DOI: 10.3901/CJME.2012.02.362, available online at www.springerlink.com; www.cjmenet.com; www.cjmenet.com.cn

Calculation on Cylinder Pressure Fluctuation by Using the Wave Equation in KIVA Program

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Received November 3, 2010; revised May 9, 2011; accepted May 12, 2011

Abstract: Cylinder pressure fluctuation during combustion process of internal combustion engine is closely related to combustion noise and knock. The current studies are based on cylinder pressure test to obtain information on combustion noise and knock, but there is little for simulation of combustion pressure fluctuation. Based on effects of combustion process in the combustion chamber on cylinder pressure by using wave equation, the mechanism of pressure fluctuation during combustion is researched with three-dimensional acoustic wave equation and flow field model of KIVA program. The cylinder pressure fluctuation curve, temperature field and acoustic field are obtained from the coupled calculation of the wave equation and KIVA program. The frequency spectrum analysis is taken with the cylinder pressure oscillation of cylinder pressure measured and calculated. The calculation result is consistent with the experimental result. This indicates that the cylinder pressure fluctuation can be correctly calculated with the wave equation. Analysis of calculation results of temperature field and acoustic field shows that sound field changes faster than flame propagates, and distribution of sound field is more complicated. Combustion pressure oscillation in the diesel engine is under highly unstable condition. This indicates that the combination of cylinder pressure fluctuation model and combustion model is an effective method to study the pressure oscillations and a new method to study the combustion noise and knock.

Key words: combustion, pressure oscillation, acoustic pressure, knock, wave equation

1 Introduction

Work-related noise, vibration and shock load in diesel engine is closely related to its combustion process. In the measured indicator diagram, the cylinder pressure curve often has jagged pressure fluctuations in the combustion zone. The traditional approach of assessing combustion noise is spectrum analysis of the cylinder pressure, using spectrum of cylinder pressure-level to assess the combustion noise[1]. PISCHINGER put forward identification method of time-frequency-window to analysis combustion noise[2], and RUSSELL, et al, put forward the concept of the average structure attenuation, using spectrum of cylinder pressure measured from engine with attenuation structure to express combustion noises[3–4]. Now a series of new techniques and methods have been used to measure and analyze combustion noises in order to further understand the characteristics of combustion noise source. Wavelet Transform, instead of the traditional Fourier transform, is used to carry out real-time oscillation spectrum analysis of in-cylinder pressure[5]. Multiple regression analysis is used to identify combustion noise, mechanical noise, dynamic noise and other noises[6]. The "coherent output power spectrum function" is used to identify combustion noise directly from the total noises[7]. Normal time-frequency transform with adaptive window is used to decompose and compose time-varying signals of combustion noise[8]. Independent component analysis is used to identify combustion noise[9]. While sound intensity measurement technique is applied to the internal combustion engine combustion noise measurement, a formula is deduced to calculate combustion noise and mechanical noise separately, thus a new method to test engine combustion noise is produced[10].

With the detailed study of combustion noise, it is found that combustion pressure in the DI diesel engine is oscillating. This oscillation is manifested as pressure difference at every points of the combustion chamber after combustion at the same time, and the pressure curve is superposition of both a smooth curve and "oscillation curve". The smooth curve represents the main energy of the combustion pressure, which is displayed as work done outside and distributed in low frequencies. The oscillation curve represents pressures which are distributed in middle and high frequencies and displayed as strong impacts on engine parts, the impacts produce vibration and noise radiation[11]. Experiments[12] show that noises are mainly produced by less than 5% of total pressure vibration energy in the cylinder. Therefore, the study and reduction of combustion pressure oscillations in the DI diesel engine is

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This project is supported by National Natural Science Foundation of China (Grant No. 50706032 and No. 50476065), and PhD Programs Foundation of Ministry of Education of China (Grant No. 20070056011)

very important for control of combustion noise. The study on combustion noises in the DI diesel engine by PRIEDE[13] shows that the energy of combustion noises in high frequency domain is concentrated at several frequencies. The study by HICKING[14] shows that the several frequencies at which noise energy is concentrated are mainly resonance frequencies of in-cylinder combustion pressure. As the structure of the diesel engine has smaller attenuation coefficient of high-frequency excitation transfer, the energy radiation at pressure resonance frequencies is larger, becoming main components of combustion noise. In 1987, PISCHINGER[15], et al, studied the effects of combustion pressure oscillations on diesel engine combustion noises, and pointed out that the combustion noise could be reduced by controlling pressure oscillations.

