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COMBUSTION CHARACTERISTICS AND HEAT FLUX DISTRIBUTION OF PREMIXED PROPANE MIXTURE IN A CONSTANT VOLUME COMBUSTION CHAMBER

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ABSTRACT–This work is to investigate the surface heat flux and combustion characteristics of premixed propane mixture in a constant volume chamber. The experiment of heat flux and combustion characteristics of premixed propane mixture are performed with various equivalence ratio and initial pressure conditions. Based on the experimental results, it is found that the maximum instantaneous temperature is increased with the increase of initial pressure in the chamber. There are significant differences in the burning velocity of premixed propane mixture at different measuring points in the constant volume combustion chamber. Also, the trends of temperature difference at each measuring points are similar to the burning velocity in the combustion chamber. It is concluded that the total heat loss during the combustion period is affected by the equivalence ratio and the initial condition of fuel-air mixture.

KEY WORDS : LPG, Combustion characteristics, Instantaneous surface temperature probe, Burning velocity, Heat flux

1. INTRODUCTION

Many efforts have been made to reduce the emission of environmental pollution from vehicles. Many researches on the improvement of combustion characteristics focus on the fuel-air mixing and combustion process in the combustion chamber. Recently, new regulations regarding the harmful exhaust gases and improvement of fuel consumption have been reinforced in each country. Combustion characteristics can be investigated as a function of equivalence ratio, kind of fuels and composition for constant combustion chamber (Cho *et al.*, 2002; Lee, 2003; Sierens & Verhelst, 2001).

The state of the mixture of air and fuel induced into the combustion chamber has influences on the combustion characteristics and the heat flux. The analyses of the process of mixture formation in the combustion chamber are very important in order to investigate the combustion performance and flame propagation phenomenon in the system. Especially, the heat flux and wall temperature in the combustion chamber have an influence on the combustion characteristics such as burning velocity, combustion pressure, and the formation of combustion products.

In this study, the combustion of premixed propane mixture is tested in a constant volume chamber which resembles a spark ignition engine cylinder. In addition, the temperature distribution is measured with the high response thermocouples. The burning velocity was also calculated by using the instantaneous surface temperature in the combustion chamber. The experimental verification of each instrument response and measurement error was carried out to measure the heat flux in the constant volume combustion chamber.

2. HEAT FLUX AND BURNING VELOCITY

2.1. Heat Flux Measurement

2.1.1 Surface temperature probe

In this work, R-type thermocouple, which has capability of high accuracy, high temperature measurement over 1000°C, low dispersion and degradation, and good oxidation resistance, and the instantaneous surface temperature probe were installed at four places of constant volume chamber to measure the temperature of combustion field.

The temperature measuring thermocouple consists of the insulating tube to prevent each element wire from shortening and also has a ceramic insulating tube to protect the element wire from extreme heating. However, the ceramic insulating tube is so brittle that the thermocouple can be cut in the insulating tube.

As shown in Figure 1, element wire is placed inside the stainless steel tube and isolated with the use of ceramic

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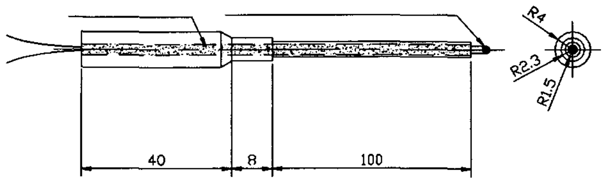


Figure 1. Structure of R-type thermocouple.

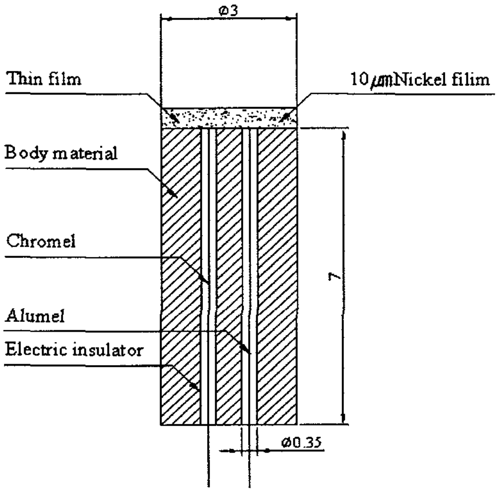


Figure 2. Structure of instantaneous surface temperature probe.

powder, while it exposes the junction to outside to measure the temperature.

