Design of Hydrogen Constant Volume Combustion Chamber

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Abstract

This research is divided into two parts. First part is a design and simulation of Constant Volume Combustion Chamber (CVCC) and the second part is calibration of swirl intensity. Both parts are fundamental for investigation of combustion characteristic of hydrogen. For the first part, CATIA program was used for CAD design. The design was under the maximum combustion pressure condition which is calculated from thermodynamic analysis of otto cycle method. The result of simulation from ABAQUS program reveals maximum pressure of 8.0 MPa, with Safety Factor in main chamber and chamber cover equal to 12.75 and 7.26, respectively. For the second part, air velocity of swirl intensity was controlled by pressured difference between outside and inside the chamber, which was measured by Photron FASTCAM program, schlieren technique and hi-speed video camera in order to estimate the velocity of air. The velocities of air motion inside the chamber were 5.73, 6.50, 7.54, 8.10 and 9.32 m/s at difference pressure equal to 0.1, 0.2, 0.3, 0.4 and 0.5 MPa, respectively.

***Keywords**:* Constant Volume Combustion Chamber, Hydrogen, Swirl intensity, Schlieren technique

1. Introduction

Nowadays, fuel prices are very high so the automotive society wants to improve fuel consumption and thermal efficiency of the engine, as well as searching for the clean alternative fuel. The clean alternative fuel means the fuel that results less emission, air pollution, and global warming effects. One of the new alternative fuels considered is hydrogen.

Hydrogen can be produced from water via electrolysis, which is considered abundant because 3/4 of the world is covered by water.

For the combustion process, if hydrogen is used in the internal combustion engine, the product after combustion is only water. Hence, air emissions will be decreased (zero emissions) [1]. The characteristics of hydrogen are high flammability, high heating value, and high octane number, which could give rise to increased thermal efficiency. The properties of hydrogen compared with CNG and gasoline were shown in Table. 1.

The Constant Volume Combustion Chamber (CVCC) is the combustion simulator. The structure is similar the real engine combustion chamber in the case of compression stroke but it does not have the piston movement [2, 3]. Thus, the volume of the CVCC is constant. Many researchers have investigated in the real engine but it has a lot of parameters that could influence the combustion characteristic. On the other hand, CVCC can be installed with various sensors and equipment such as temperature control, ignition, intake and exhaust system that could better control the parameter. Hence, the results of the experiment are more reliable.

Principle of operating of hydrogen CVCC is to effort the conditions that resemble to real engine combustion chamber, such as temperature and pressure before combustion. Hence, the maximum combustion pressure is the main parameter that governs CVCC designing and simulation.

The present study is divided into two parts. First is a design and simulation of CVCC under condition of maximum calculated combustion pressure. Second is a measurement of air velocity in swirl intensity condition. Both parts are the conditions for study in combustion characteristics of hydrogen.

Table. 1 Properties of hydrogen compared with CNG and gasoline [4]

Property	Hydrogen	CNG	Gasoline
Density (kg/m³)	0.0824	0.72	730
Flammability limits (volume % in air)	4-75	4.3-15	1.4-7.6
Flammability limits (Ø)	0.1-7.1	0.4-1.6	0.7-4
Autoignition temperature in air (K)	858	723	550
Flame velocity (m/s)	1.85	0.38	0.42
Adiabatic Flame temperature (K)	2480	2214	2580
Stoichiometric air/fuel mass ratio	34.48	14.49	14.7
Lower heating value (MJ/kg)	119.7	45.8	44.79
Heat of combustion (MJ/kgair)	3.37	2.9	2.83

2. Experimental Procedure

2.1 Combustion pressure calculation

The chemical equation between hydrogen and air are shown in Eq. (1).

$$2H_2 + (O_2 + 3.76N_2) \rightarrow 2H_2O + 3.76N_2 \quad (1)$$

The combustion pressure can be calculated by using ideal gas equation Eq. (2) and thermodynamic analysis of otto cycle method [5, 6].

$$PV = m_m R T_1 \quad (2)$$

Where:
P : Pressure of mixture
V : Volume of combustion chamber
m_m : Overall mass of mixture
R : Gas constant
T_1 : Mixture temperature

Mass of hydrogen and air in combustion chamber can be calculated by using stoichiometric air/fuel mass ratio as shown in Eqs. (3), (4) respectively.