From the study object point of view, since 2000, all calculations of the gasoline engine[16–17], the diesel engine[18–19] and HCCI[20–21] by using KIVA program have not given the quantitative relationship between in-cylinder pressure oscillation and combustion process in the simulation calculation. Ref. [22] gives a simplified wave equation of in-cylinder gas, but does not provide solution because of the complexity of the combustion process and the difficulty of finding solution, and only analyzes oscillation process qualitatively. During the combustion process, the greater the pressure rises, the more pulse components are contained, the more high-frequencies there are in the spectrum. The cylinder pressure fluctuations in the frequency domain are caused by turbulent movement of gas in the combustion chamber and special inhomogeneity of combustion. The cylinder pressure fluctuations in high-frequency domain are related to the structure of the combustion chamber, displayed as cavity resonance frequency response of the combustion chamber.

However, during the operation of the internal combustion engine, pressure changes in the combustion chamber caused by cavity resonance are the objective reality. The combustion stimulation is a broadband one, after beginning of combustion the pressure field changes in the combustion chamber stimulated by thermo-acoustic coupling is very large, and in the internal combustion engine the pressure is a main factor which affects ignition of working medium. Pressure change is not only a thermodynamic problem, but also is closely related with the acoustic characteristics of combustion chamber structure. For a long time, the complexity of the combustion process, and limitation of experimental conditions, testing techniques, equipments and others have brought many obstacles to study on combustion process. For decades, acoustics, heat transfer, fluid mechanics, and modern testing technology have made much progress, but there is still no complete physical picture and quantitative interpretation about the interaction of sound field with heat transfer and combustion.

The nonlinear pressure wave function was gained by CULICK[23]. The nonlinear terms arising from the gas-dynamics in the chamber, the combustion, and other processes were considered. The equation is a forced wave equation and the left side describes free fluctuations of the gas, while excitation source terms on the right side include combustion heat release and gas turbulent motion. This equation expressed the theoretical derivation of the pressure wave function, and discussed the combustion problem in terms of acoustics. In theory, the equation is applicable to any combustion chamber, but mostly applied to solid rockets, liquid rockets, or thrust augmenters on jet engines, where no spray effects on the pressure wave function happening in internal combustion engines[21].

In this paper the coupling calculation of pressure wave equation is derived from the combustion simulation program, then combustion pressure oscillations in the DI diesel engine are calculated and compared with experimental results, the law of cylinder pressure oscillations is summarized, and interaction of the sound field with heat transfer and combustion is studied. Based on study of engine combustion by using the wave equation and from a new perspective to examine combustion in the internal combustion engine, it is possible to reveal the mechanism of combustion noise more deeply.

2 Coupling Calculation Based on the Wave Equation and KIVA

2.1 Derivation and principle of the wave equation

LIGHTHILL equation and aeroacoustics analogy are the most general theory for sound generating from airflow. Starting from N-S equation, LIGHTHILL put the classic expression of the acoustic wave equation on the left side, and moved all other off-line terms on the right side as source terms[24–26]. These source terms can first be obtained through experiments or calculation, and then the sound field can be regarded as the sound wave produced by sound source transmission in the static medium, so at last the sound field can be calculated by using the classical acoustic method.

Simulation calculation of combustion in internal combustion engine normally comes down to a set of coupled partial differential equations. When dual-equation turbulence model is used, solution of KIVA flow field can be expressed as follows[27]: the mass conservation equation, three-dimensional unsteady compressible viscous fluid partial differential equation of momentum conservation, energy conservation equation and gas state equation.

