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Research on in-cylinder pressure oscillation characteristic during knocking combustion in spark-ignition engine

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HIGHLIGHTS

- We derived pressure wave equation of internal combustion engine.
- We modeled pressure wave equation coupled with KIVA codes with reduced kinetics mechanism.
- Pressure oscillation induced by auto-ignition was simulated accurately using the model.
- We analyzed contribution of different excitation resources to pressure oscillation.
- Pressure oscillations may be effectively restrained by appropriate levels of cooled EGR.

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ABSTRACT

Pressure oscillation is a typical phenomenon during knocking combustion in spark-ignition (SI) engines, and relevant study is mainly focused on low temperature chemical kinetics and optical experiments. In this paper, coupling of pressure wave equation and KIVA-3V code with reduced chemical kinetic scheme has been conducted to systematically investigate pressure oscillation characteristic during knocking cycles based on a SI engine. Simulation model has been tested by the validation of calculated results, including cylinder pressure, pressure oscillation and FFT spectral. Then visualized flame images from high speed camera and 3D CFD results have been presented, which shows that when auto-ignition occurs, pressure rise caused by violent heat release of auto-ignition reaction is much larger than that from spark-ignition flame front. This is confirmed by the discussion on contribution of various excitation resource to pressure oscillation, which indicates that end-gas auto-ignition reaction plays a dominant role in the pressure oscillation formation. Finally, effects of different levels of cooled exhaust gas recirculation (EGR) on pressure oscillation has been researched, which shows that appropriate amount of cooled EGR can effectively inhibit end-gas auto-ignition and high-frequency pressure oscillation due to the thermo-chemical properties of exhausted mixture.

1. Introduction

Nowadays, stringent regulations on pollutant and greenhouse emission have boosted the study on high efficiency and low fuel consumption in internal combustion engines. One of the most promising technologies is spark-ignition (SI) engine downsizing, generally assisted by turbocharging or supercharging [1,2]. It can greatly reduce pumping work and significantly improve thermal efficiency due to the fact that downsized SI engines are more often operated at wider open throttle. Relevant research shows that a reduction in fuel consumption of up to 30% can be achieved depending on the downsizing factors in New European Driving Cycle (NEDC) [3]. However, under high boosted-pressure conditions, downsized SI engines are prone to knocking combustion or knock, which has brought serious barriers for SI engines to achieve higher thermal efficiency.

Because of high thermal stress and mechanical load caused by gas dynamic processes, knocking combustion in SI engines is rather undesirable [4]. Generally, knock is due to the self-ignition (or auto-ignition) of end gas ahead of the propagating spark-ignited flame front [5]. Compression by piston movement and burnt flame expansion can arouse considerably high pressure and temperature gradient in end-gas region, which may promote low temperature chemical reactions in end-gas zones [6,7]. Then the rapid heat release of chemical reaction arouses high local over-pressure and intense pressure waves coming across combustion chamber. These pressure waves not only result in pressure oscillation with large

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Nomenclature

γ	heat capacity ratio	$\dot{Q}_c$	chemical reaction heat
c	speed of sound	κ, ε	turbulent kinetic energy and dissipation rate in κ–ε model
p	gas pressure	σ	viscous force tensor
ρ	mass density of mixture	F_s	momentum increment due to spray and other causes
u	fluid velocity	$\dot{Q}_s$	heat source cause by spray and heat conduction
$\dot{\rho}_s$	mass density change of fuel due to evaporation or condensation	α	dimensionless, related with Press Gradient Scale (PGS) in KIVA
J	heat flux caused by heat conduction and enthalpy dissipation	A_0	$A_0 = 0$ for laminar flow $A_0 = 1$ for turbulent flow

amplitude, but transmit through engine structure to the air, resulting in combustion 'pinging' knock [8]. Research on the pressure oscillation is considerably crucial since it contains more details of what actually has happened during knocking combustion [9].

Analysis of high-frequency pressure oscillation is not new topic in SI engine research. Up to now, much relevant study has been investigated in terms of pressure oscillation during knocking cycles, including onset and intensity of engine knock based on in-cylinder pressure data. Konig and Sheppard [10] conducted simultaneous measurement of cylinder pressure and flame front growth through both schlieren and natural light photography. Syrimis and Assanis [11] installed pressure sensors in combustion chamber to investigate in-cylinder pressure characteristics from spatial and temporal scope during engine knock. It showed that there is great difference in pressure distribution when knock occurs, and correlation between pressure oscillation and knock intensity was obtained. Chiriac et al. [12], Brecq et al. [13] and Wu et al. [14] utilized different knock metrics (MAPO, KLST and VDO algorithm) adopted from filtered oscillating pressure to define onset and intensity of knock accurately.

