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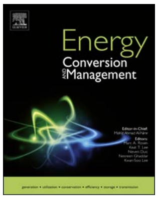

The relief of energy convergence of shock waves by using the concave combustion chamber under severe knock

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ABSTRACT

In internal combustion engines, severe knock is a destructive phenomenon that would converge the energy released by fuel burning to damage the piston so that the engine can't work anymore, which should be avoided. The destruction mechanism have been revealed in previous researches in which the focusing of shock waves is considered as a main reason to cause the energy convergence and the destruction. However, the method to alleviate such shock wave focusing hasn't been put forward yet. Based on the destruction mechanism proposed before, in this research, a concave combustion chamber has been designed to alleviate the energy convergence of shock waves under severe knock so that the destruction of the piston under severe knock can be avoided. To validate the alleviation effect of the concave chamber, detonation bomb experiments have been conducted separately for the typical cone chamber and the redesigned concave chamber. Four pressure sensors installed in different positions of either chamber were used to monitor the shock wave behaviors and compare the energy convergence intensity for both of these two chambers. The experimental results prove that the concave chamber can efficiently alleviate the energy convergence in the center region. Furthermore, a series of numerical simulations have been conducted to reveal the alleviation mechanism of the concave chamber. Two kinds of alleviation mechanism have been obtained which are separately: the shock wave diffraction and the shock wave breaking up. These mechanism can efficiently alleviate the energy convergence of shock waves. The research results can be used as a theoretical basis for the chamber design to avoid the destruction under severe knock.

1. Introduction

To further improve the efficiency and emission of IC (internal combustion) engines, different kinds of technologies have been used: such as direct injection technology combined with high compression ratio, down-sizing, increasing power density, boosting and so on. In addition, using alternative fuels like methanol, ethanol and natural gas, sometimes even using dual fuels and redesigning the IC engines like opposed-piston engines are also taken to achieve higher efficiency and lower emissions. All of these new technologies have some common characteristics: higher in-cylinder pressure and faster burning velocity, which would improve the efficiency of engines. However, as pushing IC engines to their thermodynamic limits, abnormal combustion phenomenon would occur which results in the severe knock, for instance: pre-ignition at low speed would occur in down-sized engines, which would result in super knock [1]; Spark ignition methanol engines running in a high compression ratio would also result in the severe knock [2]. Once severe knock occurs, the pressure amplitude can reach up to 30 MPa or even higher; the oscillation frequency can far more exceed 10 kHz [1]. Furthermore, such strong intensity and high frequency oscillations would destroy engine parts like valves, spark plugs and pistons after several cycles [3], which makes engines cannot work anymore.

Knock is an old phenomenon which accompanies the development of the IC engines. Specifically, the severe knock occurring in the enhanced IC engines is a main concern in the field of the industry and the scientific research. In the research of severe knock, most of researches are focused on the origins of the severe knock: Dahnz et al. attributes the super knock to the pre-ignition and attributes the pre-ignition to the presence of lubricant oil droplets released from the cylinder liner [1]; Wang et al. used the optical rapid compression machine to prove that the hot-spot causes the detonation wave, which results in the severe knock [4]. Yao et al. used two dimensional numerical simulations to prove that compression waves formed in the earlier stage continue oscillating in the cylinder, promoting the low-temperature reaction of end gas, which provides enough radicals for the formation of detonation resulting in the severe knock [5]. Furthermore, Yao et al. used the method of "Energy Injected" in the numerical simulations to indicate

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that different heat release region and rate will results in different auto-ignition modes which will decide whether the severe knock would occur [6]. Chen et al. used one dimensional numerical simulations to reveal the relationship between the end-gas auto-ignition modes and the combustion modes, which would decide the intensity of the severe knock [7]. On the other hand, lots of researches were conducted to alleviate the severe knock. Though these methods can partly alleviate the severe knock, these methods (like exhaust gas recirculation [8], fuel injection strategy [9], retarding the spark timing and so on) may also reduce the engine performance and efficiency. In a word, severe knock can't be totally eliminated by using these methods without the loss of the engine performance and efficiency. Once severe knock occurs, the engine would be damaged rapidly, which is a huge obstacle for further improving the efficiency of IC engines. Considering this, the destruction effect of severe knock and the engine durability after the promotion are especially important. However the destruction under severe knock and the related methods to avoid it haven't been thoroughly researched.