$$m_f = (1/35.48)(m_m) \quad (3)$$

$$m_{air} = (34.48/35.48)(m_m) \quad (4)$$

Combustion temperature is calculated by using Constant volume heat input equation Eq. (5).

$$m_f Q_{HV} \eta_c = m_m c_v (T_2 - T_1) \quad (5)$$

Where:
m_f : Mass of fuel (Hydrogen)
Q_{HV} : Heating value of fuel (Hydrogen)
η_c : Combustion efficiency
c_v : Constant volume specific heat capacity
T_2 : Combustion temperature
T_1 : Mixture temperature

Combustion temperature from Eq. (5) can calculate the combustion pressure (P_2) by using Gay-Lussac's law Eq. (6).

$$P_1/T_1 = P_2/T_2 \quad (6)$$

Where:
P_1 : Mixture pressure
P_2 : Combustion pressure
T_1 : Mixture temperature
T_2 : Combustion pressure

2.2 CVCC Simulation

JIS S45C steel was chosen in order to make constant volume combustion chamber [7] as shown in Fig. 1 and the properties of this steel from JIS standard was shown in Table. 2.

Fig. 1 JIS S45C steel

Table. 2 Properties of JIS S45C steel

JIS S45C Steel, Normalized	
Properties	**Metric**
Density	7.85 g/cc
Hardness, Brinell	167 - 229
Tensile Strength, Ultimate	569 MPa
Tensile Strength, Yield	343 MPa
Elongation at Break	20.00 %
Modulus of Elasticity	205 GPa
Poisson Ratio	0.29
Machinability	55 %
Shear Modulus	80.0 GPa

Quartz glasses were used for covers both sides of CVCC because it was easy to visualize the combustion phenomena (Fig. 2). The properties of quartz glasses were shown in Table. 3.

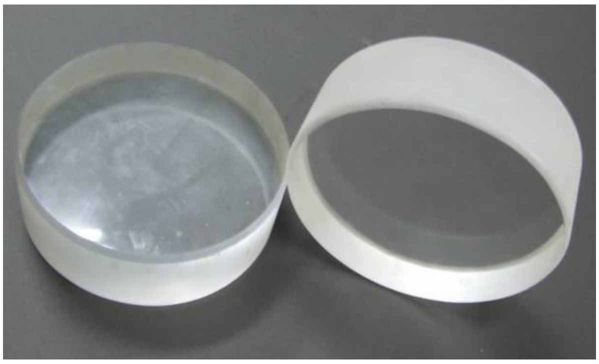
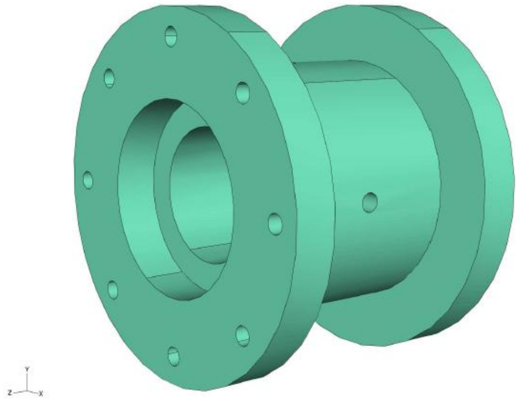


Fig. 2 Quartz glass

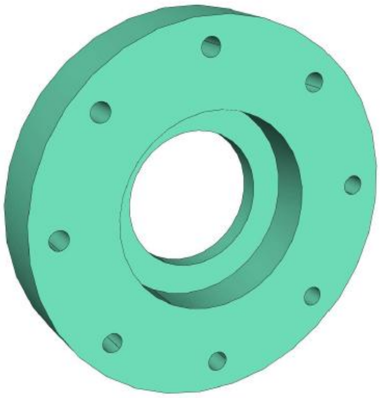
Table. 3 Properties of quartz glass

Properties	**Metric**
Specific	2.21 g/cc
Hardness	5-7 Mhos Scale
Rapture Strength	800-1000 MPa
Compressive Stress	60-700 MPa
Young's Modulus 20 °C	77.8 GPa
Young's Modulus 50 °C	82 GPa
Young's Modulus 900 °C	85 GPa
Poisson Ratio	0.17
Rigid Index 900 C	36.9 GPa
Speed of Longitudinal Wave	5.72×10^{-3} m/s

