round of 3000 and 50% load. The efficiency of 31% to 37.5% is obtained for iSFC, and comparing it with the efficiency of iSFC of Toyota Prius hybrid vehicle<sup>17</sup> which is 37%, it is concluded that fuel consumption and the output power are appropriately relevant. With increasing the equivalence ratio from 0.6 to 0.8, the amount of NOx increases, but when equivalence ratio increases to 0.99 and gets close to stoichiometric conditions, the amount of NOx decreases. Furthermore, it has been observed that with increasing RPM, the amount of NOx decreases. The lowest amount of NOx is for 3000 and 3500 rpm and equivalence ratio of 0.6. In 3000 rpm, equivalence ratio of less than 0.8, and load of 50%, we have better temperature cylinder chamber, iSFC, and iMEP, and also with respect to the importance of NOx pollutant, equivalence ratio of 0.6 among ratios of 0.6 and 0.7 is recommended because of having lower NOx pollutant.

According to the emission test at 6-point in Japan for diesel vehicles weighting more than 1700 kg, the pollutants were measured according to ppm at speeds of 1000 (Idle), 2000 (40%), 2500(60%), and 3000(80%) and loads of 25%, 75%, and 100% and multiplied by at each place factor, which is presented<sup>18</sup> in Table 4.

**Table 4.** 6-point emission standard of Japan<sup>18</sup>

Mode	Speed (%)	Load (%)	Weight factor	NOx (ppm)
1	Idle	-	0.355	348
2	40	100	0.071	170
3	40	25	0.059	36
4	60	100	0.107	225
5	60	25	0.122	38
6	80	75	0.286	772

Summing up the obtained values, the amount of NOx pollutant is 1589 ppm and as shown in Table 5. Finally it is concluded that the amount of NOx is less than allowance which is an advantage of HCCI engines<sup>19</sup>.

**Table 5.** Comparison of NOx emission with 6-point emission standard of Japan<sup>19</sup>

6-point emission standard NOx (ppm)	NOx with catalyst 80%-95%
380-500	80-318

As shown in Figure 19, to validate this study and its results, a simulation was carried out and compared according to study<sup>20</sup>. There is a good relevance, as it is

observed, between two simulations, especially from the beginning of the combustion. In general, regarding the changes in pressure and temperature, the current study is line with other studies, showing similar results<sup>20</sup> as change of rpm and equivalence ratio are considered<sup>21-24</sup>.

## 5. Conclusion

A hybrid vehicle with appropriate fuel consumption and electric motor was studied, and a HCCI in 3500, 3000, 2500, 2000, and 1500 rpm and equivalence ratio of 0.5 to 0.99, k-zeta-f turbulence model, eddy breakup combustion, NO extended, Fuel splashing the walls, wave atomization spray, heat transfer and evaporation drops, with AVL Fire software, using CFD method, was simulated, and it was found that with decreasing equivalence ratio from an specified value (less than 0.5 in this project), there will be an abnormal combustion. With increasing equivalence ratio, the pressure and temperature increase inside the cylinder chamber. With increasing rpm, pressure and temperature decrease inside the cylinder chamber. With increasing rpm, special fuel consumption decreases, and with increasing engine uploading, special fuel consumption increases. With increasing rpm (up to 3000) and engine uploading, the effective mean pressure increases. The amount of NOx pollutant is less than allowance.

We may couple the engine with a generator and make it work in a specified and optimized condition. So, considering total affective parameters in motor performance such as pressure and temperature inside the cylinder chamber, the special fuel consumption and the effect of equivalence ratio and environmental and economic limitations, the engine performance is more in range of 2500 to 3500 rpm and 50% and 60% uploads, and 3000 rpm round, 50% upload, and equivalence ratio of 0.6 are suggested as the best.

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