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The influence of different auto-ignition modes on the behavior of pressure waves

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ABSTRACT

For internal combustion engines, the knock of Homogeneous Charge Compression Ignition engines, the conventional knock of gasoline engines and the super knock are all caused by the auto-ignition of unburned mixture which leads to the oscillation burning, but their Maximal Pressure Oscillation Amplitude (MPOA) and Maximum Pressure Rising Rate (MPRR) are totally different. In order to explore the reason, we propose three typical auto-ignition modes and then bring up the method of "Energy Injected" (EI) which is based on the experiment measured heat release rate. Through changing the heat source term in the energy equation for different auto-ignition modes, we conducted a series of numerical simulations for these three modes. After that, the following pressure oscillations can be compared and analyzed. The numerical simulation results show that different combustion pressure waves with different oscillation characteristics come from different auto-ignition modes, thus the macroscopic MPRR and MPOA are totally different. Furthermore, the method of "EI" based on the experiment measured heat release rate can accurately and rapidly help to research the formation and propagation of pressure waves in the engine combustion chamber.

1. Introduction

With the shortage of fossil fuels and serious problems of environment, the internal combustion (IC) engine, as a widely used power plant, is facing the new technological revolution. As the development direction of IC engine, Homogeneous Charge Compression Ignition (HCCI) technology and downsizing technology are widely approved. But in heavy load condition, HCCI and downsizing technology would encounter the same problem: knock. Such problem prevents HCCI and downsizing technology from being applied in all working conditions. Knock is an old phenomenon in IC engines. In 1919, Ricardo put forward the theory of auto-ignition to explain the knock [1]. The further researches of Lewis and Von Elbe prove that the severe combustion of end gas is caused by the prior reaction which leads to auto-ignition before flame front reaches. In order to measure the intensity of the knock and its destructive effect, scholars introduce two indicators below: Maximal Pressure Oscillation Amplitude (MPOA) and Maximum Pressure Rising Rate (MPRR) [2]. The MPRR and MPOA (usually smaller than 1 MPa) of the conventional knock in gasoline engines are both small [3], but if engines operate in knock condition for a long time, it will also damage engines and lead to a worse emission. At the request of the down-sizing, the compression ratio and boost pressure of conventional gasoline engines are higher and higher, which brings in super knock. Compared with conventional knock, detonation may happen in super knock. When super knock happens, the MPOA increases sharply which can even reach up to 25 MPa and the MPRR is also high [4]. For the knock of HCCI, though the MPRR is very high, the MPOA is small [5]. Thus it can be seen that these two indicators which are both regarded as the measurement of the knock, however, have different performance in different combustion technologies. All caused by the auto-ignition of unburned mixture, however the performance of pressure waves is totally different, and the reason should be related to the different modes of auto-ignition which will be discussed in this research.

Comparative studies of different knock phenomena in different combustion technologies are seldom. Eng [6] has compared the different knock phenomena of Spark Ignition (SI) engines and HCCI engines in 2002. In his research, the MPOA of HCCI engines is much higher than that of SI engines. This is because the compression ratio of HCCI is much higher than that of SI. But as SI engines continue down-sizing, the supercharge pressure and the compression ratio are higher and higher [7] which results in super knock at last.

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Nomenclature

IC	internal combustion	BMEP	break mean effective pressure
HCCI	homogeneous charge compression ignition	SA	spark advance
MPOA	maximal pressure oscillation amplitude	ATDC	after top dead center
MPRR	maximum pressure rising rate	CA	crank angle
SI	spark ignition	UDF	user defined function
EI	energy injected	DME	dimethyl ether
GDI	gasoline direct injection	RCM	rapid compression machine
3D	three dimensional	C–J	Chapman–Jouguet
2D	two dimensional		
MUSCL	monotone upstream-centered schemes for conservation laws		

In this case, however, the MPOA of SI (25 MPa) is much higher than that of HCCI. The mechanism that results in such change would be revealed in this paper.