During combustion in the internal combustion engine, various gas movements will produce different sound sources. Using LIGHTHILL equations for reference, all terms that are deviated from the wave equation are put at the right side as sound sources, then the acoustic wave equation in the engine cylinder is to be deduced and solved. In order to deduce the acoustic wave equation in the cylinder, it is necessary to introduce the small amplitude sound speed formula and internal energy formula for ideal gas, Meyer relation, and the ratio between heat capacity at constant pressure and heat capacity at constant volume, then the pressure fluctuation equation in the engine cylinder Eq. (1) can be obtained through deduction:

$$\frac{\gamma}{c^2}\frac{\partial^2 p}{\partial t^2}-\frac{1}{a^2}\nabla^2 p=\frac{2\gamma}{c^3}\frac{\partial p}{\partial t}\bullet\frac{\partial c}{\partial t}-\frac{\partial\left[\frac{\rho u}{\gamma c^2}\nabla\bullet(c^2)\right]}{\partial t}+$$
$$[\nabla^2\bullet(\rho uu)+A_0\frac{2}{3}\nabla^2(\rho k)-\nabla^2\bullet\sigma-\nabla F_{\mathrm{s}}-\nabla\rho g]+$$
$$\gamma\frac{\gamma-1}{c^2}\frac{\partial}{\partial t}[-p\nabla\bullet u+(1-A_0)\sigma\nabla u-\nabla\bullet J+A_0\rho\varepsilon+\dot{Q}_{\mathrm{c}}+\dot{Q}_{\mathrm{s}}]. \tag{1}$$

Where γ—Adiabatic index;
c—Speed of sound;
p—Gas pressure;
ρ—Total mass density of fluid (not including the mass of sprayed fuel particles) ;
u—Fluid velocity;
$\dot{\rho}_{\mathrm{s}}$—Mass change of fuel due to evaporation or condensation. Where α is dimensionless, related with Pressure Gradient Scaling (PGS) in KIVA, real-timely calculated in the program, used for strengthening computational efficiency of the low Mach number flow. In the paper $a=1$. $A_0=0$ for laminar flow calculation, $A_0=1$ for turbulent flow calculation;
k—Turbulence production term in the k-ε model;
ε—Dissipation rate of turbulence production term in the k-ε model;
σ—Viscous force tensor;
F_{s}—Momentum increment due to spray and other causes;
J—Heat flux caused by heat conduction and Enthalpy dissipation;
$\dot{Q}_{\mathrm{c}}$—Chemical reaction heat;
$\dot{Q}_{\mathrm{s}}$—Heat source term caused by spray and heat conduction.

Eq. (1) is three-dimensional partial differential wave equation of second order which describes acoustic oscillation during combustion in the engine. The left side describes free fluctuations of gas, while multiple excitation source terms at the right side excite, or obstruct, or attenuate, or dissipate gas oscillation in the cylinder, can be taken from the KIVA program. Among the excitation source terms at the right side the first and second terms are the derived ones, indicating that time and space inhomogeneity of sound speeds in the sound field can produce sound sources. The third major term comes from the momentum equation, the fourth major term from the energy equation.

2.2 Coupling calculation method

In accordance with combustion characteristics of the internal combustion engine, if the harmonic approach is used, it will be very difficult to solve the equation for the combustion chamber with multi-frequency acoustic structure, because the volume of combustion chamber is continuously changing, plus temperature of the combustion chamber is changing and its acoustic characteristics are also changing. At the same time the complex fluid flow and the uncertainty of combustion area determine the uncertainty of excitation source. Therefore for the wave equation in cylindrical coordinates, it is very complex or even impossible to obtain three-dimensional analytical solutions of the wave equation with source terms excited by combustion. In order to obtain to coupling relationship between the process of combustion heat release and the wave equation, in addition to direct perception of superficial phenomenon through experimental measurements (such as by means of high-speed photography), theoretical analysis and numerical solution methods should be used in order to explain thermoacoustic coupling during combustion in internal combustion engine more deeply.

