

## Effects of intake temperature on performance and operation range of an HCCI engine fueled with n-butanol

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**Abstract.** To investigate the effects of intake temperature on the performance and operation range of HCCI engine fueled with n-butanol, the 2<sup>nd</sup> cylinder of a water-cooled, naturally aspirated diesel engine with 2-cylinder was modified to operate on HCCI combustion mode. The indicated mean effective pressure (*IMEP*), indicated thermal efficiency (*ITE*) and operation range were compared and analyzed under the conditions with different intake temperature at engine speed of 1000r/min. The experimental results show that the *IMEP* and *ITE* are maximized at 140°C and reduced with the increase or reduction in intake temperature at lower excess air ratio ( $\lambda$ ). However, at higher  $\lambda$ , the *IMEP* and *ITE* are increases as the intake temperature rises. The operation range of the HCCI engine is obviously expanded when the intake temperature varies from 110°C to 140°C while is almost constant after the intake temperature is over 140°C. All of the results indicated that a lean mixture accomplish with a reasonable higher intake temperature may improve the combustion of HCCI engines.

### 1. Introduction

Diesel engines have a wide range of applications including transportation, manufacture and elsewhere due to their high thermal efficiency and durability, while there still have major problem of simultaneously reduce NO<sub>x</sub> and smoke emissions due to governing combustion mechanisms. Homogeneous charge compression ignition (HCCI) combustion has been utilized as a new combustion mode to overcome this problem and combines the benefits of conventional SI and CI engines [1]. The lean homogeneous air-fuel mixture of HCCI leads to lower combustion temperatures that reduce nitrogen oxide (NO<sub>x</sub>) and smoke emissions [2]. Furthermore, the HCCI engine has high thermal efficiency due to the premixed air-fuel mixture burns volumetrically in a faster process. Moreover, the increasing use of alternative fuels such as natural gas, biodiesel and alcohols are considerably changing the fuel chemical composition for diesel engines. Among all the alternative fuels, n-butanol is a clean burning renewable liquid fuel with higher energy density and cetane number than alcohol fuel such as methanol and ethanol, which makes it suitable for the performance requirement of HCCI engine [3]. Thus the n-butanol HCCI engine has aroused wide attention.

In recent years, most of studies have been conducted to investigate the effects of various parameters on the performance, combustion, operation range and emissions of HCCI engines. The experimental research on combustion and performance of an HCCI engine conducted by Uyumaz under different intake temperature and showed that the start of combustion was advanced with the increase of intake temperature [4]. He et.al conducted an experimental study on a single cylinder port fuel injection engine to investigate the combustion and emission characteristics of HCCI engine under different relative air-fuel ratios and found that the *IMEPs* in HCCI combustion mode was limited by combustion stability under lean mixture conditions [5]. Li et.al investigated the effects of intake temperature on the combustion characteristics of an HCCI engine fueled with n-butanol and pointed out that the proper increase of intake temperature might improve the combustion stability of HCCI engines [6].

However, the HCCI engines still have various problems including the narrow operation range, the difficulty of controlling combustion between knocking under a high load or rich mixture and misfiring under a low load or lean mixture [7]. Therefore, it is essential for engine design and operation to investigate the performance especially operation range under various parameters such as intake temperature. In this study, an experiment of the influence of intake temperature on the performance and operation range of an HCCI engine fueled with n-butanol is investigated. The aim of this study is to explore the performance and operation range of the HCCI engine under different intake temperature and provide the basis for the intake temperature optimization in the HCCI engine.

## 2. Experiment layout

### 2.1 Experimental apparatus.

To evaluate the performance and operation range of the HCCI engine, a modified double-cylinder, four-stroke, water-cooling, naturally aspirated and direct-injection engine was used in this study. The specifications of test engine are given in Table 1. Engine loads and speeds are controlled by an eddy current engine dynamometer (CW25, Cama, Luoyang, China ) of 25 kW.

Table 1 Specifications of test engine

Items	Specifications
Model	CT2100Q
Combustion chamber shape	$\omega$
Cylinder bore (mm) $\times$ Stroke (mm)	100 $\times$ 105
Displacement (L)	1.65
Compression ratio	17:1
Intake valve opening angle	17°CA BTDC
Intake valve closing angle	43°CA ABDC
Exhaust valve opening angle	47°CA BBDC
Exhaust valve closing angle	17°CA ATDC

To operate the test engine on HCCI combustion mode, a few modifications was made in the test engine. Fig. 1 shows the schematic of experimental apparatus used in this study. Among them, the 1<sup>st</sup> cylinder was kept on its original combustion mode, but the 2<sup>nd</sup> cylinder was converted into HCCI combustion mode. Both of the two cylinders were equipped with an independent intake and exhaust system, and an intake-air heating device, installed in the front of intake system for the 2<sup>nd</sup> cylinder, was used to control intake temperature of the 2<sup>nd</sup> cylinder. The corresponding concentration homogeneous mixture was provided to the 2<sup>nd</sup> cylinder by PFI fuel injection system.