In the measurement of surface temperature, many factors, such as the materials of probe, the element wire's thermal characteristics and size, the thickness of insulation layer and instantaneous contact surface, are related with the measurement error. Figure 2 shows the structure of instantaneous surface temperature. In this work, the probe of instantaneous surface temperature is made of chromel and alumel as illustrated by Enomoto in 1990.

The body metal of the instantaneous surface temperature probe is manufactured with the same material to that of constant volume chamber. The thin film forms membrane with the nickel plating of 10 μm in thickness. The diameter of thermocouple element wire which is isolated with the electric insulator is 0.35 mm.

2.1.2. Wall heat flux

If heat flux is one dimensional flow, the equation for unsteady thermal conduction is given by

$$\frac{\partial T}{\partial t}=a\frac{\partial^2 T}{\partial x^2} \tag{1}$$

where, T is temperature (K), a is wall heat diffusion coefficient (m^2/s), t is time (sec) and x is the depth (m) from the wall surface.

The solutions of equation (1) (Kim *et al.*, 2001) is as follows.

$$T(x,t)=T_0+\sum_{n=1}^{\infty} e^{-xa\sqrt{n\omega/2a}}\cdot[A_n\cos(n\omega t-x\sqrt{n\omega/2a})$$
$$+B_n\sin(n\omega t-x\sqrt{n\omega/2a})]$$

Temperature T(0, t) of the inside wall ($x=0$) can be shown as

$$T(0,t)=T_0+\sum_{n=1}^{\infty}[A_n\cos(n\omega t)+B_n\sin(n\omega t)] \tag{2}$$

In equation (2), T(0, t) of the obtained experimentally and A_n and B_n are the coefficients in the Fourier series, ω is an angular velocity when the experiment time is 2τ.

$$T(0)=\frac{1}{2\tau}\int_0^{2\tau}T(0,t)dt$$

$$A_n=\frac{1}{\tau}\int_0^{2\tau}T(0,t)cos(n\omega t)dt$$

$$B_n=\frac{1}{\tau}\int_0^{2\tau}T(0,t)\sin(n\omega t)dt$$

According to the heat flux at the inside wall, $q_w(t)$ is given by

$$q_w(t)=-k\left[\frac{\partial T(x,t)}{\partial x}\right]_{x=0}$$

$$=\frac{k}{L}(T_0-T_m)+k\sum_{n=1}^{\infty}\sqrt{n\omega/2a}\cdot[C_n\cos(n\omega t)$$
$$+D_n\sin(n\omega t)] \tag{3}$$

where, $C_n=A_n+B_n$, $D_n=B_n-A_n$, T_m is cold junction temperature, L is wall thickness and k is thermal conductivity.

2.2. Burning Velocity

This experiment used a steady-state one dimensional flame surface model and determined the flame movement from the ignition point to the inside wall of the chamber.

The burning velocity S_u can be expressed by using the maximum temperature of gas in the constant volume chamber (Metghalchi and Keck, 1982). In this experiment, T_0 and P_0 are the initial temperature and pressure before the iginition, T and P are the maximum temperature and pressure on the surface of combustion chamber after the process.

$$S_u=S_{u,0}\left(\frac{T}{T_0}\right)^a\left(\frac{P}{P_0}\right)^b \tag{4}$$

where

T = maximum temperature
P = maximum pressure

T_0 = 298 K, P_0 = 1 atm
a = 2.18–0.8(φ–1)
b = 0.16+0.22(φ–1)
$S_u = B_m + B_\varphi(\varphi - \varphi_m)^2$
φ_m = 1.08
B_m = 34.2(cm/s)
B_φ = −138.7(cm/s)
φ = equivalence ratio

3. EXPERIMENTAL APPARATUS AND PROCEDURE

3.1. Experimental Apparatus

The constant volume chamber used in this study is 80 mm in diameter and 110 mm in length. The volume of the circular cylinder is 552.9 cm^3 and the material of the cylinder is stainless steel.