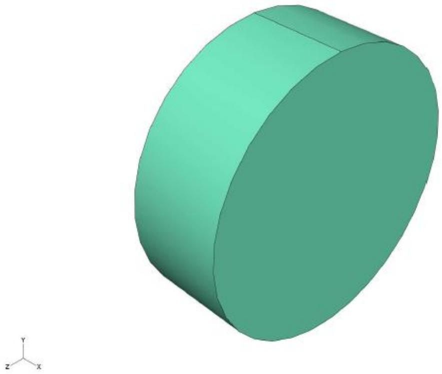
From combustion pressure calculated, CATIA and ABAQUS program were used for designing and simulation. Properties of material were set to simulation program, as shown in Fig. 3.



(a) Main chamber



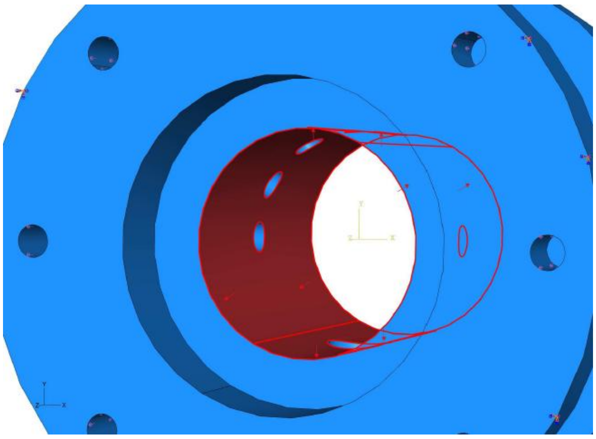
(b) Chamber cap



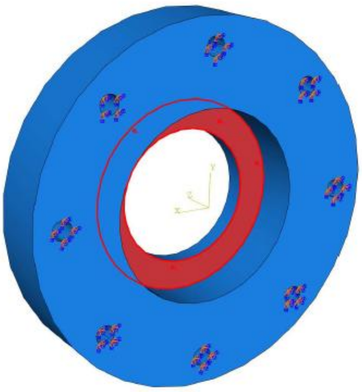
(c) Quartz glass

Fig. 3 Material setting

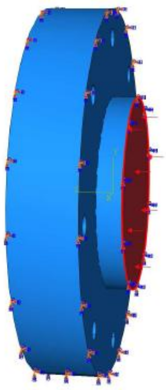
The over pressure (8.0 MPa) was used for simulation condition to assure that accident will not occur as shown in Fig. 4.



(a) Main chamber



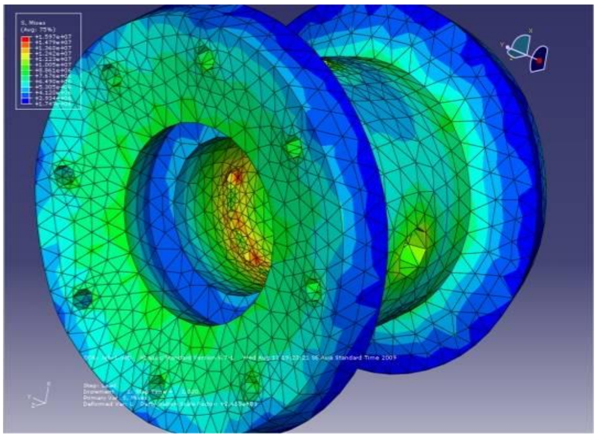
(b) Chamber cap



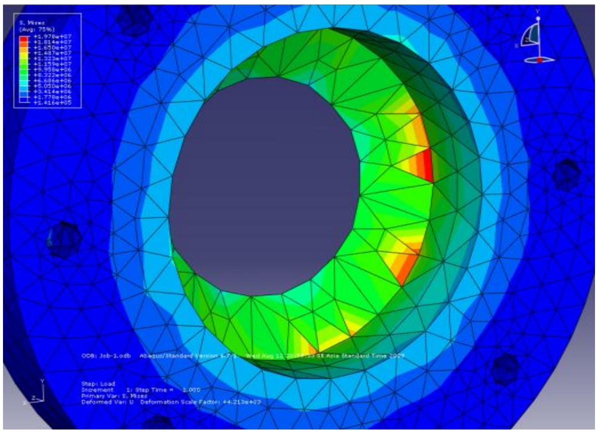
(c) Quartz glass

Fig. 4 Load setting at 8.0 MPa

From previous research [7, 8], this combustion chamber was used in order to study in gasoline and ethanol blended combustion. The result of maximum combustion pressure from the calculation is 4.2 MPa, and Fig. 5 shows the simulation result of 5.0 MPa. The safety factor of main chamber and chamber cap from simulation result are 21.47 and 17.34 respectively.