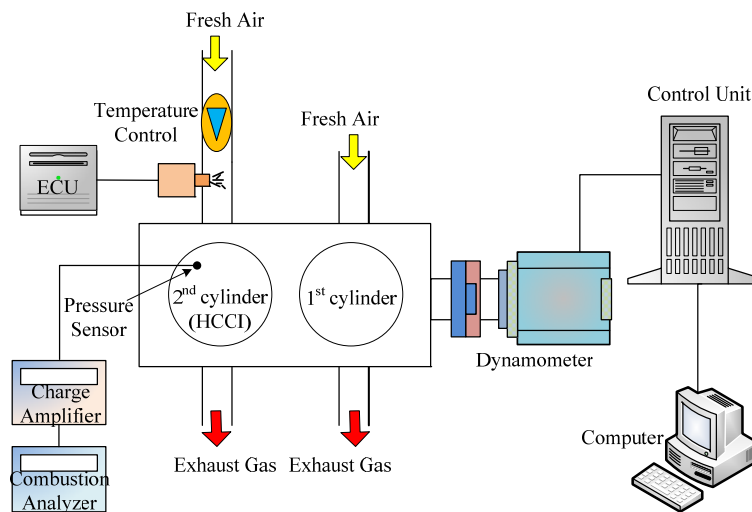


Fig. 1 Schematic of experimental apparatus

The in-cylinder pressure was measured by a piezo-electric type pressure sensor (6052A, Kistler) installed on the 2<sup>nd</sup> cylinder and was amplified by a charge amplifier (5019, Kistler). The pressure

data were taken over 150 cycles and acquired by a combustion analyzer (Kibox 283A, Kistler). The *IMEP* was calculated based on the cylinder pressure.

## 2.2 Experimental procedure.

Before the start of experiment, the 1<sup>st</sup> cylinder was started with diesel firstly, to warm-up the engine, until the coolant temperature reached about 75°C and the lubricating oil temperature reached about 65°C. Then, adjusted the engine to test conditions and stopped supplying diesel fuel to the 1<sup>st</sup> cylinder; meanwhile started the 2<sup>nd</sup> one for HCCI combustion and recorded cylinder pressure data. The steady state tests were repeated at least twice to ensure that the results were repeatable within the experimental uncertainties.

## 2.3 Data processing.

The indicated mean efficiency pressure (*IMEP*) is a parameter that represents the effect of cylinder pressure on engine output and is defined as work output per cycle by the engine displacement in the following equation.

$$IMEP = \frac{1}{V_s} \oint P dv = \frac{1}{V_s} \sum_{i=0}^n \left( \frac{P_{i+1} + P_i}{2} \right) (V_{i+1} - V_i) \quad (1)$$

Where,  $P_i$  is the pressure data sampled by the number  $n$  per cycle with the rotation angle of output shaft and  $V_i$  represents the volumetric data defined by the geometric dimensions of cylinder.

The indicated thermal efficiency (*ITE*) is a parameter that represents the economy performance of per cycle and is defined as the indicated work output divided by the quantity of heat release.

$$ITE = \frac{IMEP \times V_h}{m_{cyc} H_u} \times 100\% \quad (2)$$

Where,  $V_h$  is displacement volume,  $m_{cyc}$  is the fuel mass of each cycle and  $H_u$  is the low heating value of tested fuel.

## 3. Results and discussion

### 3.1 Indicated mean effective pressure.

Fig. 2 shows the *IMEP* of the HCCI engine under different intake temperature and engine speed ( $n$ ) of 1000 r/min. It is shown that *IMEP* for different air-fuel ratios appear different trends with the variations of intake temperatures. At lower  $\lambda$ , the *IMEP* is maximized at 140°C and it decreases with the increase or reduction in intake temperature. However, at higher  $\lambda$ , the *IMEP* is increased as the intake temperature rises. This is because as the intake temperature rises, the temperature of compression phase and fuel mixture raises, in this case, the fuel mixture is more homogeneous and the combustion is more complete. Meantime, higher intake temperature increases activation energy of mixture molecular, which may promote the chain reaction, accelerate chemical reaction rate and enhance combustion intensify. But at lower  $\lambda$ , the peak of in-cylinder pressure and heat release are advanced before top dead center when intake temperature is over 140°C, this factor may cause an increase of compression negative work which subsequently make *IMEP* decreases. It is also shown that *IMEP* increases with the  $\lambda$  decreases. The reason is that lower  $\lambda$  increases the fuel containing in air-fuel mixture per unit value, which may cause the effective collision between fuel mixtures molecular more frequently and increase the rate of the formation for free radical subsequently.

