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Investigation of energy transformation and damage effect under severe knock of engines

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HIGHLIGHTS

- Heat release of fuel will transform into the destructive force under severe knock.
- Multiple pressure transducers installed in the bomb reveals shock wave behavior.
- Numerical simulations evidence the interaction of shock waves and its effect.
- Piston damaged under severe knock is caused by the shock wave convergence.
- Wave convergence leads to locally high damaging temperature and pressure.

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ABSTRACT

Under severe knock of IC (internal combustion) engines, engine parts like pistons are vulnerable to be damaged rapidly, the mechanism of which remains unsolved. Especially how the chemical energy released from fuel burning is transformed into the force damaging the material of pistons is still unclear. In order to reveal the in-cylinder energy transformation as well as its damage mechanism under severe knock, an assumption of shock wave from severe knock converging in combustion chamber was proposed. Based on the assumption, several quasi three-dimensional numerical simulations had been conducted to investigate into the flow behaviors of pressure wave in chamber. The results calculated from the numerical simulations showed that the shock waves transformed from the energy released by fuel burning could be categorized into Axial Wave and Radial Wave respectively. The interaction between these two types of waves would result in severe energy convergence on certain positions, which was strong enough to damage the piston. The intensity of energy convergence was not only related to the interaction of the two types of shock waves but also to the chamber shape while severe knock happened. A detonation bomb device with the interior configuration similar to that of product spark ignition engines was designed and a series of three-dimensional experiments had been conducted in it. Acetylene which is easy to cause detonation was taken as fuel and burned with pure oxygen inside of the bomb. The experimental results showed that the regions near the center and at the edges did exhibit the greatest amplitude pressure oscillations compared with those at the other regions. And the experimental results were well fit with those results from simulation calculation. Meanwhile, the similar results were achieved when the actual in-cylinder pressure curves obtained from IC engine bench tests under severe knock were analyzed. The damaged pistons were presented to validate the experimental and numerical results. Based on this knowledge, the assumption of piston damaged by knocking wave convergence was validated. Additionally, the method of power vector introduced and combined with strength calculation and energy calculation were conducted to further illustrate that the piston was vulnerable to be damaged by energy transformation under severe knock.

1. Introduction

With the rapid increasing consumption rate of conventional petroleum-based fuels, energy problem is severer. IC (internal combustion) engines as widely used power machines are facing

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Nomenclature

EGR	exhaust gas recirculation
IC	internal combustion
MAPO	maximum amplitude of pressure oscillations
NVH	noise vibration and harshness
RCM	rapid compression machine
3D	three-dimensional
DBD	detonation bomb device
SI	spark ignition
DDI	detonation direct initiation
DDT	deflagration to detonation
C-J	Chapman-Jouguet
AUSM	advection upstream splitting method
MUSCL	monotone upstream-centered schemes for conservation laws
AW	axial wave
RW	radial wave
$\vec{Pv}$	power vector
P	local pressure
$\vec{V}$	velocity vector
σ_b	tensile strength
τ	shear strength
F	force required by punching a hole on a piston
d	the diameter of a punched hole
h	the thickness of the piston surface
A	the area of the punched hole
E_d	the energy required to destroy a piston
E_c	the energy released by fuel in every working cycle
N	number of cylinders
R	rotate speed
PW	engine power
C	specific fuel consumption
H	low heating value of gasoline

further technological advance to increase the efficiency of fuel utilization. Among them, downsized and boosted direct injection spark ignition engines have been widely recognized as an efficient way to improve the thermal efficiency as well as to lower the fuel consumption [1,2]. However further downsizing by further increasing the compression ratio and boost pressure will cause "super knock" at last [3–7]. Besides that, the introduction of some new technologies to increase the efficiency of energy utilization, like alternative fuel engines, opposed piston engines and so on will also bring in severe knock under high load operating conditions [8,9]. No matter the super knock or severe knock as well as how it forms, the destructive effect is obvious which can damage engine pistons in a short period. However, as we know, the material of pistons is so tough that it's not easy to be failed. Therefore the energy transformation in this process is worthy of more attention to reveal the inner mechanism so that preventative methods can be provided.