As shown in Figure 3, for the incidence of laser beam, there are two windows made of MgF_2 glass with high transmissivity on the side of 193 nm wave length and two observation windows with quarts glass.

The observation windows are big enough to observe the flame of the combustion chamber. As illustrated in Figure 4, the four thermocouples are installed at different places around the spark plug to measure the temperature of combustion field.

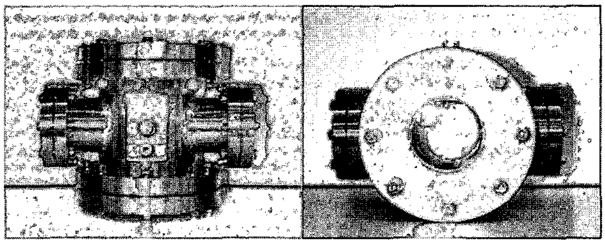


Figure 3. Photograph of the constant volume combustion chamber.

Table 1. Ignition system.

Item		Specifications
Ignition coil type		Mold type
Ignition coil	Primary coil	0.5 ± 0.05 Ω
	Secondary coil	12.1 ± 1.8 kΩ
Spark plug model no.		N9YC4
Dwell time		3.5 mm
Electrode gap		1 mm
Electrode material		Tungsten
Electrode diameter		2.5 mm
Electrode shape		Flat

A pre-heater and five 200W plate-heaters are placed to maintain the temperature of the constant volume chamber at 80°C. The ignition system uses the direct ignition.

Data acquisition system is used for the collection of the data from the measuring instruments.

3.2. Experimental Methods

The mixing chamber and the constant volume chamber are maintained at vacuum state before the experiment. At this state, the fuel C_3H_8 is supplied through the pressure regulator, membrance filter (0.5 μm), solenoid valve, preheating device, and the mixing chamber at the constant temperature of 80°C. The fuel volume, which is calculated with the partial pressure ratio, would be

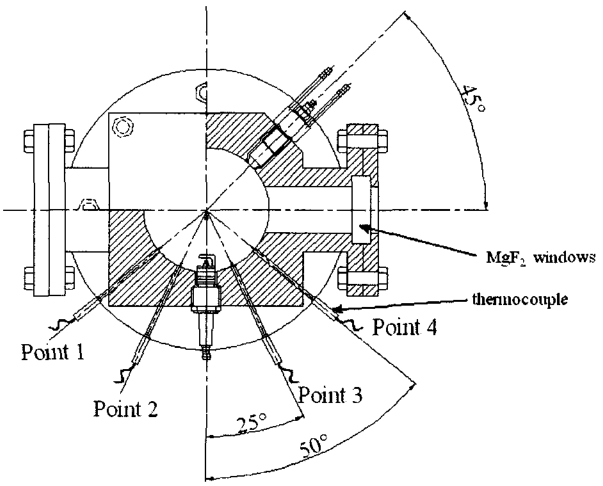


Figure 4. Schematic diagram of the constant volume combustion chamber.

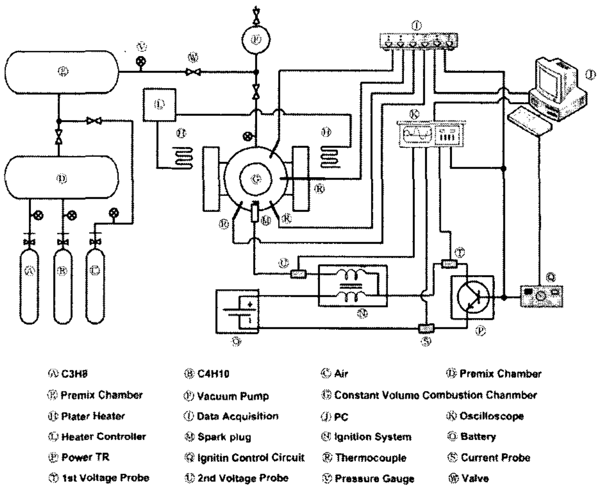


Figure 5. Schematic diagram of the experimental apparatus.