The platform chosen for coupling calculation of is in open KIVA. KIVA uses the arbitrary Lagrangian-Euler method to get solutions, this is the difference method developed to solve the problem of ever-changing of solving area with finite volume method. It can solve variables of flow field in common engineering, such as temperature field, overall pressure field, density field, fuel concentration field, distribution field of turbulence energy and its dissipation rate and so on. However KIVA software need introduce other model to take into account pressure fluctuations in combustion process[28]. In this article the acoustic theory is introduced into calculation of the combustion process in order to reflect the pressure fluctuations in the combustion process to evaluate directly specific relationship between the acoustic wave and combustion process.

One method is to combine the acoustic wave equation with KIVA combustion software, during simulation calculation variable values can be read from KIVA and then used for calculation of acoustic wave and evaluation of pressure fluctuations. As the acoustic fluctuation is a micro variable in higher-order than gas flow variables. Under normal circumstances, dividing time step for combustion simulation calculation into very small (usually after start of burning, in order to ensure computational stability rather than divergence, time step has to be automatically divided very small, sometimes even a tenth of time in which acoustic wave travels a one grid, about 10^{-7} s) and ignoring acoustic fluctuation is reasonable and feasible. However, under some conditions when everything matches (for example at ignition time, initial burning temperature, fuel octane number, mixture concentration, compression ratio and other conditions), it may lead to strong acoustic resonance of gases in the combustion chamber at the beginning of burning which is excited by source terms, then the temperature of unburned gases fluctuates. It may even lead to crude operation of diesel engine. By this time how pressure fluctuations affect combustion process will be know by solution of the wave Eq. (1) and illustration of the results.

2.3 Wave equation and flow of KIVA coupled calculation

Eq. (1) shows that the sound field in the combustion chamber is affected by a number of excitation sources, during KIVA calculation process these terms need to get real-time data, and then the wave equation is solved, as in the flow chart 1(see Fig.1). Calculation of the source terms is related to several flow field subroutines and chemical reaction subroutines in KIVA. It should be noted that, in order to simplify the flow chart, the indirect solving processes in KIVA are omitted, and chemical reaction model and flow field model with many subroutines are indicated with one process.

The chemical reaction model used in KIVA divides all the chemical reaction into two categories, the chemical reaction kinetics and equilibrium reaction. The partial balance flow equation is adopted to simulate the oxidation of fuel and the exothermic process.

