Effects of Intake Temperature and Excessive Air Coefficient on Combustion Characteristics and Emissions of HCCI Combustion

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Abstract

The combustion of homogeneous charge compression ignition (HCCI) fuelled with ethanol, methanol and gasoline was achieved on a modified CT2100Q engine by heating the intake air. The effects of intake temperature and mixture concentration on HCCI combustion characteristics and emissions were analyzed in this paper. The results indicate that with the increase of intake temperature, the in-cylinder peak pressure significantly increases and the crank angle corresponding to it gets a visible advance. But for gasoline, the changing trend is a little different. The emissions of HC and CO both decrease and NOx emission for gasoline slightly increases with the increase of intake temperature. As the mixture concentration increases, the in-cylinder peak pressure increases and the crank angle corresponding to it slightly advances. The emissions of HC and CO both increase with the increase of excessive air coefficient (λ). Methanol has the minimum HC emission among the three fuels. NOx emission is very low for the three fuels, and when the excessive air coefficient is larger than 2.5, NOx emission becomes zero.

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1. Introduction

Homogeneous charge compression ignition (HCCI) as a new combustion mode, which combines the best features of spark-ignition (SI) gasoline engine and compression-ignition (CI) diesel engine, has the advantages of higher thermal efficiency and lower emissions of NOx and particulate matter (PM), therefore, it has been honored as a promising way that can meanwhile reach the requirements of saving energy and reducing emissions for internal combustion engines in the future [1-4].

However, there are still lots of challenges to overcome for the practical application of HCCI combustion mode, such as expanding operation region, controlling ignition timing, higher emissions of CO and HC and cold start etc. [5-7]. Among these barriers how to optimally control the ignition timing in
accordance with different engine speeds and loads is crucial. Many studies show that HCCI is controlled by the combustion chemical reaction kinetics. And unlike conventional combustion, a direct method to control the start of combustion is not available. Therefore, it has great significance to research the impacts of boundary conditions on HCCI combustion process.

The boundary conditions contain a number of parameters, intake temperature, intake pressure, excessive air coefficient, compression ratio and engine speed. This paper studies and analyzes the effects of intake temperature and excessive air coefficient on HCCI combustion by engine experiments.

2. Test Fuels and Equipments

2.1 Test Fuels

Physical and chemical properties of fuels have an impact on power and economy, so having an improved understanding of fuel properties is foundational. The purities of methanol and ethanol are both 99.7%, come from Xi’an chemical reagent factory, and 93# gasoline from Petro China. Table 1 shows their physical and chemical properties.

2.2 Test Equipments

The test engine made by JiangSu ChangTong HTHI Corporation is CT2100Q diesel engine, which is double-cylinder, four-stroke, compulsory water-cooling, naturally aspirated and direct-injection. Some changes were made in the engine for the test, among the two cylinders the second was modified as the test one. Fig. 1 gives the details about the test system. There is an independent inlet and exhaust system in the test cylinder, a controlled intake-air heating device was installed in the front of the inlet system, and the electromagnetic fuel injector in front of the intake valve about 60 cm, which provides enough time to form uniform air-fuel mixture. The first cylinder was not remade, still keeping its original fuel-providing system. When the experiments begin, start the first cylinder fuelled with diesel firstly, which drives the test one for preheating, not until the coolant temperature gets to 90°C and engine oil temperature 85°C are the engine speed and intake temperature adjusted to the set points. Then when all the parameters are stable, stop providing fuel to the first cylinder, meanwhile start the second one for HCCI combustion and record the values. Effects of Intake Temperature on Combustion Characteristics and Emissions

![Figure 1. Test system.](image_url)
3. Effects of intake temperature on combustion characteristics and emissions

3.1 Effects of Intake Temperature on Combustion Characteristics

1) Cylinder pressure and rate of pressure rise

Effects of intake temperature on cylinder pressure and pressure rising rate of methanol, ethanol and gasoline are showed in Fig. 2.