For the research of the knock, scholars are usually busy with the method to detect and avoid it [8–12], while the researches about the pressure waves caused by the auto-ignition are less. However, such pressure wave research is very important as it is not only related to engine noise but also related to engine damage. The conventional knock with lower MPOA and MPRR contributes the most to the engine noise; super knock with higher MPOA and MPRR would even damage engines in a short time [13–17]. But it is hard to see that the knock of HCCI engines would damage engines severely in such a short time. These phenomena are all decided by the pressure wave behavior which would be discussed in this paper.

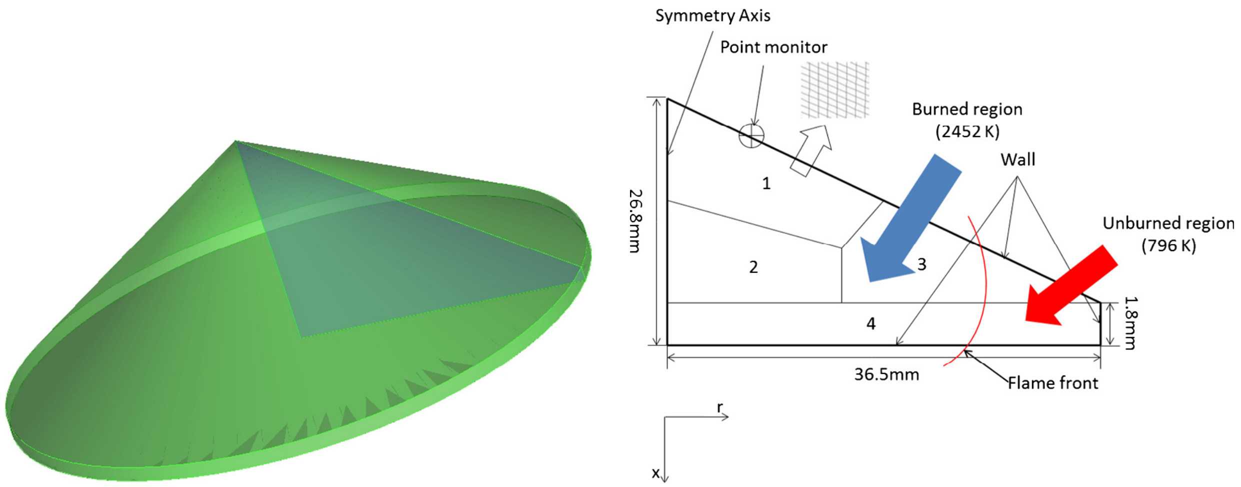
In the severe knock, the amplitude of the pulsations is no longer small relative to the mean pressure within the cylinder. So it is hard to be explained by the small perturbation acoustic wave equation, acoustic models and cavity resonance [18–20]. Therefore the severe knock phenomenon should be explained by pressure wave theory and even shock wave theory in this research.

In order to illustrate the different pressure wave performances in different kinds of knock and to reveal the internal mechanism for such difference, we propose three typical auto-ignition modes and then bring up the method of “Energy Injected” (EI) which is based on the experiment measured heat release rate. The fundamental mode is based on the super knock and the heat release rate is also obtained from the super knock experiment [21]. In order to establish the comparability, the energy injected in the other two auto-ignition modes are as the same as the fundamental one (all based on the heat release rate of super knock [21]), however, the resulting pressure wave behaviors of these three typical modes have significant differences which will be discussed below in detail. Through changing the heat source term in the energy equation for different auto-ignition modes, we conducted a series of numerical simulations for these three modes. Then the following pressure oscillations can be compared and analyzed. Through the analysis of the pressure wave behavior, the problems raised before can be solved.

2. Mathematical and physical model

2.1. Simplification of physical model

The numerical simulation is conducted in the cone roof combustion chamber of the gasoline direct injection (GDI) engine. The three dimensional (3D) model of such combustion chamber is shown in Fig. 1(a). In order to save the computation time, the cone roof combustion chamber is simplified to a two dimensional (2D) axisymmetric model as shown in Fig. 1(b). It can be seen that the 2D model is obtained from the vertical section of the 3D model (the blue part in Fig. 1(a)). The axisymmetric coordinates *R*–*X* is used in this numerical simulation. On the cylinder cover, a point



(a) The 3D model for the combustion chamber

(b) The 2D axisymmetric numerical model

Fig. 1. The model of cone roof combustion chamber.