### 3.2 Indicated thermal efficiency.

Fig. 3 shows the *ITE* of the HCCI engine under different intake temperature. It is found that there is almost same trend for *ITE* as *IMEP*. There are two reasons for this result. First, higher intake temperature means more energy entering into the cylinder and more energy may be converted to work during the combustion phase. Second, more rapid chemical reaction rate and heat release rate may be obtained at higher intake temperature which may shorten the combustion duration. The shorter

combustion duration may make the HCCI combustion process closer to a high efficiency combustion mode, constant volume combustion, and it may also reduce heat loss during the combustion process. However, the ignition timing is advanced as the increase in intake temperature especially for lower  $\lambda$ . This factor causes the compression negative work increases and may reduce the *ITE* at lower  $\lambda$ . It is also shown that a lean fuel mixture accomplish with a reasonable higher intake temperature may be a potential tool to improve the combustion of HCCI engines.

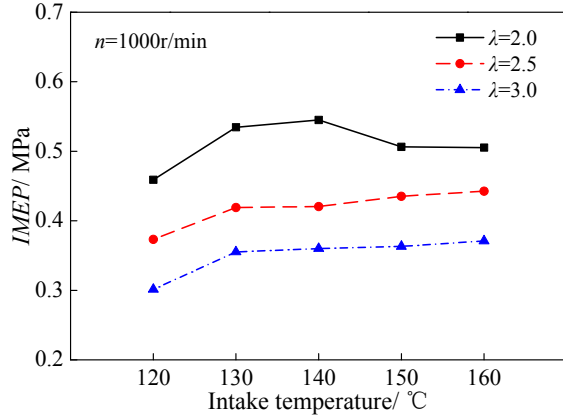


Fig. 2 IMEP under different intake temperature

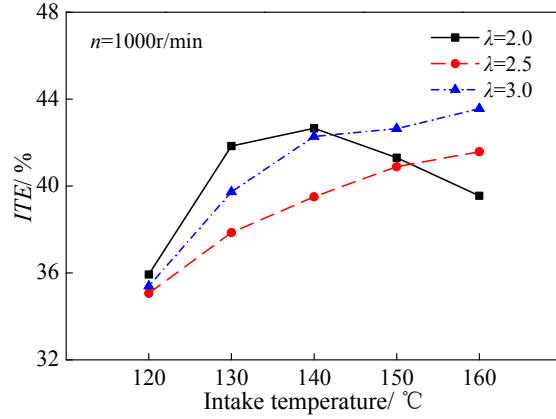


Fig. 3 ITE under different intake temperature

### 3.3 Operation range.

Fig. 4 shows the operation range under different intake temperature. The range of  $\lambda$  under different intake temperature is used to represent operation range. It is found that the increase in intake temperature may efficiently expand the operation range of the HCCI engine. This is because although the ignite temperature is high at lean mixture, the higher intake temperature may provide sufficient ignition energy to the lean fuel mixture and ensure the combustion stability under the conditions of lean mixture. The operation range of the HCCI engine is obviously expanded when the intake temperature varies from 110°C to 140°C while is almost constant after the intake temperature is over 140°C. This is attributed to the mixture is very lean and knock occurs easily at higher intake temperature. All of the results indicate that the HCCI combustion is sensitive to intake temperature and a proper increase in intake temperature is helpful in expanding the operation range of HCCI engines.

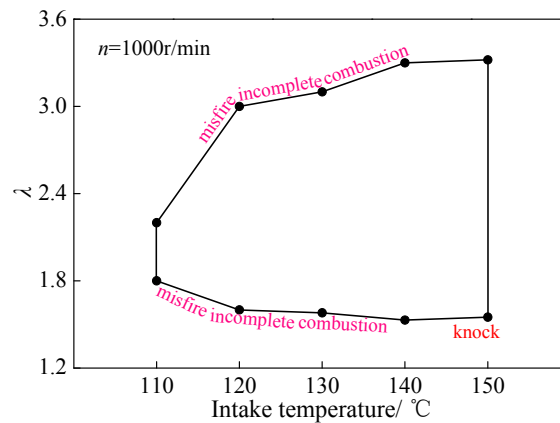


Fig. 4 Operation range under different intake temperature

## 4. Conclusions

(1) The *IMEP* and *ITE* are maximized at 140°C and it decreases with rises/reduces in intake temperature at lower  $\lambda$ . However, at higher  $\lambda$ , the *IMEP* and *ITE* are increases as the intake temperature rises.

(2) The HCCI engine is sensitive to intake temperature and a proper increase in intake temperature may obviously expand the operation range of the HCCI engine when the intake temperature varies from 110°C to 140°C. However, the operation range is almost constant after the intake temperature is over 140°C due to misfire and knock.

(3) A lean fuel mixture accomplish with a reasonable higher intake temperature may be a potential tool to improve the combustion of HCCI engines.

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