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The effect of the energy convergence and energy dissipation on the formation of severe knock

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HIGHLIGHTS

- Chamber shape is found to be a key factor for the occurrence of the severe knock.
- Convergent structure causes energy convergence in the edge region.
- Concave chamber can break up the shock wave to dissipate the energy.
- Energy convergence results in the detonation as well as the severe knock.
- Avoiding the convergent structure or dissipating the energy can prevent severe knock.

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ABSTRACT

In order to increase the energy utilization efficiency and decrease the emission, internal combustion engines have been pushed to their thermodynamic limits. As a result, abnormal combustion phenomenon would occur which results in the severe knock. Severe knock is usually caused by the onset of the detonation which will damage the engine parts in a short period. How to avoid such destructive detonation as well as severe knock is the aim of this research. This research found that the onset of the detonation is highly related with the chamber shape. In order to validate this relationship, two chamber shapes were studied in a series of bomb experiments. Both of them are the cone-roof type, but one has no clearance while the other one has a clearance of 12 mm. High-energy ignition spark ignites a deflagration from the center of the bomb. Four pressure sensors installed in different positions of either chamber were used to monitor the pressure wave behaviors and the onset of detonation. The experimental results show that under the same initial conditions, the detonation always occurs in the non-clearance chamber but never occurs in the chamber with a larger clearance. Furthermore, a series of numerical simulations have been conducted to reveal the mechanism of the detonation formation caused by the chamber shape. It's found that the non-clearance chamber has a convergent structure on the edge which will focus the pressure wave and its energy on the edge position causing the formation of detonation. Compared with it, the chamber with a larger clearance doesn't have such convergent structure so that the detonation as well as the severe knock won't occur. Therefore, according to the research results, if the chamber shape is properly designed to dissipate the energy or avoid the energy convergence, the severe knock may be weaken or even be avoided though the engines are further pushed to obtain a higher efficiency.

1. Introduction

IC (internal combustion) engines are widely used machines to convert the chemical energy into the mechanical energy to serve humanity, which is a common approach to apply the energy. Since the energy used mainly comes from the fossil fuel which is a non-renewable resource and the emission of the IC engines would contaminate the atmospheric environment, IC engines meet an urgent demand of technical improvement to increase the energy utilization efficiency and decrease the emission. How to wisely apply and convert the chemical energy into the mechanical energy in the IC engines get more and more attention. Lots of new technologies have been applied: in-cylinder direct injection combined with high compression ratio and intake boosting (known as engine down-sizing strategy), which can reduce the

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Nomenclature

IC	internal combustion	C-J	Chapman-Jouguet
DBD	detonation bomb device	r	chemical reaction rate
AUSM	advection upstream splitting method	k	reaction coefficient
MUSCL	monotone upstream-centered schemes for conservation laws	c_{A_i}	the molar concentration of the specie i
		A	reaction constant
		E	activation energy
		R	gas constant

global displacement to decrease the emissions and make the engine work in a high efficiency region; the usage of alternative fuels like natural gas, ethanol, methanol and so on combined with high compression ratio; the redesign of the IC engines to achieve higher thermodynamic efficiency like opposed-piston engines and so on. All of these technologies have some common characteristics: higher in-cylinder pressure and faster burning velocity, which would increase the power density as well as the performance and approach the constant volume combustion to improve the efficiency. As the engines are further pushed to their thermodynamic limits, abnormal combustion would occur which would result in the destructive severe knock. For instance, pre-ignition would occur in down-sized engines, which would result in super knock [1]. Once severe knock occurs, the pressure amplitude can reach up to 20 MPa or even higher; the oscillation frequency can far more exceed 10 kHz [2]. Such severe knock is destructive, which would destroy engine parts like pistons, valves and spark plugs after several cycles [3]. Therefore, it can be seen that the severe knock is a huge obstacle for the further increase of the energy utilization efficiency.