According to the previous research [10], the pressure to destroy the material of the piston should be as high as 900 MPa. Even though the tensile strength of the piston material will decrease sharply with the increase of the temperature, it still needs 360 MPa to destroy the piston at 300 °C. Traditional pressure sensors for the bench test has a range of no more than 30 MPa which is hard to explain the destructive phenomenon. Therefore, a hypothesis has been proposed in our previous research that it's the convergence of the shock wave destroy the engine parts. According to previous studies [11], two kinds of shock waves were recognized once severe knock occurs, separately the AW (axial wave) and RW (radial wave) which are based on their propagation directions. AW propagates towards the axial direction while RW propagates towards the radial direction. The intersection of these two kinds of waves would result in the energy convergence on some certain positions. According to the POD method (Proper Orthogonal Decomposition) proposed in our previous research [12], the convergence/destruction position and the convergence modes can be quickly identified for different combustion chamber shape. Such convergence would result in a high local pressure and high local temperature acting on the piston surface which approaches the allowable stress of the material and leads to the destruction [10]. Therefore it can be concluded that the destruction of engine parts under severe knock is caused by the energy convergence of shock waves with the intersection of AWs and RWs. However, though the convergence mechanism and the destruction effect of severe knock has been revealed, how to avoid such destruction is still unclear.

Based on the theoretical basis provided from above studies, a method has been proposed in this research to alleviate the energy convergence of shock waves so that the engine destruction under severe knock can be avoided. Besides, the mechanism for the relief of energy convergence is also given. In order to alleviate the energy convergence, AW and RW should be attenuated quickly and the intersection of AW and RW should also be attenuated. Based on these two points, a new combustion chamber has been redesigned. A DBD (detonation bomb device) with the redesigned combustion chamber was developed for the experimental research. Four pressure sensors were installed in different positions of the combustion chamber to monitor the pressure wave behavior and validate the alleviating effects of energy convergence by using the redesigned chamber. Combined with the DBD experiments, numerical simulations were conducted to further give the alleviation mechanism.

This research provided a method to alleviate the energy convergence of shock waves so that IC engines can be more durable even though severe knock occurs. Also, the mechanism to avoid the energy convergence has been given which can provide a theoretical basis for the chamber design to avoid energy convergence of shock waves as well as the destruction under severe knock.

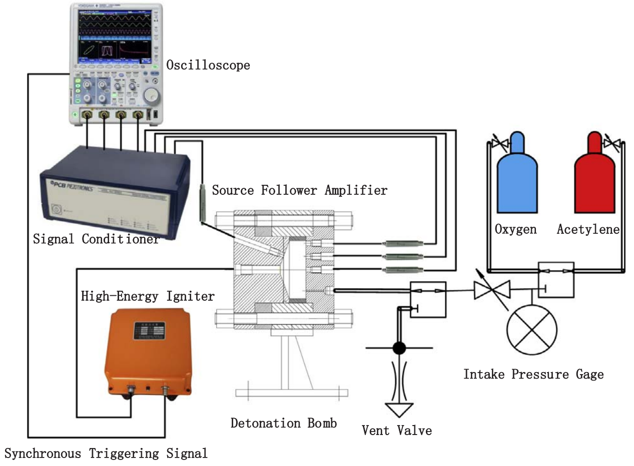


Fig. 1. The system of the detonation bomb device [11].

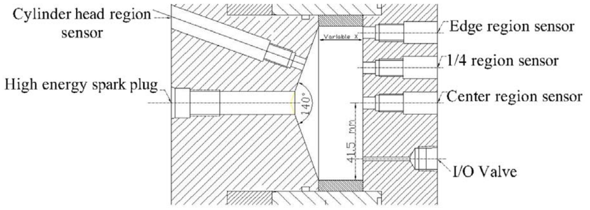
2. Experimental setup

The DBD experiments conducted in this research are contrast experiments, which will be contrasted with our previous work [11] to validate the alleviation effect of energy convergence. The relevant experimental setup and chamber shape change are introduced as below.

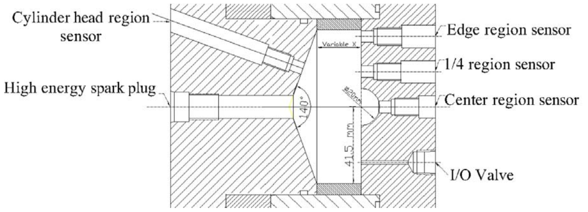
2.1. Detonation bomb device

The details of the DBD setup can be found in Ref. [11]. Briefly, the DBD consists of four parts: the intake-outlet system, high-energy ignition system, signal acquisition/processing system and a detonation bomb. The schematic of the DBD can be seen in Fig. 1.

The chamber shape in previous work is a cone-roof one which is a typical chamber shape of real spark-ignition engines. Since the cone-roof one can lead to the extreme shock wave focusing in middle region which causes piston damaged after several cycles of severe knock, the chamber shape is redesigned to a concave one which has a pressure relief pit in the center region on the piston. This redesigning scheme is proposed on the theoretical basis obtained from our former researches. The detailed structure change and differences can be seen in Fig. 2. Besides, the photos of these two kinds of pistons are given in Fig. 3. For both chambers, the cylinder bole is 83 mm and the angle of the cylinder head is 140°. The diameter of the pressure relief pit is 20 mm. The clearance of this bomb is variable from 0 mm to 32 mm corresponding



(a) Cone-roof combustion chamber



(b) Concave combustion chamber

Fig. 2. The shape and structure of the detonation bomb.