A study of Combustion Chracteristics of DME -Air mixtures

笹川, 健太 / SASAGAWA, Kenta

(発行年 / Year)
2008-03-24

(学位授与年月日 / Date of Granted)
2008-03-24

(学位名 / Degree Name)
修士(工学)

(学位授与機関 / Degree Grantor)
法政大学 (Hosei University)

2007 年度

修士論文

A study of Combustion Characteristics of DME–Air Mixtures Under Micro-Gravity Environment

微小重力環境における DME－空気混合気の燃焼特性の解明に関する研究

指導教員　　岡島　敏
　　　　　　川上　忠重

法政大学大学院工学研究科機械工学専攻
学籍番号　06R1112

ササガワ　ケンタ
笹川　健太

A study of Combustion Characteristics of DME -Air mixtures Under Micro-Gravity Environment

By

Kenta SASAGAWA, Graduate student

Abstract

Di Methyl Ether (DME, CH_3-O-CH_3) has great future prospect as a new kind of fuel. At present, we are facing various global issues. Two representative things are here. One is that the environment is being harmed by exhaust fumes. And the other is that fossil fuel resources are being drained. It makes oil expensive and causes increase of prices of commodities and transportation cost.

DME has some advantages to solve these problems. First one is that DME, differing from gasoline and light oil, does not contain sulfur and nitrogen molecules. So its exhaust gas is free of sulfur oxide and soot. Further, the gas contains nitrogen oxide much less than exhaust gas coming from gasoline and light oil. From this character, DME has little possibility to cause environmental pollutions. Second one is that its boiling point under standard atmospheric pressure is -25 degrees Celsius and saturated vapor pressure is 0.6 MPa. So, DME would be liquefied and fit to be stored and transported at liquid state like liquefied petroleum gas. The last one is that its cetane number is higher than that of light oil. With these characteristics, DME should be used as alternative fuel for diesel engines and liquefied petroleum gas engines.

From this point of view, the experiment has been carried out to observe some basic combustion characteristics of DME such as flame speed, burning velocity and pressure effect. Micro-gravity method achieved in freely falling chamber is used to examine burning velocity of lean side DME-air mixture because micro-gravity environment makes it possible to realize spherical flame propagation even for near the flammability limit by eliminating buoyant effect induced from gravity. The initial condition of temperature is 298 K. And range of equivalence ratio and pressure are from ϕ =0.65 to ϕ =1.5 and from 0.1 MPa to 0.3 MPa respectively.

The main results obtained in this study are as follows

1) The maximum and minimum burning velocities of DME-air mixture, under atmospheric pressure, are 44.2 cm/sec at equivalence ratio ϕ =1.1 and 16.5 cm/sec at ϕ =0.65.
2) Burning velocity of DME-air mixtures is higher than that of Methane and Propane-air mixtures in rich side but little lower in lean side under atmospheric pressure.
3) Burning velocity of DME-air mixtures decreases about 4.6 cm/sec as the pressure increase 0.1 MPa at each equivalence ratio.

Key words: DME, burning velocity, micro-gravity

Index

Chapter 1 Introduction

1-1 Background

The Industrial revolution has occurred in England at the end of 18th century. It was a turning point to change people's life from agricultural to industrial. In that time, human got utilization of thermal power as energy resources for industries. Today, over 80% of energy for our cultural lives is generated by combustion.

Figure 1 indicates demand prediction for various energy source published by International Energy Agency [1]. "toe" is an abbreviation of "ton of oil equivalent". 1 toe equals to 10^7 kcal. According to Fig.1, fossil fuels such as petroleum, natural gas, and coal, amount to 80 % of all energy supply and this situation continues to 2030 or more. International Energy Agency says if the world's economic growth rate is supposed to be 3.0 % a year, the world energy demand should increase 1.7 % a year. As the result, it would reach at 15.3 billion toe (1.66 times as much as the value of 2000) by 2030. It is not sure that the prediction is accurate or not but energy demand must be increasing. And various fossil fuels still stay as main energy source in the near future.