Related tests indicate that as the temperature increases the chemical reaction rate accelerates. Van’t Hoff drew a similar conclusion: with regard to the common reactions, the rates will increase by 2-4 times when the temperature increases by 10°C and the other parameters remain un-changed. As intake temperature increase, the number of activated molecules increases, the probability of molecular collision increases, therefore, the reaction rate is improved and the reaction time is shortened. With the increase of the intake temperature, peak pressures of methanol and ethanol increase, also the crank angles corresponding to peak pressures advance. But for gasoline, the trend is slightly different, which may be caused by the complex components of gasoline to complicate the reactions. The changing tendency of pressure rising rate is different from that of cylinder pressure. For gasoline the pressure rising rate before the top dead center (TDC) of T=140°C is higher than that of T=160°C, which causes the peak pressure of T=140°C is larger than that of T=160°C. The reason is when mixture concentration is constant, chemical reaction rates are mainly affected by pressure, not temperature. But the important factor to influence in-cylinder peak pressure is still intake temperature.

2) Heat release rate (HRR)

Effects of intake temperature on HRR can be seen in Fig. 3. From the figure, it can be found that HRR of methanol and ethanol are higher than that of gasoline, which may determined by fuel characteristics. Gasoline is a mixture of multi-boiling-point hydrocarbons, for which the crank angel corresponding to the maximum HRR is earlier than methanol and ethanol. Methanol and ethanol are both single-boiling-point compounds, whose numbers of carbon atoms are both less than those of gasoline, and they are also easy to produce aldehydes, so their maximum HRRs are higher than that of gasoline.

Table 1. Physical and chemical properties of methane, ethanol and gasoline

<table>
<thead>
<tr>
<th>Items of Properties</th>
<th>Properties Methanol</th>
<th>Properties Ethanol</th>
<th>Properties Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>CH₄OH</td>
<td>CH₃OH</td>
<td>C₈H₁₈</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>46 g/mol</td>
<td>32 g/mol</td>
<td>114 g/mol</td>
</tr>
<tr>
<td>Oxygen content (%)</td>
<td>34.8%</td>
<td>50%</td>
<td>0%</td>
</tr>
<tr>
<td>Hydrogen content (%)</td>
<td>13.4%</td>
<td>12.5%</td>
<td>15.1%</td>
</tr>
<tr>
<td>Carbon content (%)</td>
<td>52.2%</td>
<td>37.5%</td>
<td>84.0%</td>
</tr>
<tr>
<td>Specific gravity (g/cm³)</td>
<td>0.785g/cm³</td>
<td>0.795g/cm³</td>
<td>0.740g/cm³</td>
</tr>
<tr>
<td>Research octane number</td>
<td>103</td>
<td>110</td>
<td>95</td>
</tr>
<tr>
<td>Cetane number</td>
<td>8</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>Stoichiometric ratio</td>
<td>9.98</td>
<td>6.47</td>
<td>14.8</td>
</tr>
<tr>
<td>Latent heat of vaporization (kJ/kg)</td>
<td>904kJ/kg</td>
<td>1161kJ/kg</td>
<td>297kJ/kg</td>
</tr>
<tr>
<td>Flame propagation velocity (cm/s)</td>
<td>57.3cm/s</td>
<td>57.3cm/s</td>
<td>57.3cm/s</td>
</tr>
<tr>
<td>Lower heating value (MJ/kg)</td>
<td>26.8MJ/kg</td>
<td>19.7MJ/kg</td>
<td>42.5MJ/kg</td>
</tr>
</tbody>
</table>
3.2 Effects of Intake Temperature on Emissions

In some condition, $\lambda=2.5$, $n=1100$ r/min, effects of intake temperature on emissions of HCCI combustion can be seen in Fig. 4 and Fig. 5. When there is no nitrogen in fuels,
NOx are mainly produced from the nitrogen of air through the following mechanisms: thermal or Zeldovich mechanism, Fenimore or fast mechanism and N₂O intermedia mechanism, plenty of evidences indicate that there is still the fourth mechanism, NNH mechanism [8-9]. Referring to Fig. 4, NOx emissions of methanol and ethanol are zero, and with the increase of intake temperature, NOx emission of gasoline increases, yet not higher than 15×10⁻⁶. The reason is that the temperature and reaction time have a great impact on the formation of NO. When intake temperature keeps 140° or 110°, the peak cylinder temperature is lower than 1800K, hence the production of NO ends in this condition, it may follow N₂O inter-media mechanism. When intake temperature is 160°, the in-cylinder temperature becomes higher, so emission of NOx slightly increases.

With the increase of intake temperature, CO and HC emissions both reduce for the three fuels. The reason is that when intake temperature becomes higher, reaction rates get faster to accelerate the production of radicals, which are helpful for the oxidation of carbon monoxide. Unburned hydrocarbon can reflect the level of burning efficiency. High temperature can depress quenching effects to speed burning and then to promote the burning efficiency, at the same time, more unburned HC exiting in slits and
absorbed in cylinder lubricating oil are involved in the combustion, therefore, the phenomenon of incomplete burning and misfire reduces, thus decreasing HC emissions.

