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INITIATIONS OF ENGINE KNOCK: TRADITIONAL AND MODERN

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ABSTRACT

There is no faultless fundamental explanation of the engine knock over the range of engine conditions at which knock occurs. The widely accepted end-gas autoignition theory is available only for the knock at low engine speeds. There has to be other mechanisms which lead high-speed engine knock, potentially most damaging. In this paper the approaches to the in-cylinder autoignition are reviewed and three novel mechanisms are proposed on the basis of our experimental observations. The proposed mechanisms would give more appealing interpretations for the high-speed knocking and former non-autoignition theories of knock initiation.

INTRODUCTION

It is agreed that engine knock is due to a local rapid combustion in engine cylinder. The widely accepted theory that engine knock is caused by an autoignition of end-gas ahead of a flame front could not explain all kind of engine knock over the whole range of engine operating conditions.

On the traditional concept, whether knock would occur or not depends on the result of competition between propagating flame and preknock reactions in the end-gas. Knocking would appear when the induction time for the end-gas autoignition is less than the time required for the cylinder charge to burn through a spark-initiated propagating flame. It has been well recognized that flame propagation of in-cylinder charge will be accelerated almost directly with increase in turbulence intensity. On the other hand, the effect of fluid motion on autoignition in the charge is recently examined /1/, and deceleration effects on preflame reactions are shown. Engine speed will give a positive effect on the flame propagation and a negative effect on the onset of ignition by intensified turbulence. Based on these two characteristics and the traditional autoignition concept, the most effective way to eliminate engine knock should be a high-speed operation of the engine. Practically the knock caused at 1500 rpm will be suppressed at higher speeds such as 2500 rpm. In this "low-speed engine knock", sometimes called acceleration knock, the traditional autoignition theory still remains alive.

However, engine knock appears again at higher engine speed more than 3000 and even at as high as 5000 rpm /2/. This "high-speed knock" is usually the so-called constant-speed knock, which can much more easily lead engine damage. This kind of knock cannot be explained by the simple autoignition theory. There has to be more than one course for engine knock which gives pressure oscillations.

Two approaches to understand the end-gas autoignition, low-temperature and high temperature ones, are discussed here and three novel mechanisms are proposed to elucidate the high speed knock.

TRADITIONAL LOW-SPEED KNOCKING

1) Low-Temperature Approach

In this approach, the autoignition has been considered to be preceded by the low-temperature oxidation of fuel characterized by low-temperature flames; cool flame and blue flame. It has been widely accepted that engine knock is caused through these oxidation processes in the unburned gas. But cool flames have seldom been observed in real engines, though they have been found in longer time scales produced by motored engines and rapid-compression machines in laboratories. It seems to be premature to jump to conclusion that the low-temperature oxidation reactions are not likely to occur in the end-gas in real engine cylinders. Most activities of this approach are experimental. Kinetics models using several pseudo elementary reactions have been developed /3,4/, which is successfully applied to simulate the existence of negative temperature coefficient region in the low-temperature oxidation.

The temperature when hot-flame appears during knocking cycle is, however, almost 1000 K /5,6/. The most decisive reactions for the onset of knock would be those carried out under the temperature just below 1000 K. Temperature of cool flame appearance is much lower than 1000 K. The low-temperature approach, the most traditional one, should be criticized owing to the temperature too low for engine knock, especially when claimed that knock has to be accompanied by cool flame.

2) High-Temperature Approach

Smith et al. have concluded in a study with n-butane fuel that the low-temperature oxidation reactions or the cool flame aspects for the end-gas autoignition have little effect on the engine knock /7/. For their ignition simulation, the comprehensive reaction mechanism was applied, which was available only for high-temperature thermal-ignitions higher than 1300 K. This is the high-temperature approach. It will be the most important merit of this approach to use the real elementary reactions associated with experimentally confirmed rate constants for ignition simulation. The approach is quite modern even though the low-speed knock phenomenon is essentially traditional.

In their experiment, the end-gas was heated up within a very short duration by the burned-gas expansions of propagating flames from four quarters. It was an extreme combination of no cool flame reactions, very short compression duration and high temperature at the hot-flame onset. The experimental data and simulation showed good agreement for the ignition occurring above 1000 K, but poor below 1000 K.

It is still difficult to include adequately the low-temperature oxidation mechanism into the comprehensive mechanism. There was nothing for it but to do because the low-temperature mechanism of n-butane oxidation is not yet developed. The high-temperature approach should be also criticized owing to the temperature too high for engine knock, especially when claimed that low-temperature oxidation reactions have little effect on the engine knock. Counterevidences on this approach have shown that the importance of the low-temperature oxidation grows below 1000 K when the compression is slow /8/.