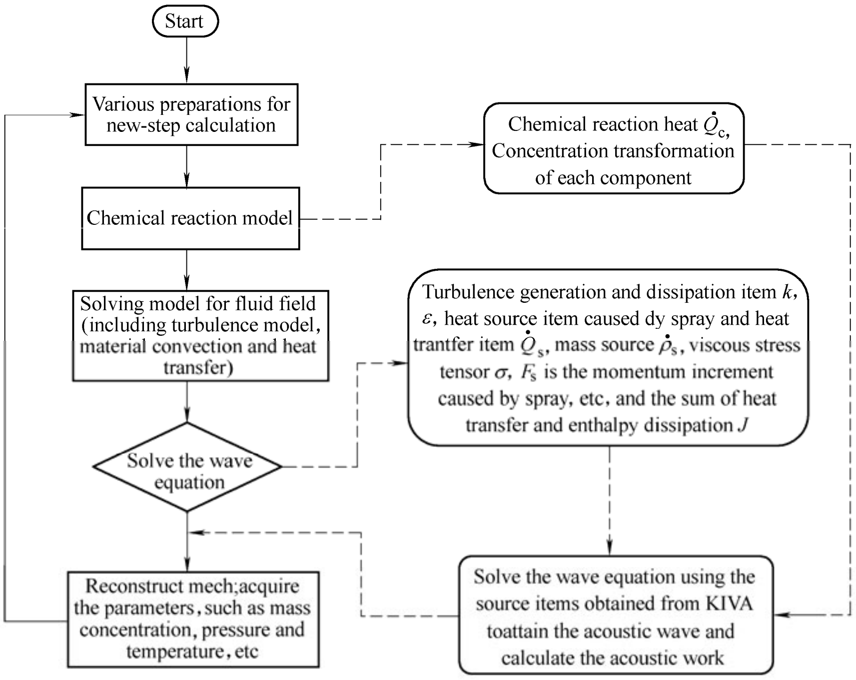


Fig. 1. Flow chart of calculation of acoustic characteristics by using wave equation and KIVA program

2.4 Time step for KIVA calculation

As the combustion chamber pressure fluctuates very quickly, in order to guarantee the convergence of computing, time step and space step for calculation must meet a certain relationship. KIVA uses courant number $C_s = c\Delta t/\Delta x$ to specify time step to ensure convergence of the pressure field. For example, if the length of radial grid is 2 mm, the time step $\Delta t \leqslant 2\times 10^{-6}$ s can accurately display the pressure fluctuation.

Take the gasoline engine for example as shown in Fig. 2. Calculate relationship of time step virus time (crank angle) in KIVA when the ignition advance angle is 20° CA. Fig. 2 shows that the time step in KIVA changes continuously with the increase of time. Before ignition, the time step is normally large because of small change of pressure field. After ignition the time step may decrease to the order of 10^{-6} s at any moment, or even to 10^{-7} s. It is obvious that the rapid release of heat has severe effects on acoustic field in the combustion process, so computation amount of combustion simulation program for solving the pressure wave will increase greatly.

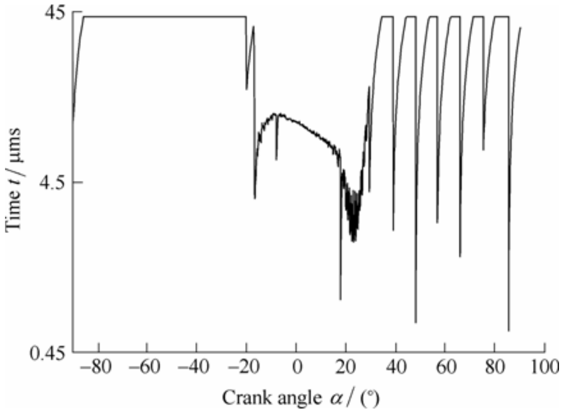


Fig. 2. Auto-adjustment of time step in KIVA calculation process

3 Preliminary Study on Pressure Fluctuation During Combustion in the Diesel Engine

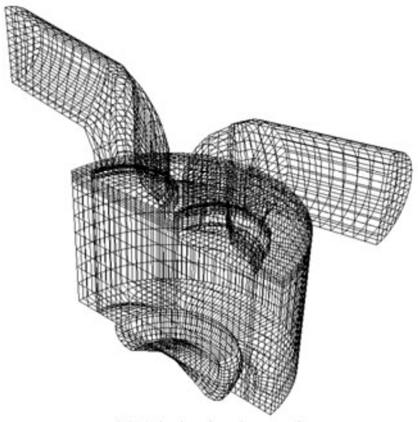
In order to study the acoustic characteristics of the diesel engine, combustion calculation and pressure oscillation calculation are carried out for a diesel engine which has

100 mm bore, 12 °CA fuel injection advance angle, ω formed combustion chamber, and   is running at 2 100 r/min speed. It technical specifications are shown in Table 1.