adjusted with the micro needle valve. The pressure of the mixing chamber maintains at 5 bar and is monitored with the digital pressure gauge. The fuel and air mixture in the mixing chamber is supplied to the constant volume chamber at 0.5–1.0 bar pressure. After the fuel is supplied, the ignition system is operated, and the temperature and the pressure of the combustion field are measured in the combustion chamber.

4. EXPERIMENTAL RESULTS AND DISCUSSION

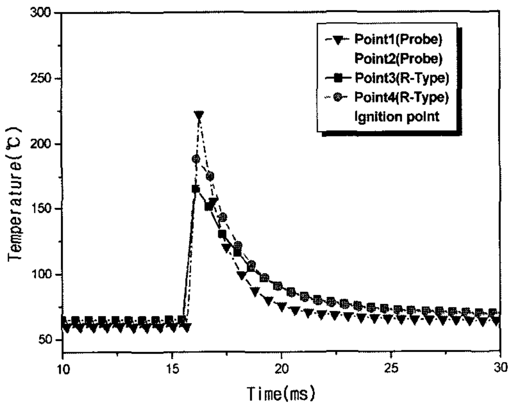
4.1. Maximum Surface Temperature of the Combustion Chamber Wall

Figures 6-8 show the variation of the surface temperature of the combustion chamber wall with the elapsed time at the equivalence ratio $\phi = 0.8$, 1.0, and 1.2 at 0.5 bar and 1.0 bar.

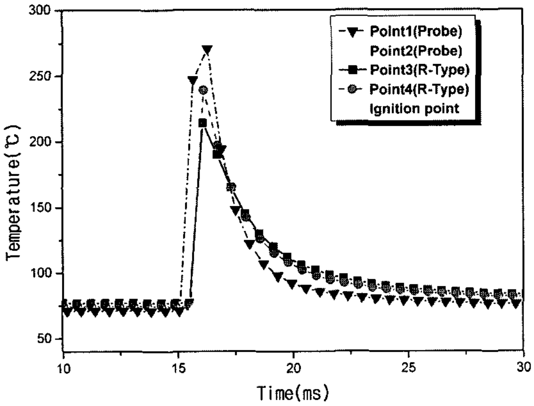
Based on the measuring results of the surface temperature, it is found that the maximum instantaneous temperature in the combustion chamber has differences between the measurement points.

The characteristics of the instantaneous wall temperature at the same initial condition according to positions of the measuring point during the burning period indicated similar trend at different initial pressure as shown in temperature distribution. It was also found that the measured temperature by the instantaneous surface temperature probe is higher than that by the R-type thermocouple. These differences show the maximum instantaneous temperature depending on the types of thermocouple are caused by the characteristics of the responses of thermocouples and measuring instruments.

The maximum instantaneous temperature also relies on the measuring points of thermocouples. As illustrated in Figure 9, the temperature at point 1 shows 50°C higher than that of point 3. The ignition need to occur at the spark plug before the flame front has to be propagated in spherical form. Therefore, the maximum temperature measured by thermocouples should be symmetrical with respect to the spark plug, as shown in the shapes of the combustion chamber. It is caused by the vortex flow