It has not been recognized that there is a vacuum between both these two approaches, which blank is the most important range for the engine knock. For example from the experimental point of view, there is a vacuum of ignition delays between the data obtained by rapid-compression machines and by shock tubes. The continuously ranging experimental data from 600 to 1800 K would be desired for engine knock before developing mechanism. A few trials to obtain these data have now been presented using shock tubes /9,10/.

Approaches to the low-speed knock are characterized by its bias to the ignition field, independent of the interaction with the propagating flame behavior.

MODERN HIGH-SPEED KNOCKING

High-speed operation is required to take high power from small engines. The high-speed knock is a modern problem.

One of the most probable sources other than autoignition was the turbulent flame acceleration. Curry /11/, and Maly and Ziegler /12/ proposed concepts of knock as a consequence of acceleration of the propagating flame. These flame acceleration theories for engine knock have later been questioned or will be given another interpretation here.

Three experimental studies are presented to show a possibility of other initiationsfor the knocking in high-speed spark ignition engines than the usual end-gas autoignition: two of these are related to the interaction between the propagating flame and preknock oxidation reactions. Under high-speed conditions the time taken for the compression and heatup of the mixture becomes shorter, and the fluid motion and turbulence in the charge are intensified. At high engine speeds these physical characteristics will have a great potential as well as the chemical oxidation processes.

1) Short Compression Duration

Duration taken to compress the mixture has a profound influence on the ignition delay even when the same temperature and pressure conditions are established at the end of its duration. Distinct difference has been shown between the data for shock wave ignition and for rapid-compression machine in the acetaldehyde mixture /8/. The delay in the rapid-compression machine are longer by an order of magnitude than in the shock tube.

Contrary to our expectations, a shorter compression duration would give a shorter ignition delay. Long compression duration may permit ample developments of low-temperature oxidations during its process, which results in a conversion of constituents of the charge from the original mixture of fuel and oxidizer. The products of low-temperature oxidation occurring in advance during the compression do not always promote hot-flame generation and give no positive effects for reducing ignition delays. The fuel directly carried into the final high temperature and pressure conditions will be exposed to the higher-temperature dissociation process compared with slow-compression case.

It will easily recognized that the high-temperature approach for the low-speed knock mentioned above is more informative or effective rather to this high-speed, short compression duration case.

2) Chemical Inhibitory Effect on Flame Propagation

Spark-initiated flame propagates into the end-gas in which preknock oxidationdevelops. During this process it is observed that flame hesitates to propagate into theend-gas; a propagating flame does not spread as a semicircular flame front in a uniform manner across the combustion chamber. A wedge-shaped end-gas is always formed ahead of the retarded flame front in the knocking cycle /13/. The pressure buildup prior to the hot-flame is slightly slower than that in knock-free cycles. It is postulated that the "stressed" end-gas will give a chemical inhibitory effect and cause a slowdown of the incoming propagating flame: this provides sufficient time for the end-gas autoignition even under high-speed engine conditions.

Formaldehyde is the most important species in the low-temperature oxidations of hydrocarbon fuels. t is considered that the OH radicals produced at the propagating flame front may be snatched away for the formaldehyde oxidation of the preknock reactions in theend-gas. This reaction produces HCO, a typical species characterizing blue flame emission.

3) Shear-Layer Entrained Knocking

Mixing of partially reacting gases inside the flame zone with an unburned preflame mixture could be a trigger for a thermo-chemical ignition /14/. Turbulent eddy was provided in the wake behind a obstacle under a strong swirl of in-cylinder charge. Irregularly accelerated burning occured in the wake when the unburned end-gas is engulfed in the propagating flame frontal zone. The mixed gases were cooled down first almost to the unburned mixture temperature by the mixing operation. A rapid high-temperature aerodynamic flame and pressure vibration followed after a short induction time in the similar way of autoignition.

The interaction can become more possible between the preflame mixture and the propagating flame zone in high-speed engine cylinders. Shear-layer mixing is a key mechanism of flame acceleration and knocking under strong fluid flows in combustion chambers.

A knocking-like fast burning occurs in trailing side in a Wankel-type rotary engine where the mixture is carried by the rotor revolution into the flame, propagating opposite direction of the rotor /15/. This is a typical example of shear-layer entrained knocking in a commercial engine. Other examples can be found in conventional reciprocating engines.

The similar conclusion can be conducted from a high speed photographs of very early days of knocking research /16/ that the knock reaction does not necessarily originate in the end-gas, and the engulfment of unburned gases by flame front is an important cause, though the interpretation in the paper was somewhat different.

It is now difficult to judge which mechanism is best applicable. Each one would not proceed independently but in parallel. The proposed mechanisms here would give better understandings and help to find countermeasures for the high-speed knocking.

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