Additionally, there is close correlation between cavity resonance of combustion chamber and in-cylinder pressure oscillation [15]. The amplitude of pressure oscillation associated with each resonant mode immediately after knock occurrence depends on initial boundary conditions. The frequency of pressure oscillation depends on the size and shape of combustion chamber, auto-ignition location, resonant mode and speed of sound. Scholl et al. [16] considered that the resonating frequency depends on combustion temperature, equivalence ratio and exhaust gas recirculation (EGR) in knocking cycles. Based on acoustic theory, Hicking et al. [17] put forward multi-frequency characteristics of pressure oscillation, and explained pressure oscillation in terms of cavity resonance. Although research on pressure oscillation and engine knock has been carried out by experimental approaches, very few simulation literature on pressure oscillation has been published so far due to the great instability and nonlinearity of pressure oscillation, and it is of great importance to put forward effective approaches to inhabit these damaging pressure spikes [18,19].

In our previous work [20], pressure wave equation of internal combustion engine was derived from three-dimension flow field, and then was coupled with KIVA-3V combustion code. This paper paid more attention to high-frequency pressure oscillation during end-gas auto-ignition in knocking cycles through 3D CFD numerical simulation. The origin of pressure oscillation was studied in order to put forward effective inhibition approaches for engine knock, like cooled EGR. Here the calculation code can be applied to accurately simulate in-cylinder pressure oscillation when weak knock occurs. However, research on shock waves with high Mach number in heavy knock or super-knock is beyond the scope of present study, and maybe some relevant research findings would be published in the future.

The paper was organized as follows. The following section gave a brief introduction to pressure wave equation of internal combustion engine. After validation of the numerical model in normal combustion cases, we further discussed and analyzed calculated results, including cylinder pressure, pressure oscillation and FFT spectral characteristics. Then high-speed flame propagation images were compared to corresponding results from 3D CFD calculation. Contribution of different source term in flow field to pressure oscillation was researched in details in the next, followed by the effect of different levels of cooled EGR on the suppression of pressure oscillation, and finally came the conclusions.

2. Coupling of pressure wave equation and KIVA-3V code

2.1. Wave equation of internal combustion engine

Lighthill equation and aeroacoustics analogy are the most general theories for sound generation. Based on Navier–Stokes equation, Lighthill put the classic expression of acoustic wave equation on the left side, and moved all other off-line terms on the right side as source terms [21–23]. These source terms were obtained through experiments or calculation results, and then the whole sound field was described by the sound wave caused by these sources transmission in static medium.

Actually, combustion process in internal combustion engines can also be regarded as a set of coupled partial differential equations [24], including mass conservation equation, compressible partial differential momentum conservation equation, energy conservation equation, gas state equation, etc. Using Lighthill equation for reference, all terms deviated from the wave equation are put at the right side as pressure sources, then the pressure wave equation of internal combustion engine can be obtained:

$$\frac{\gamma}{c^2}\frac{\partial^2 p}{\partial t^2}-\frac{1}{a^2}\nabla^2 p=\frac{2\gamma}{c^3}\frac{\partial p}{\partial t}\frac{\partial c}{\partial t}-\frac{\partial\left[\frac{\rho u}{\gamma c^2}\nabla\cdot(c^2)\right]}{\partial t}+\left[\nabla^2\cdot(\rho uu)+\frac{2}{3}A_0\nabla^2(\rho k)-\nabla^2\sigma-\nabla F_s-\nabla\rho g\right]+\gamma\frac{\gamma-1}{c^2}\frac{\partial}{\partial t}\left[-p\nabla u+(1-A_0)\sigma\nabla u-\nabla J+A_0\rho\varepsilon+\dot{Q}_c+\dot{Q}_s\right] \quad (1)$$

Eq. (1) is a three-dimensional partial differential equation of second order which describes pressure oscillation during combustion in internal combustion engines. The left side describes free fluctuations of gas in cylinder, while the right side represents multiple excitation sources that can be taken from KIVA-3V code. Among these excitation sources, the first two terms are the derived ones which indicate the non-uniformity of sound speed in time and space can produce pressure sources in the whole flow field. The third term comes from momentum equation, and the fourth term is from energy equation. However, it is only valid in the absence of shock waves with high Mach number and detonation. The