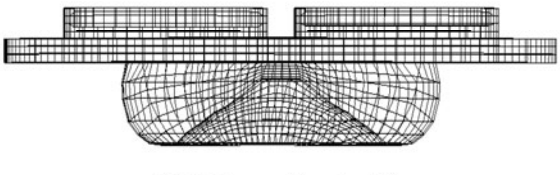
Table 1. Technical specifications of diesel engines chosen for calculation

Item	Parameters description
Type	Vertical, inline, 4-stroke
Number of cylinder	4
Cylinder bore × stroke/(mm × mm)	100 × 105
Form of cylinder liner	Wet
Combustion chamber model	Direct injection, ω formed
Piston displacement $V_{\mathrm{L}}/\mathrm{L}$	3.298
Intake method	Natural intake
Min. stable idle speed $n/(\mathrm{r} \cdot \mathrm{min}^{-1})$	⩽750
Compression ratio ε	17.5:1
Min. fuel consumption $g_{\mathrm{emin}}/(\mathrm{g} \cdot \mathrm{kW}^{-1} \cdot \mathrm{h}^{-1})$	⩽224
Max. torque/speed $T_{\mathrm{emax}}/n((\mathrm{N} \cdot \mathrm{m})/(\mathrm{r} \cdot \mathrm{min}^{-1}))$	245/2 000–245/2 200
Cooling method	Force water cooling circulation

The meshes used for calculation are shown in Fig. 3 (a) below. In order to save computing time, it is supposed that the combustion is symmetrical with respect to the vertical plane through the mid-points of inlet and outlet, so calculation can be done only in a half of the circular meshes. Fig. 3 (b) shows that when the piston is near TDC, the part of inlet and outlet mesh has nothing to do with the combustion calculation and is deleted, only the combustion chamber is remained, so calculation amount decreases greatly.



(a) Whole circular meshes



(b) Meshes used for calculation

Fig. 3. Mesh for calculation and mesh adjustment in combustion process

In order to compare the measured and calculated pressure, the pressure data at the position of actual location of the pressure sensor were extracted from simulation results. Fig. 4 is the comparison of the calculated indicator diagram and the experimental indicator diagram. Fig. 4 shows that the in-cylinder pressure curve calculated by coupled combustion program has the characteristics of pressure fluctuations, calculated results and measured results are consistent with each other well. In order to further understand the characteristics of cylinder pressure fluctuations, high-frequency pressure components of the experimental results and calculated results are analyzed.

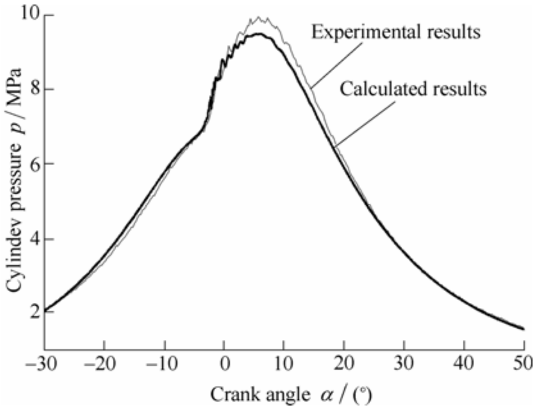
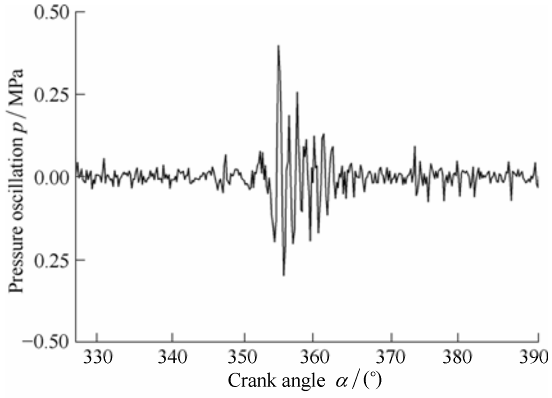


Fig. 4. Comparison of indicator diagrams of calculation results and experiment results of diesel engine