4. Effects of Excessive Air Coefficient on HCCI Combustion Characteristics and Emissions

4.1 Effects of Excessive Air Coefficient on HCCI Combustion Characteristics

Effects of excessive air coefficient on cylinder pressure and pressure rising rate can be seen from Fig.6. The changing tendencies for the three fuels are roughly same. As

Figure 6. Effects of $\lambda$ on cylinder pressure.
\( \lambda \) increases, the peak pressure in cylinder and the maximum pressure rising rate both decrease, also the crank angles corresponding to them both delay. This is because the larger \( \lambda \) is, the less energy in unit volume there is for mixture. Among the three fuels, methanol’s peak pressure is the lowest, which mainly caused by its highest latent heat of vaporization and lowest low calorific value. When the mixture is rich, more energy and time is needed to auto-ignite and burn for methanol, so its HRR becomes lower, and the degree of constant volume reduces.

Among the three fuels, the highest pressure rising rate is for gasoline and the lowest for methanol. This is mainly determined by their self-characteristics and chemical reaction kinetics.

### 4.2 Effects of \( \lambda \) on Emissions

Effects of \( \lambda \) on emissions of methanol, ethanol and gasoline HCCI combustion can be seen in Fig. 7 and Fig. 8. The emission tendencies are similar for the three fuels. As \( \lambda \) increases, NOx emission decreases, when \( \lambda \) is equal to or larger than 2.5, NOx emission becomes zero. The thermal NO formation is primarily influenced by temperature, time keeping in the high temperature and the quantity of oxygen. So when mixture becomes lean, temperature in cylinder decreases, which is awful for the production of NOx, thus NOx emission decreases.

Even if the oxidation of CO is important, it is more important that CO oxidize hydrocarbons. CO emission for traditional internal combustion engines is primarily controlled by fuel/air equivalence ratio. For rich mixtures, CO concentration increases steadily with the increase of equivalence ratio, however, for lean mixtures, equivalence ratio only has a slight effect on CO emissions. CO emission for HCCI engines is mainly controlled by chemical reaction kinetics. The creation and oxidation of CO is one of the basic reactions in oxidation mechanisms of methanol, ethanol and gasoline. The main elementary reaction is \( \text{CO} + \text{OH} = \text{CO}_2 + \text{H} \), which is also a chain transferring reaction, producing a hydrogen atom. Then the hydrogen atom will react with oxygen, that is \( \text{H} + \text{O}_2 = \text{OH} + \text{O} \), then the created OH and O will be oxidized through the following reactions: \( \text{CO} + \text{O}_2 = \text{CO}_2 + \text{O} \) and \( \text{CO} + \text{OH} = \text{CO}_2 + \text{H} \). The latter reaction is more important. With mixture becomes lean, the quantity of OH radical decreases, which is bad for the oxidation of CO, so the CO emission increases.
The tendency of HC versus equivalence ratio is similar to that of CO. UHC is mainly due to the chain termination during the reaction chain propagation (incomplete combustion). For HCCI combustion, there are possibly four kinds of HC formation mechanisms: quenching effects at the chamber wall; slit effects; adsorption effects of cylinder lubricant oil film; partial burning and misfire. With the increase of excessive air ratio, mixture becomes lean, peak temperature in cylinder decreases, incomplete combustion is easier to happen and burning velocity becomes slow, so unburned hydrocarbons increase.

5. Conclusions

(1) With the increase of intake temperature, the pressure in cylinder increases. Ethanol and gasoline are more sensitive to the intake temperature.

(2) With the increase of intake temperature, the emissions of HC and CO decrease for all the three fuels, methanol and ethanol are more sensitive to intake temperature. During the range from 110°C to 160°C, NOx emissions of methanol and ethanol are all zero, but for gasoline, NOx emission increases with the increase of intake temperature, yet not higher than 15×10^{-6}.

(3) λ reflects how much energy in unit volume of gas mixture. With the increase of λ, the in-cylinder peak pressure and temperature decrease.

(4) As λ increases, NOx emission quickly reduces. When λ is equal to or larger than 2.5, NOx emission becomes zero, but the emissions of HC and CO increase. HC emission of methanol is the minimum in the test fuels.

References