(a) Main chamber



(b) Chamber cap

Fig. 5 Simulation result of ethanol combustion

The results of real combustion pressure, as shown in Fig. 6, are not over in order to compare with the calculation result.

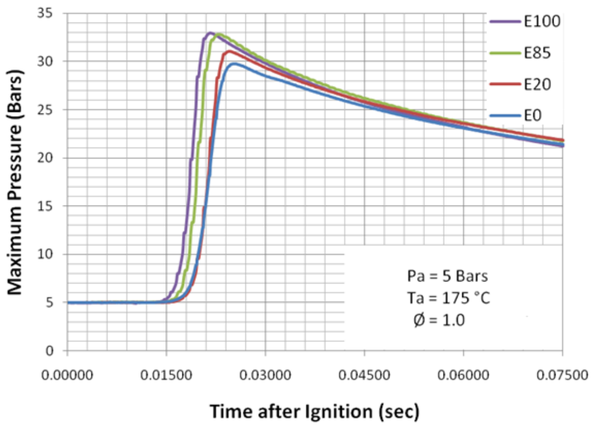


Fig. 6 Real combustion pressure from gasoline and ethanol blended

2.3 Swirl Intensity calibration

In this study, Swirl intensity is one of parameters that affects to combustion phenomena [9, 10] (Fig. 7).

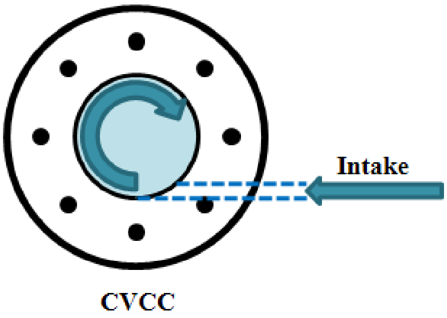


Fig. 7 Swirl intensity in CVCC

Thus, swirl intensity must be calibrated. The differential intake pressure was used in order to calibrate. The unit of swirl intensity is m/s and the initial pressure before combustion was fixed at 0.5 MPa so the differential pressure that set are 0.1, 0.2, 0.3, 0.4 and 0.5 MPa.

High speed video camera (Photron FASTCAM SA3 at 6,000 fps, 1/10,000 sec of shutter speed and monochrome color) and schlieren technique (light source from xenon lamp 6,000 K) was used in order to capture the motion of air in CVCC by using the various air densities, as shown in Figs. 8, 9.

