Effects of Swirl Flow and Inhomogeneous Concentration Fields on Combustion of Propane-Air Mixture in a Constant-Volume Vessel

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INTRODUCTION

Direct injection gasoline engines enable thermal efficiency to improve very much in low load [1]. While homogeneous mixture is supplied by early injection in high load, ultra lean condition of which equivalence ratio is less than 0.4 is provided in the cylinder in low load. Then, flammable mixture near stoichiometric condition is provided near the spark plug, and the mixture in the vicinity of the cylinder wall is very lean at the ignition timing by late injection. After such engines have been produced for commercial use [2], some concepts have been proposed for providing the fuel in the cylinder. However, the phenomena in the cylinder are so complicated that they have to be simplified to each physical phenomenon. Therefore, some works have been done using constant volume vessels [3-8].

In this study, swirling flow was generated in a cylindrical vessel with gradient of fuel concentration from the center to the cylindrical wall. A flame developed almost axisymmetrically because the spark location was located at the center. The turbulence intensity and the fuel concentration were measured using an LDV and an LIF method, respectively. The flame propagation was visualized with a high-speed video camera. The combustion characteristics were investigated under some flow and concentration fields.

EXPERIMENTAL PROCEDURE

Figure 1 shows a schematic diagram of the experimental apparatus. A constant-volume vessel of disk type is 125 mm in diameter and 35 mm in width. When a control signal was given to an SSR that forces an air cylinder to move, a special valve was open for 200ms and air flowed into the vessel from an air tank. Then, a swirling flow was produced due to the configuration of the valve outlet. Propane was injected slowly from an accumulator into the combustion chamber through an injector installed at the center of one of the side walls. Richer mixture existed near the center and leaner near the wall, so that stratified concentration field could be realized almost axisymmetrically. The overall equivalence ratio, ϕ_m, was set to 0.3. The ignition timing was changed using two parameters, that is to say, the time from the closure of the special valve, t_{sv}, and the time from the end of injection, t_{ei}. Swirling flow was measured with an LDV without combustion as shown in Fig.2 [9]. Asisymmetric flow filed was produced in the combustion chamber and the turbulence became smaller with increasing the time from the closure of the valve. Concentration measurement was performed with a laser induced fluorescence (LIF). The fourth harmonic wavelength of Nd:YAG laser was used as an incident light and tracer was mixed with the fuel. A laser sheet passed through the combustion chamber and the fluorescence image was captured by a CCD camera with an image intensifier under without combustion. The mixture was ignited at the center of the combustion chamber. A flame was visualized through an optical window with a high-speed video camera (4500 fps).

The concept of experimental conditions is illustrated in Fig.3. The swirling flow decays, and the steep stratified concentration field becomes homogeneous with elapsed time. Therefore, various turbulence and concentration fields could be realized in this combustion vessel.

RESULTS

Pressure history in the combustion chamber was analyzed and mass fraction burned was determined from a thermodynamic model. The maxima of pressure and burn rate, and initial stage of the combustion period, are presented in Fig.4. Figure 5 shows examples of the flame propagation visualized with a high-speed video camera under the condition of t_{ei}=60ms. Slightly off-axis flame and some luminous parts could be seen locally in the flame due to inhomogeneous concentration field. The combustion efficiency was 40, 70, and 90 % for t_{sv}=10, 100, and 300ms, respectively when the unburned hydrocarbons in the burned gas was analyzed after the combustion. The maximum pressure was the largest at t_{sv}=300 ms and it became smaller with increasing turbulence intensity (smaller t_{sv}). When the turbulence intensity increased, the fuel diffused so rapidly that the flame could not propagate due to very lean region near the cylindrical wall. And the time from the end of injection, t_{ei}, increased, the maximum pressure decreased due to diffusion of the fuel. The value of $(dx/dt)_{max}$ shows almost the same at t_{sv}=100 and 300 ms, while the value decreased in larger t_{ei} at t_{sv}=10 ms. The initial stage of the combustion from 0 to 5 % of mass fraction burned, t(00-05), showed almost the same value for t_{sv}=10 and 100 ms. The value of t(00-05) and its fluctuation increased at t_{sv}=300 ms. In this condition, the turbulence was so small that very rich mixture remained near the spark location and the initial combustion was slower, although the combustion efficiency was about 90%.