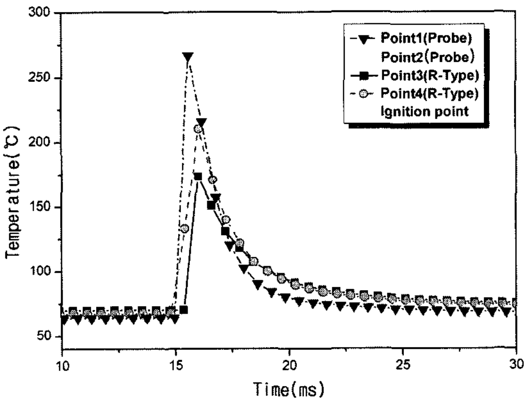


(a) P = 0.5 bar

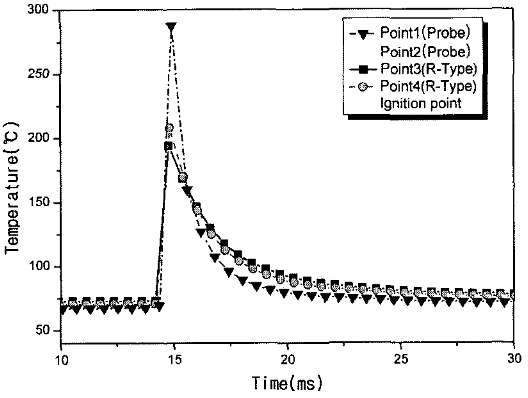


(b) P = 1 bar

Figure 6. Maximum surface temperature of the combustion chamber wall at $\phi = 0.8$.

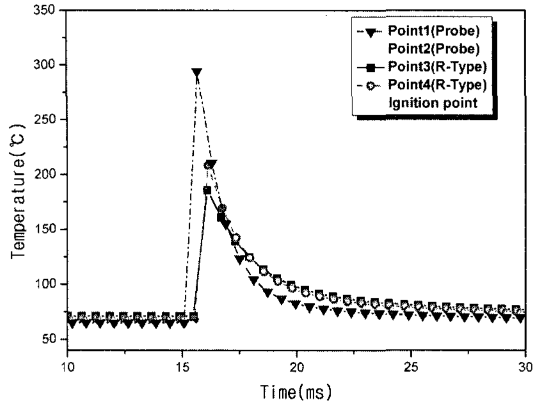


(a) P = 0.5 bar

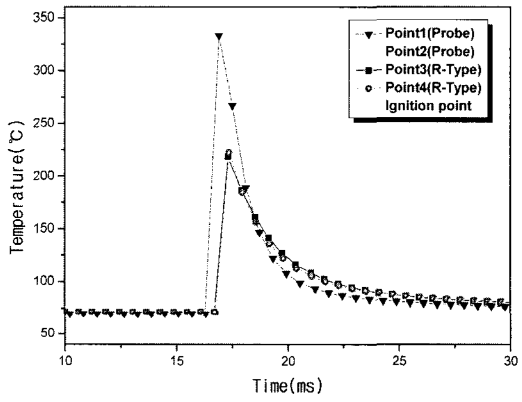


(b) P = 1 bar

Figure 7. Maximum surface temperature of the combustion chamber wall at $\phi = 1$.



(a) P = 0.5 bar



(b) P = 1 bar

Figure 8. Maximum surface temperature of the combustion chamber wall at $\phi = 1.2$.

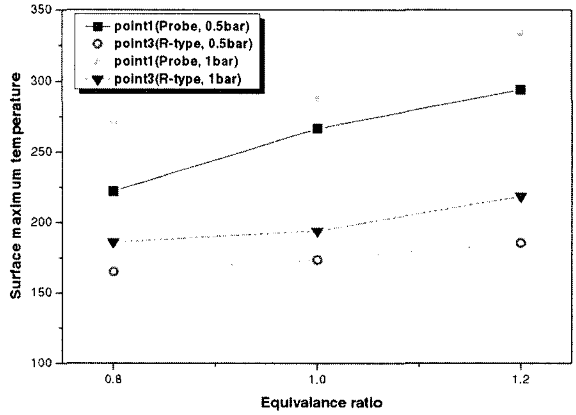


Figure 9. Maximum surface temperature of the wall at different equivalence ratios and probe positions.

occurring inside the combustion chamber.