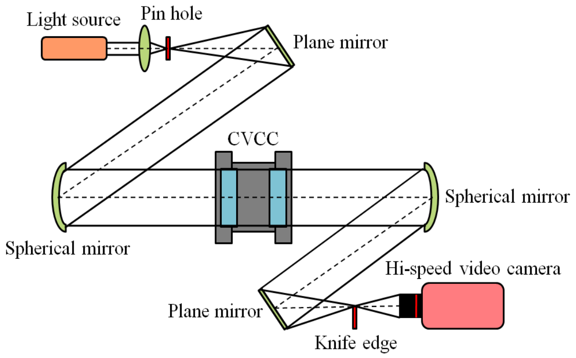


Fig. 8 Schlieren technique and high speed video camera diagram

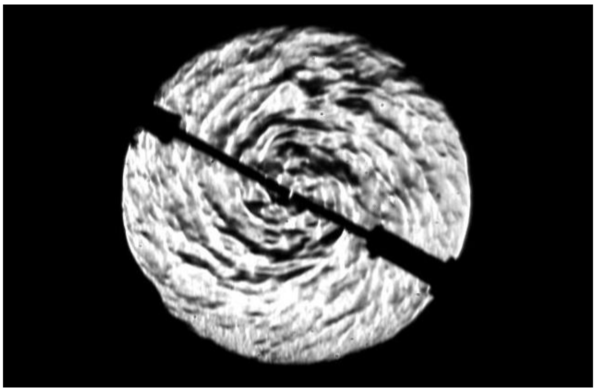
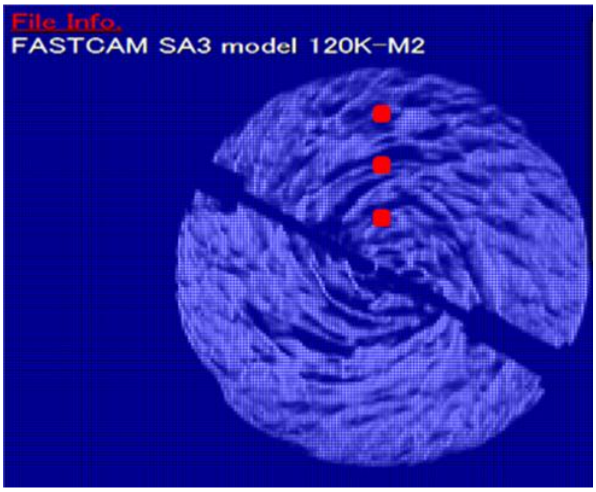
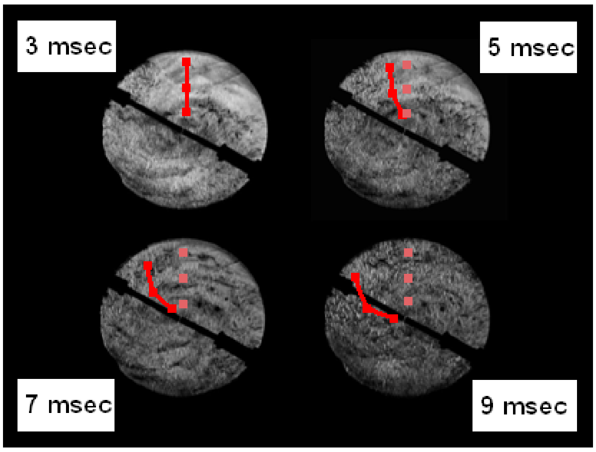


Fig. 9 Swirl intensity phenomena from schlieren technique and high speed video camera

In the measurement process, Photron FASTCAM program was used to measure the velocity of air elements by tracking 3 moving points (center, middle and side). In the given period of time, the air elements get the distance so air velocity can be determined, as shown in Fig. 10.



(a) Measured by using FASTCAM program



(b) Example of movement of air elements
Fig. 10 Air velocity measurement

3. Results and Discussion

3.1 Designing Result

The suitable design of CVCC is shown in Fig. 11. The main parameters that affected the design process are the area for installing testing equipments and safety factor from highest combustion pressure.

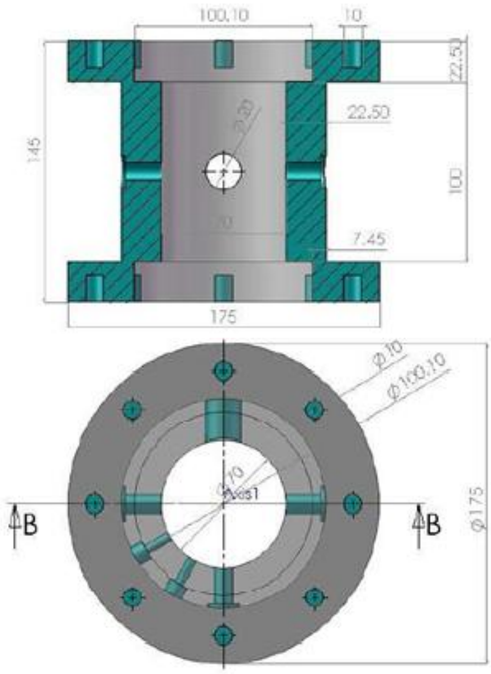
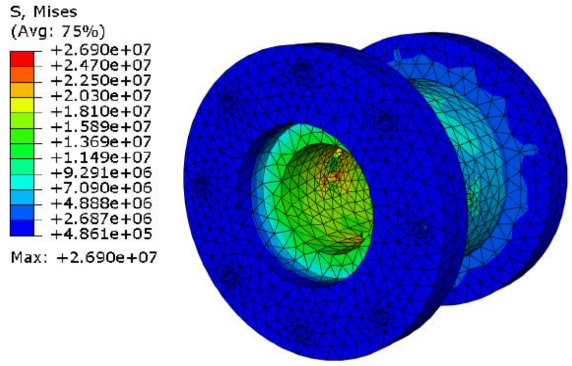