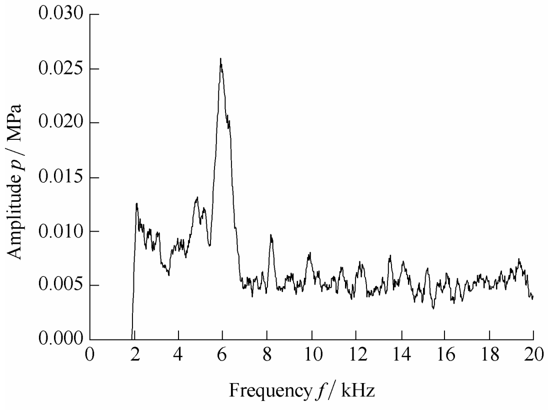
Fig. 5 is the experimental results obtained from high-frequency pressure oscillation and spectral analysis 2 kHz high-pass filtration. Fig. 6 is the calculated acoustic fluctuations and spectrum in the combustion chamber. Fig. 5 and Fig. 6 show that, high-frequency components of pressure fluctuations are denser than the calculated results, the maximum amplitudes of fluctuation are almost same, and the frequencies of the maximum amplitudes are about 6 kHz. Therefore, the results of coupled calculation of the wave equation and the combustion program can accurately reflect in-cylinder pressure.

Now the normal combustion process (expressed by temperature field) and acoustic oscillation process in the combustion chamber are obtained, and the results are shown in Fig. 7 which is a contour diagram against crank angles. Fig. 7 (a) is temperature field and Fig. 7 (b) is the sound field. Because of limit of paper length, only a part of calculated results against crank angles are given. The unit of the temperature field is K, unit of the sound field is Pa, and the crank angle at top dead center is 0 °CA.

The temperature field in Fig. 7 shows that, when the piston approaches the top dead center, several flame kernels are first formed near the fuel injector nozzle because of appropriate spray concentration here. Then the flame develops continuously until spreads to the whole chamber. This is a gradual process, the combustion chamber temperature can reach up to 2 500 K (average temperature is generally about 1 800 K). In contrast, the sound field in the chamber changes very rapidly and there is no sign showing that the whole acoustic field spreads gradually. The acoustic pressure amplitude oscillates back and forth between positive and negative values; the maximum amplitude is near top dead center 0 °CA, about 500 kPa. After top dead center the piston moves downward, the acoustic pressure in the cylinder still oscillates, but the acoustic pressure amplitude decreased rapidly. Here, the distribution diagram of temperature field changing is mainly used as an indicator of the combustion process, providing a reference object for acoustic field changing.

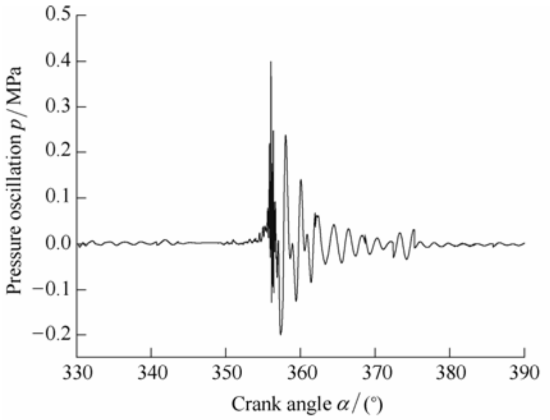


(a) Experimental pressure

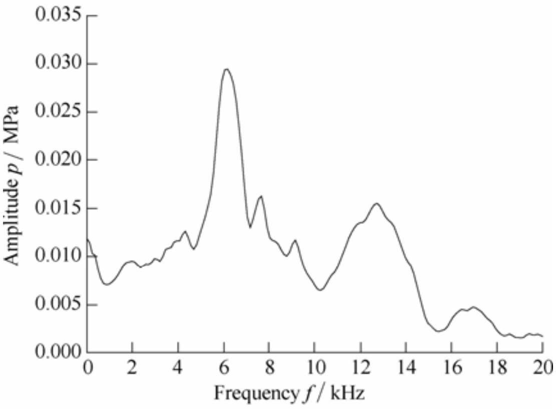


(b) Experimental date FET (2 000 Hz high pass filter)

Fig. 5. Experimental pressure fluctuations and spectrum in combustion chamber of diesel engine