Nowadays, it is worried about that fossil fuel resource is going to be exhaust. Many predictions about the exhaustion have been presented. In present time, it is said that the estimated amounts of petroleum, natural gas and coal are going to be exhaust in 40, 80 and 200 years. Even many unconfirmed oil fields may exist, the scale of new found oil fields become smaller and smaller. It is sure that oil resources are finite.

Some problems caused by exhaust gas are becoming seriously. Main ingredients of exhaust gas are nitrogen oxide, hydro carbon, carbon dioxide and sulfur dioxide. Nitrogen oxide and hydro carbon are applied strong ultraviolet rays in the atmosphere and they generate photochemical oxidant such as ozone and aldehyde. The kinds of oxidants cause harmful photochemical smog for living things. Increase of carbon dioxide as green house gas accelerates global warming. Nitrogen oxide and sulfur dioxide are oxidized and changed in nitric acid and sulfuric acid respectively. They dissolve in water vapor in the upper air and fall as acid rain.

As stated above, a lot of energy and environmental problems are surrounding us. It is recognized very generally that present energy generate and using system cannot be maintained for long periods. From now, useful technologies required to be not only innovative but also nature-friendly. From this point of view, new energy resources are researched and DME (Di-Methyl-Ether, CH_3-O-CH_3) taken up in this paper is one of the new resources.

DME is attracting great deal of attention as new kind of fuel on improvement of GTL (Gas to Liquid) technology. International Energy Agency recognizes it as multi-source and multi-use fuel for future energy system. Other multi-source fuels are, for example, natural gas, coal bed methane, coal, super heavy oil, residual oil, associated gas of oil fields, wasted woods, sewer sludge, animal’s excrement and urine, and wasted plastics. Multi-use fuels are for thermal power generation, high efficiency power generation, combined heat and power generation, industrial furnaces, boilers, alternative energy generation [2].

1-2 Di-Methyl-Ether

1-2-1 Advantages of DME

Table 1 [3] shows basic physical properties of DME compared to other fuels. Main characteristics of DME are as follows.

1) The boiling point under standard atmospheric pressure is -25 degrees Celsius and saturated vapor pressure is 0.6 MPa. That is lower than 0.93 MPa of Propane and 246 MPa of Methane. So, DME would be liquefied easily comparatively. Because of that, DME is fit to be stored and transported at liquid state.
2) DME molecule does not have direct bond of carbon atoms. Mass content of oxygen atom in one DME molecule is 35 %. Because of that, DME combustion does not produce smoke and soot. Furthermore, because it does not have sulfur and nitrogen molecules, no sulfur oxide and little nitrogen oxide are contained in exhaust gas.
3) The cetane number is 55 and it is higher than light oil's. DME could be utilized as alternative fuel for high efficiency diesel engine.
4) DME is a synthetic substance and made artificially from coal, biomass resources and so on. Oil exhaustion problems would be eased by utilization of DME fuel.

1-2-2 Demerits of DME

As the above-mentioned, DME has some advantages but it has demerits as energy resources for industries.

1) Less lubricating ability than light oil
2) Swelling effect to rubber and plastics
3) Less calorific value per volume than light oil and liquefied petroleum gas.

1-2-3 Manufacturing process

Figure 2 shows manufacturing process of DME. Raw materials of DME are natural gas, coals and biomass and so on. They are reformed to another gas that contains carbon monoxide and hydrogen. Two different processes can be selected to make them DME, direct and indirect elaboration. Indirect elaboration process is used generally today. Direct elaboration is more efficient technology than indirect process and it is being developed.

1-3 Experimental purpose

The experimental purpose is to study basic combustion characteristics of DME-air mixture such as flame propagation speed, burning velocity, and pressure effect for utilization of DME fuel as new energy resource.

Micro-gravity method was used in this research. Why because, flame speed of very lean mixture combustion is so slow and the flame shape is deformed by buoyant force under normal gravity. In case of that it is hard to observe accurate flame behavior. So, by letting the experimental apparatus fall freely from top of the falling tower, micro-gravity environment can be realized. Combustion flame propagates spherically and accurate burning velocity can be measured under micro-gravity, even in case of very lean mixture combustion.