In recent years, lots of scholars have been focused on the origins of the severe knock as well as the formation of the detonation in IC engines. Dahnz et al. attributes the severe knock to the pre-ignition and attributes the pre-ignition to the presence of lubricant oil droplets released from the cylinder liner [4]; Based on one dimensional numerical simulations, Chen et al. [5] proves that the severe knock is caused by the formation of detonation waves. Wang et al. defines three stages from pre-ignition to severe knock: from pre-ignition to deflagration, from deflagration to detonation and from detonation to strong pressure oscillations [6]; Furthermore, Wang et al. attributes the detonation to the interaction of the shock wave and the cylinder wall [7]; Through the Large Eddy Simulation study, Robert et al. found that if the shock wave generated by the auto-ignition spot is strong enough, a coupling between the shock wave and the auto-ignition spot would occur which will result in severe knock [8]; According to the one dimensional numerical simulations, Pan et al. found that the wave-wave interaction, wave-wall interaction and reaction front–wave interaction can all facilitate the transition to detonation waves as well as the severe knock [9]. Yao et al. used the method of "Energy Injected" in the numerical simulations to indicate that different heat release distribution and rate in the pressure wave region will result in different auto-ignition modes: thermal explosion, deflagration and detonation, which will decide whether the severe knock would occur [10].

From these researches, it can be seen that the onset of the detonation as well as the severe knock depends on the relationship between the pressure wave and the chemical reaction. On the one hand, the pressure wave would be strengthened by the chemical reaction; on the other hand, the chemical reaction would also be promoted by the pressure wave. Either intensification of the pressure wave or the chemical reaction would facilitate the coupling between them which would result in the detonation as well as the severe knock. Based on this idea, the combustion chamber shape is considered as a significant factor in this research, which would affect the intensity of the pressure wave as well as the energy distribution thus promoting the onset of the detonation. However the effect of the combustion chamber shape on the detonation formation is seldom researched before. Most of the previous experimental researches were conducted in a simple cylindrical combustion chamber, in which more complicated chamber shape effect is hard to consider; Most of the previous numerical researches are either limited by the one dimensional method or neglect the effect of the chamber shape.

Our previous research has revealed that the reflection of the pressure wave on the cylinder wall would promote the low-temperature reaction of the end gas, which provides enough radicals for the formation of detonation [11]. Our further researches focusing on the shock wave behavior have found that the edge of the non-clearance cone-roof chamber has a convergence structure which would focus the shock wave there and the focused energy would destroy the piston after the occurrence of the sever knock [12]. Furthermore, the energy convergence mode has been recognized by using the POD method (proper orthogonal decomposition) [13]. Combined with these research results together, an assumption has been proposed in this research that, before the occurrence of the severe knock, the convergence structure of the non-clearance cone-roof chamber may focus the pressure wave and energy on the edge thus facilitating the onset of the detonation, which is considered as the origin of the severe knock.

There are some researches focused on the onset of the detonation caused by the shock wave focusing [14]. Most of them were conducted in a shock tube and the aim is to serve the ignition of the detonation engine, while such phenomenon is seldom researched in IC engines. However, in IC engines, such phenomenon is also significant which can help to avoid the severe knock.

In the field of IC engines, scholars tried to find other ways to suppress the severe knock, like exhaust gas recirculation [15], water injection [16], fuel injection strategy [17], over-fuelling [18], retarding the spark timing and so on. Though these methods can suppress the severe knock, these methods may also reduce the engine performance (like the volumetric power, torque and so on) and efficiency. In this research, we want to find a way to avoid the severe knock without the loss of the engine performance and efficiency.

Considering the convergent structure may focus the energy to ignite a detonation causing severe knock, two cone-roof chamber shapes were studied here. One has no clearance while the other one has a clearance of 12 mm. These two kinds of chambers were successively installed in a DBD (detonation bomb device) to conduct the experiments. Four pressure sensors installed in different positions of either chamber were used to monitor the pressure wave behaviors and the onset of detonation. Furthermore, a series of numerical simulations and chemical calculations were conducted to reveal the mechanism of the detonation formation caused by the chamber shape.

It should be noted that the cone-roof chamber shape studied here is a simple model which possesses the main characters of the spark ignition engine chamber. For sure, the tested shape has some differences in detail from the real IC engine chamber. However, different types of engines have different chamber shapes to meet different demands. Even though belongs to the same type, the chamber shapes also vary with the brand or the model. In this research, the severe knock is attributed to the energy convergence phenomenon which may occur in any shape. Different chamber shapes may have different kinds of energy convergence phenomenon. The purpose of this research is to reveal such convergence phenomenon and find out how it's affected by the chamber shape so that the future chamber design can consider such factor as it may cause the severe knock. Therefore, in experiments, we didn't use a