Figure 6 shows the relation between equivalence ratio near the center measured with the LIF method and the combustion period of initial stage for various conditions in t_{sv}=10, 100 and 300ms in ϕ_{center}=0.3 with error bars that mean the standard deviation of concentration fluctuation near the center of the combustion chamber. In t_{sv}=10ms, the standard deviation was small because the fuel near the center diffused very much. In t_{sv}=100ms, the standard deviation was large while in t_{sv}=300ms, the fuel did not diffuse very much. Therefore, inhomogeneous mixture includes stoichiometric one even if it is lean or rich on the average in t_{sv}=10 and 100ms and the averaged lean and rich limits of flammability became wide.

SUMMARY

The flame propagation and the combustion characteristics of an inhomogeneous fuel-air mixture were investigated. The results obtained in this study are summarized as follows:

(1) A swirling flow with gas injection at the center produces various turbulence intensity and inhomogeneous fuel concentrations by changing the times of the end of gas injection and closure of the special valve.

(2) Inhomogeneous mixture near the center of the combustion chamber includes stoichiometric one even if it is lean or rich on the average in t_{sv}=10 and 100ms because of diffusion with swirl flow, so that the averaged lean and rich limits of flammability became wide.

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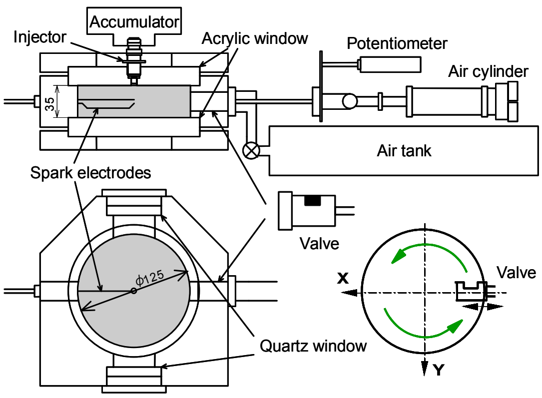