Fig. 11 The dimension of combustion chamber

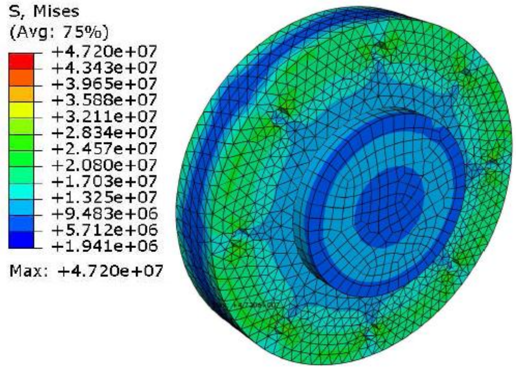
Dimension of quartz glass is 100 mm. with 35 mm. thickness. The diameter of combustion chamber is 70 mm. while length is 100 mm. Hence, volume of CVCC is 385 cc., which is similar to the volume of conventional small gasoline engine. All equipment, such as intake port, exhaust port, heater, spark plugs and sensors, can be installed on 115 mm. of outer diameter. Nontheless, all of equipment are not necessary to simulate explicitly because the standard can be used in high pressure that is over the maximum combustion pressure. Hence, it can ensure that all of equipment parts, attached to combustion chamber, are not damaged.

3.2 Simulation Result

The result of maximum combustion pressure from the calculation is 6.9 MPa. In term of safety, over pressure was set in the simulation program at 8.0 MPa. The result is shown in Fig. 12, where von mises stress of main chamber is 26.9 MPa at edge of spark plugs hole, and von mises stress of chamber cap is 47.2 MPa at edge of bolt mounting. Therefore the safety factors are 12.75 and 7.26, respectively. The finding can guarantee that this CVCC will be adequate in term of safety.



(a) Main chamber



(b) Chamber cap with quartz glass
Fig. 12 Simulation result

According to the simulation result, hydrogen combusts with safety condition so the real combustion chamber is fabricated by such design, as shown in Fig. 13, 14.

Fig. 13 Real main chamber, chamber cap and quartz glass

Fig. 14 Real combustion chamber including equipment

3.3 Swirl intensity calibration result

Results of swirl intensity calibration were plotted as scattering graph and trend line. The example at pressure difference of 0.5 MPa is shown in Fig. 15.

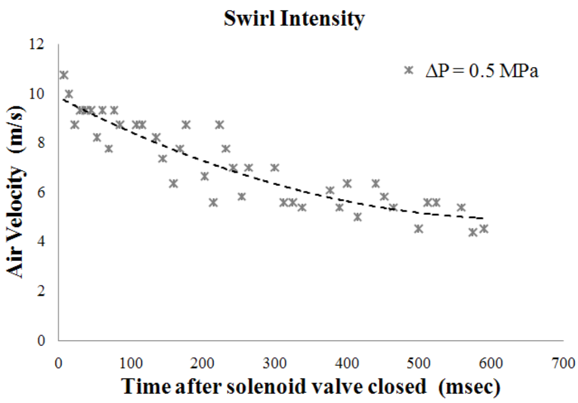


Fig. 15 Air velocity in condition of ΔP = 0.5 MPa

At the beginning, the results are disrupted values but become more stable closed to trend line when 35 msec after solenoid valve close. Therefore, the result at 35 msec was chosen for this study, as shown in Fig. 15. The air velocities are 5.73, 6.50, 7.54, 8.10 and 9.32 m/s for differential pressures of 0.1, 0.2, 0.3, 0.4 and 0.5 MPa respectively (Fig. 16). From this study, the differential intake pressure clearly had more effect for swirl intensity. If the pressure difference increases, the air velocity also increases.