Figure 10 shows the ignition delay by various equivalence ratios. Ignition delay shows the tendency that the time lag of ignition becomes shorter as the mixture becomes richer and that it becomes longer as the combustion chamber pressure becomes higher.

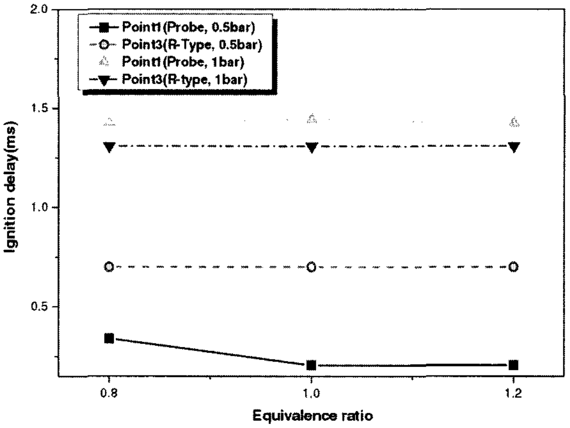


Figure 10. Ignition delay for different equivalence ratios.

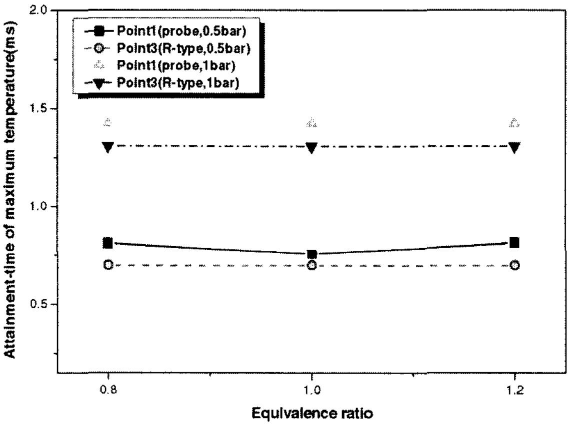


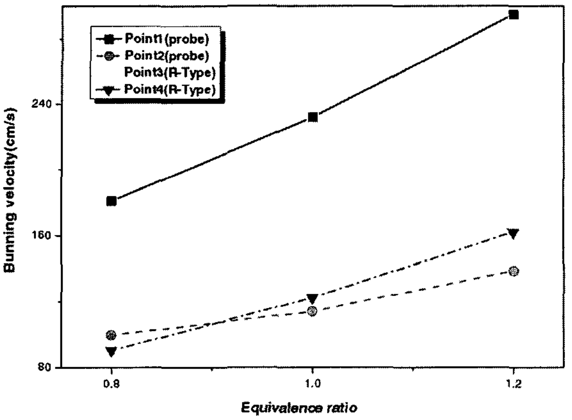
Figure 11. Attainment-time of the maximum temperature for different equivalence ratios.

Figure 11 shows the attainment-time of maximum temperature at various equivalence ratios.

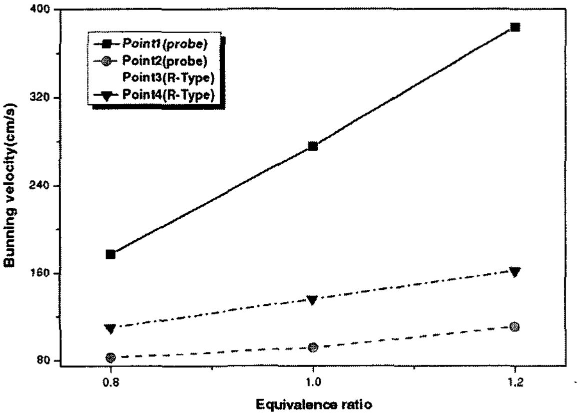
As shown in this figure, the attainment time of maximum temperature is longer at higher chamber pressure.

In the constant volume chamber, the flame propagation velocity is varied in accordance with the rise effect of temperature and pressure of unburned gas because of pressuring effect of burned gas.