Fig.1 Schematic diagram of experimental apparatus

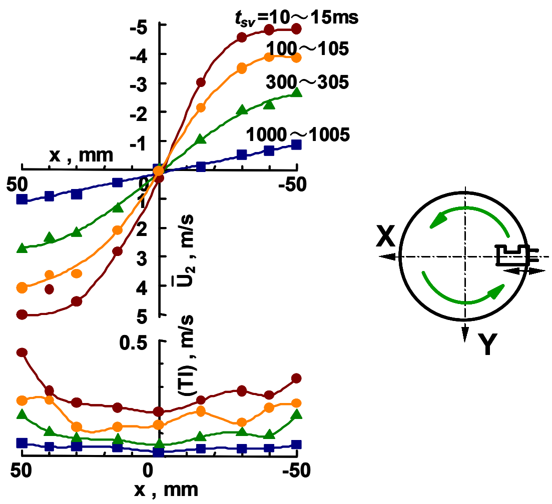

Fig.2 Mean velocity and turbulence intensity

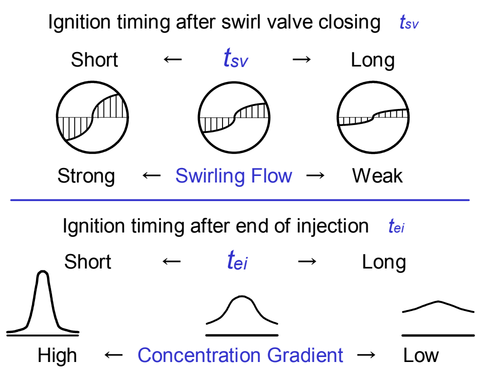

Fig.3 Concept of experimental conditions

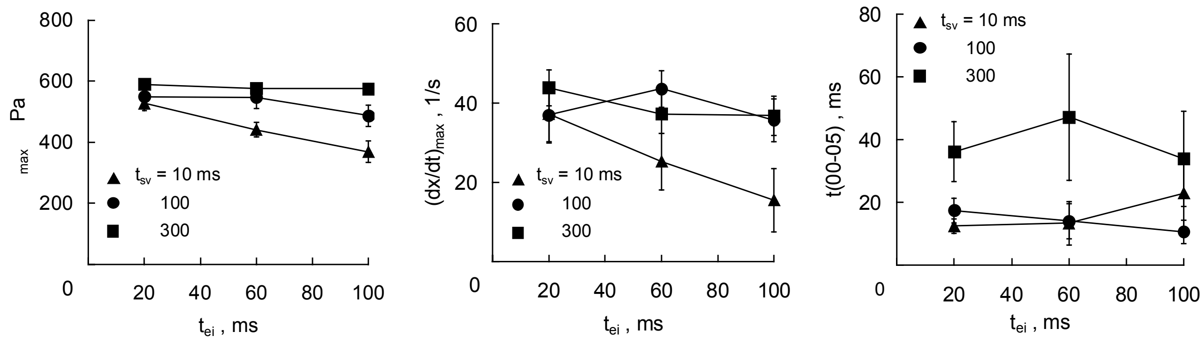

Fig.4 P_{max}, $(dx/dt)_{max}$ and t(00-05) under various experimental conditions (ϕ_m=0.30)

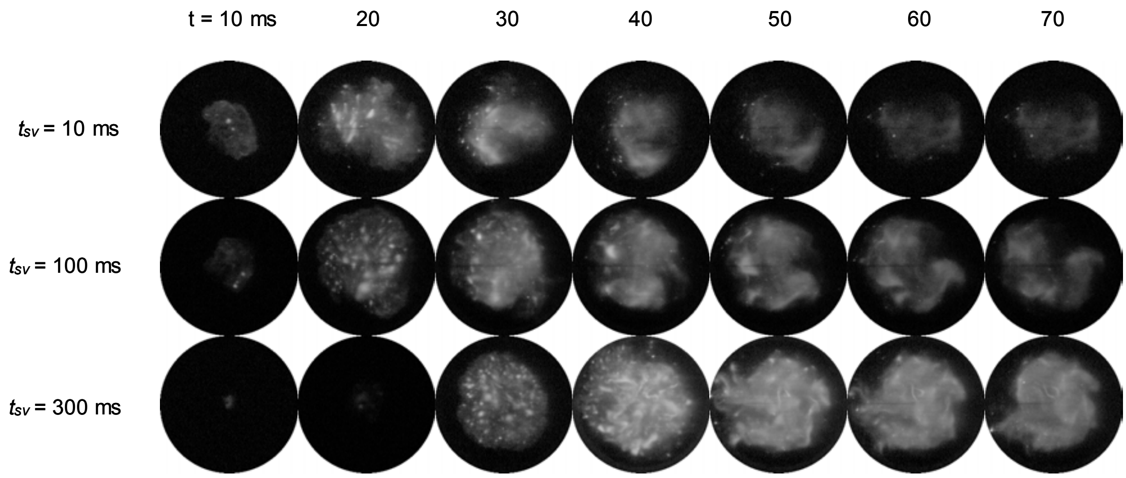

Fig.5 Images of flames propagating in the vessel (t_{ei}=60ms, ϕ_m=0.30)

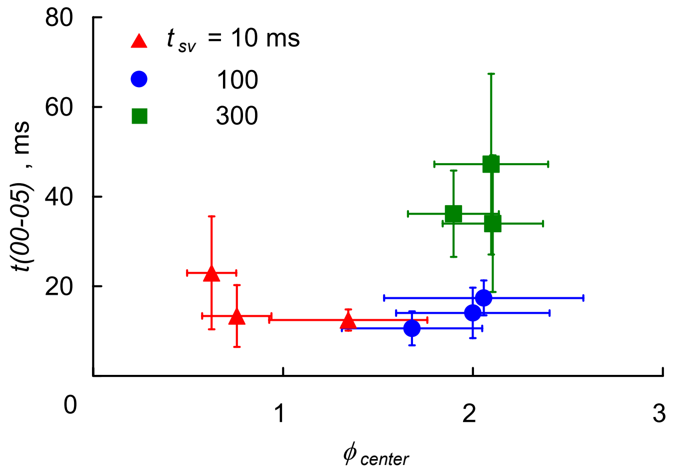

Fig.6 Initial combustion, t(00-05), versus equivalence ratio near the center (ϕ_m=0.30)