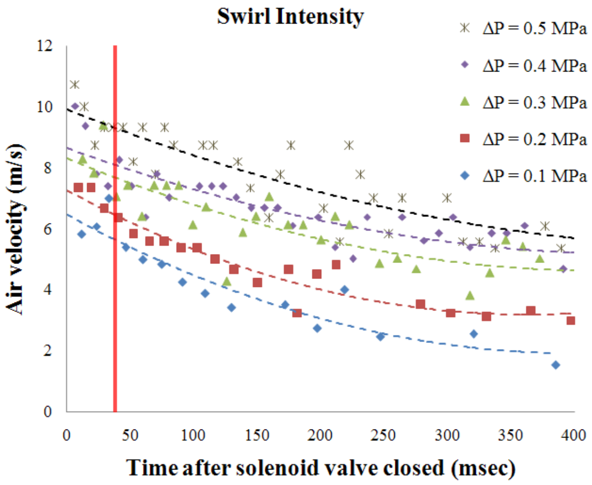


Fig. 16 Air velocity in 5 conditions

4. Conclusions

1. The designing of CVCC is accomplished for the study of hydrogen combustion with 3 important issues,

1.1 Similarity with real engine

1.2 Combustion pressure

1.3 Enough area around CVCC in order to install any equipment

All of issues can be designed and produced successfully by recourse to internal combustion theory and comparison with ethanol-gasoline blended study.

2. The real CVCC (main chamber, chamber caps and quartz glass) was also produced by design successfully.

3. When pressure difference between inside and outside of CVCC is increased, the diffusion of air will increase. Thus, air velocity of swirl intensity will increase as well. The best air velocity is that after the intake valve closed immediately but at that time, values obtained are also very scattered. Thus, 35 msec after intake valve closed is the most appropriate time since it does not spread much and close to the trend line.

4. From the experiment results, it is obvious that the way to find swirl intensity by using schlieren technique, high speed video camera and computer program is not too difficult. Next study, Hydrogen-air mixed will be calibrated.

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6. References

[1] T. Bohacik, S. De Maria and W.Y. Saman. (1996). Constant-Volume Adiabatic Combustion of Stoichiometric Hydrogen-Oxigen Mixtures, *WREC 1996*, University of South Australia.

[2] F.V. Tinaut, A. Melgar, B. Giménez and M.Reyes. Characterization of The Combustion of Biomass Producer Gas in a Constant Volume Combustion Bomb, *Fuel 89*, (2010) 724-731.

[3] Dhananjay Kumar Srivastava, Kewal Dharamshi and Avinash Kumar Agarwal. Flame kernel characterization of laser ignition of natural gas–air mixture in a constant volume combustion chamber, *Optic and Lasers in Engineering 49*, (2011) 1201-1209.

[4] Technical Review of Hydrogen-fueled Internal Combustion Engines, Sandia National Laboratory.

[5] Willard W. Pulkrabek. Engineering Fundamentals of the Internal Combustion Engine, Prentice Hall, New Jersey.

[6] Stephen R. Turns. An Introduction to Combustion: Concepts and Applications, 2nd edition, ISBN 0-70-230096-5, McGraw-Hill Series in Mechanical Engineering.

[7] T. Dugkhuntod, P. Nomthongthai and Y. Songsaengchan. Ethanol Combustion Characteristics in a Constant-Volume Combustion Chamber (in Thai), Department of Mechanical Engineering, KMITL (2009).

[8] P. Ornman, H. Kosaka, N Chollacoop and C. Charoenphonphanich. Study on Combustion Characteristics of Direct Injection Stratified Charge in Ethanol/Gasoline Blends, *The First TSME International Conference on Mechanical Engineering*, (2010).

[9] Jinhua Wang, Zuohua Huang, Haiyan Miao, Xibin Wang and Deming Jiang. Characteristics of direct injection combustion fuelled by natural gas–hydrogen mixtures using a constant volume vessel, *International journal of hydrogen energy 33*, (2008) 1947-1956.

[10] P. Ornman, C. Charoenphonphanich, N. Chollacoop and H. Kosaka. Effect of Ethanol Concentration of Gasohol on Lean Flammability Limit in Direct-Injection Stratified Charge Engine, *The 7th International Conference on Automotive Engineering (ICAE-7)*, (2011).