The spherical flame varies with time due to the influence of combustion chamber wall, and the flame propagation velocity also changes in every point of the space. Especially, the combustion period increases about 8% with the equivalence ratio ranging 1 to 1.2 when the initial pressure increases from 0.5 bar to 1 bar. The combustion duration increases about 22% with the equivalence ratio ranging 0.7 to 0.9. In this study, it could be also found that the attainment-time of maximum temperature becomes longer when the mixture is richer



(a) P = 0.5 bar



(b) P = 1 bar

Figure 12. Burning velocity of the wall.

or leaner than $\phi = 1.2$.

According to Kim *et al.* (2001), the maximum instantaneous temperature occurs between 315 to 320 ms after the ignition. In this research, the attainment-time of maximum temperature with the equivalence ratio shows about 1 ms in the case of the stoichimetric mixture or slightly rich mixture.

4.2. Burning Velocities and Heat Flux

Figures 12 shows the burning velocity obtained by measuring the instantaneous flame temperature at 0.5 bar and 1 bar, respectively, in the test section. A combustion temperature has direct influence on the chemical reaction speed and the flame speed. Table 2 is listed the burning velocities of fuel-air mixture in the constant volume chamber at each initial pressures.

There were significant differences in the burning velocity at each measuring point. As a whole, the trends of the heat flux distribution were similar to that of the burning velocity.

Table 2. Burning velocities.

Initial pressure (bar)	Equivalence ratio	Burning velocity (cm/sec)			
		Point1	Point2	Point3	Point4
0.5	0.8	181.0	99.6	122.7	90.4
	1.2	294.9	138.4	154.5	162.0
1.0	0.8	177.2	82.8	137.5	110.0
	1.2	384.0	110.4	168.4	162.0

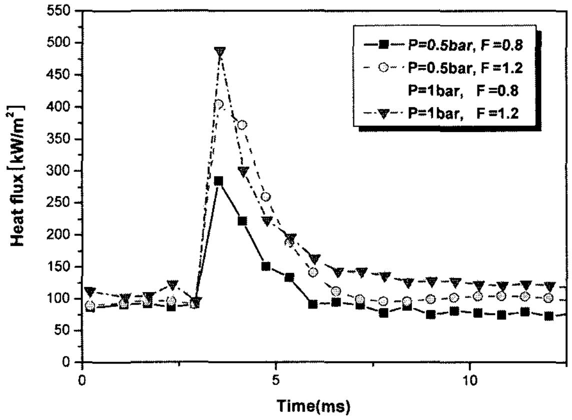


Figure 13. Wall heat flux at the point 2.

Metghalchi and Keck (1980) has shown that the burning velocity becomes the maximum value at $\phi = 1.05$–1.10. Similar trends are obtained in the present study at $\phi = 0.8$–1.2. The burning velocity is proportional to the square of a mixture temperature, so it proves that the mixture temperature affects the burning velocity.

As indicated in Figure 13, the heat flux is increased rapidly at the time after the ignition. According to the increase of initial pressure in the combustion chamber, the maximum heat flux to the wall is increased rapidly as shown in the flux distribution.

The maximum heat flux is 284.7 kW/m^2 at the point 2 when the mixture pressure is 0.5 bar and the fuel equivalence ratio is 0.8. And it is 487.6 kW/m^2 when the pressure is 1.0 bar, and the fuel equivalence ratio is 1.2. The maximum heat flux of the wall surface becomes higher as the initial pressure increases and the mixture become richer.

5. CONCLUSIONS

In this paper, the effect of initial condition on the heat flux and combustion characteristics in a constant volume combustion chamber are investigated experimentally. The result obtained from this work are summarized as follows.

(1) The maximum instantaneous temperature of the

flame in the constant volume combustion chamber increases with the increase of initial pressure conditions.

(2) The flame propagation velocity is increased with the increase of initial pressure and combustion duration is longer at lower initial pressure.

(3) It is concluded that the total heat flux during the combustion period is affected by the equivalence ratio and it decreases near the end of flame propagation.

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