Based on the knock intensity, scholars classify the engine knock into different kinds of types like light knock, heavy knock, severe knock, super knock and so on. However, there is no unified quantitative threshold to distinguish or define them. Different researchers may give their own definitions to classify the knock intensities [10,11]. In this paper, the knock is divided into two types: light knock and severe knock. The difference is that the MAPO (maximum amplitude of pressure oscillations) of light knock is small which has acoustic characters and belongs to the linear phenomenon whereas the MAPO of severe knock is large enough so as to transform into a shock wave and belongs to the non-linear phenomenon. Considering this, the MAPO of severe knock usually has the same order of the in-cylinder static pressure and sometimes even higher, which means it would be as large as several mega Pascal. The knock discussed in this study is mainly focused on the severe knock and the discussion mainly targets at one single engine cycle rather than an operating point with a series of cycles. Also, this research does not deal with the causes of knock combustion. It's worth noting that though the key point in this research is severe knock, light knock is also not tolerated in IC engines due to NVH (noise vibration and harshness) and loss of engine efficiency. Further, successive light knock events can lead to increasingly heavier knock events due to the breakdown of thermal boundary layers. Therefore light knock is also unexpected and should be eliminated.

Light knock usually exhibits lower pressure oscillations (usually smaller than 1 MPa) and can be avoided by conventional methods, such as EGR (exhaust gas recirculation), alcohol addition, ignition retard and so on [12–14]. Different from light knock, severe knock is destructive and some are hard to be controlled [15]. A typical kind of severe knock is the super knock which occurs in highly boosted SI (spark ignition) engines. In recent studies, it's found that this kind of severe knock is mainly caused by the pre-ignition of oil/fuel mixture before the spark ignition. However, the pre-ignition doesn't always lead to knocks, which strongly depends on the occurrence time and positions of the pre-ignition point [16]. Besides this, severe knock can also be caused by other different kinds of factors like surface ignition, hot spot on carbon deposit and so on. Once severe knock occurs, the MAPO can reach up to 30 MPa or even more; the oscillation frequency can usually exceed 10 kHz. Considering such phenomenon, detonation is supposed to be formed in IC engines when severe knock occurs. Bradley [17–21] conducted a series of simulations and analyses, then attributed the detonation formation in IC engines to a proper gradient of reactivity in hot spots. Wang [22–26] conducted engine bench tests combined with RCM (rapid compression machine) experiments to reveal the detonation formation process under severe knock related conditions. A. Robert [27] conducted several LES numerical simulations to reveal the process that deflagration transfers into detonation in IC engines. Chen [28] conducted several one dimensional simulations to research the detonation formation under different kinds of thermodynamic conditions and chamber lengths. Yao [29,30] proves that detonation might be formed under severe knock by the analysis of auto-ignition modes. Based on previous researches, once severe knock occurs, detonation has been proved to exist in combustion chambers of IC engines by both experimental researches and numerical researches.

However such detonation wave will cause the destruction of engine parts easily including spark plugs and pistons [31–33]. Furthermore, the damaged pistons have a common characteristic: the damaged positions always occur in the center region and edge region which results from the concentrated impact. In the past, piston failure is usually attributed to the thermal stress, thermal fatigue and mechanical fatigue [34–36]. The effect of shock waves on the piston failure is seldom investigated. Klein [37] has researched the Rayleigh wave in the piston, which makes the piston surface eroded at last. In his research, the detonation wave was only used to render a resonant Rayleigh wave but the convergence of the shock wave was not discussed. Maly [38] has investigated the effect of shock waves on the failure of topland region. However the central region failure and the convergence of shock waves have not been discussed in this research.