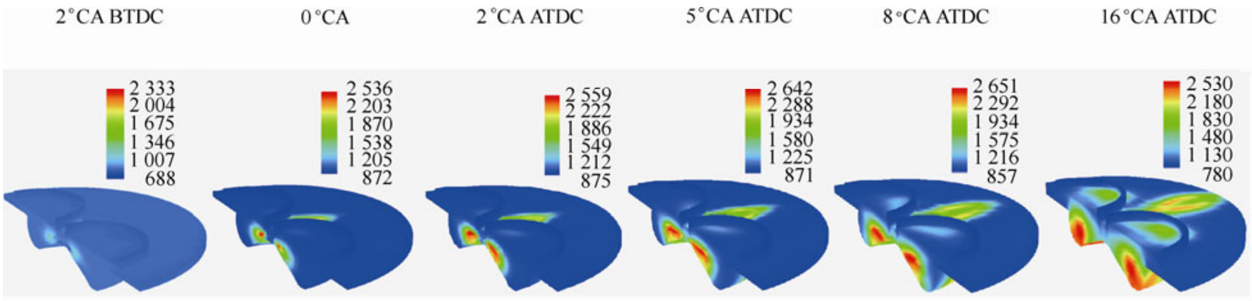


(a) Calculation of pressure oscillation

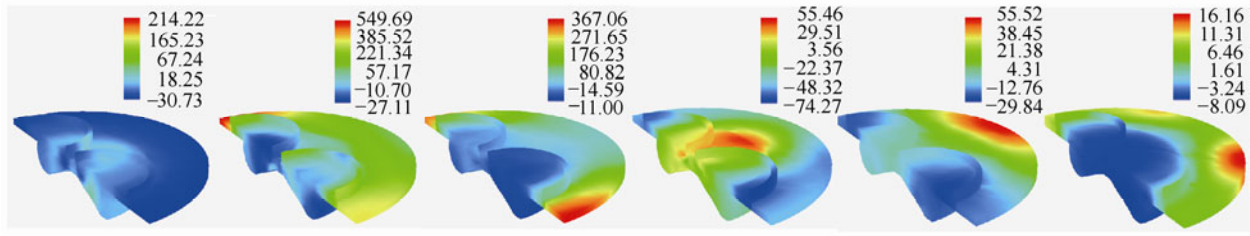


(b) Pressure oscillation FFT (calculated values)

Fig. 6. Calculated pressure fluctuations and spectrum in combustion chamber of diesel engine



(a) Temperature field T / K



(b) Acoustic field p / kPa

Fig. 7. Temperature field and acoustic field in combustion process in diesel engine, temperature fluctuations caused by fluctuation of acoustic field

4 Conclusions

(1) The study on characteristics of the acoustic changing in the combustion chamber by using the wave equation and KIVA combustion program can reveal mechanism of effect of the chamber acoustic properties on the acoustic fluctuations during the combustion process in the combustion chamber. The coupling model of the acoustic model and combustion model of the combustion chamber is established, the coupling calculation method of the wave equation and KIVA is discussed, and the time step for coupling calculation is determined.

(2) In order to study the effect of pressure fluctuations during the combustion process in the internal combustion engine, wave equation is deduced from KIVA calculation model, and then the calculated results are compared with the experimental results. Good consistency of two kinds of results shows that coupling study based on the combustion process can investigate pressure fluctuation mechanism in the combustion chamber from a new angle.

(3) The combustion induces the sudden increase of pressure, which excites the pressure oscillation in the acoustic cavity of the combustion chamber. Under high temperature and high pressure and in a very small space sound speed is very large, the sound field changes rapidly. Oscillation frequencies are usually in high frequency band, showing that severe acoustic oscillations occur mainly in the vicinity of top dead center.

(4) Study on pressure fluctuations in internal combustion engine can further enrich and improve the combustion theory, promote and develop the design concept of internal combustion engine, and understand the combustion process and generation mechanism of combustion noise in the internal combustion engine from a new angle.

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