Chapter 2 Experimental apparatus and methods

2-1 Experimental apparatus

2-1-1 Outline of test assembly

The outline of the experimental assembly is shown in Fig.3. The test apparatus is assembled with steel rods. The dimensions are 360 mm high by 670 mm wide by 510 mm deep. Some devices are set up such as cylindrical combustion bomb, ignition device, high speed video camera and brass weight for total balance. The total weight of the assembly is about 35 kg.

The basic system of this assembly has been used for years. This time, it was customized for present experiment. The main customized factors are as follows.

1) Lightening the total weight for easy carrying in the experiment under micro-gravity condition.
2) Exchanging the glass window for thicker one, for high pressured mixture combustion.
3) Simplification of the electric circuits.
4) Setting up additional shutting valves between combustion bomb and inlet, outlet pipes

2-1-2 Combustion bomb

Cross section of the cylindrical combustion bomb of duralumin is shown in Figure 4. Dimensions of the chamber are 110 mm diameter and 110 mm length. The inside wall is painted with black ink to prevent flame reflection. A glass window is on its side wall to observe flame propagation. Two spark plugs with piano wires for ignition are inserted into the bomb and the tips are set at center of the bomb where mixture is ignited. The bomb has valves for inflow of DME-air mixture made in mixing tank and sucking out burnt gas by vacuum pump.

As same as main experimental apparatus, the combustion bomb was made for correct experiment. Manufacturing drawings are shown in Fig.5 and Fig.6.

Customized points are as follows.

1) For simplification of opening and shutting the side wall, fixing method with bolt took the place of rotary method.
2) Internal height and diameter of the combustion bomb are designed same size to ensure more measurement range with less pressure increasing in flame propagation process.
3) Lightening the weight for easy carrying in the experiment under micro-gravity condition.

2-1-3 Ignition device

Spark ignition method is adopted to ignite DME-air mixture. The system is consisted of a D.C. power supply, a spark coil, spark plugs, piano wires, and a mercury switch. Sharpened piano wires, 0.7 mm diameter, are used as spark electrodes and spark gap is 2 mm.

Mechanical ignition process is as follows.

1) Turn on the D.C. power supply and mercury switch.
2) Let the experimental apparatus fall freely.
3) By that the mercury switch is turned off during falling, high voltage is occurred to spark and ignite the mixtures.

2-1-4 High speed camera

In this research, Phantom V4.1 camera of Nobby Tech Ltd. and Phantom 590 analyzer software were used. The shutter speed was set in the range from 400 to 1000 frames per second. Computer analyzes the photograph data of flame propagations in details.

2-1-5 Falling tower

The outline of falling tower used in this research is shown in Fig.7. The tower is 2.7 m in height and the falling distance is 1.7 m. The experimental assembly is hung on polypropylene rope at the top of the tower then fallen freely by cutting the rope. As shown in Fig.8, the assembly should be fallen with an air drag shield otherwise the falling speed will be reduced by air drag. Without the shield, a weak convection current occurs and it prevents accurate spherical flame propagation. With the shield, the assembly almost falls freely and it can be feasible to realize micro-gravity environment. The shield has dimensions of 470 mm high by 610 mm wide by 765 mm deep. At the bottom of the tower, a cushion is set as a shock absorber. This falling tower system can realize 10^{-5}G environment for 0.6 seconds [4].

2-2 Experimental condition

The mixture is made of DME fuel and dried air, 79 vol. % nitrogen and 21 vol. % oxygen. The equivalence ratio is arranged in 0.65 to 1.5 range. Initial temperature is room temperature. Mixture pressure is arranged in 0.1 MPa to 0.3 MPa range. The flame propagation speed is measured at the location where the propagation is stabile, about 20 mm in length from the center of bomb. At the location, the influence of pressure rise can be ignored.

2-3 Making mixture

2-3-1 Numerical formulation

Reaction formulation (1) shows chemical reaction system of complete combustion for stoichiometric DME-air mixture.

$$CH_3OCH_3 + 3O_2 + 3 \times \frac{79}{21} N_2 \rightarrow 3H_2O + 2CO_2 + 3 \times \frac{79}{21} N_2 \quad (1)$$

By formulation (1), theoretical DME fuel-air ratio (volume ratio) is

$$\left(\frac{V_f}{V_a} \right)_t = \frac{1}{(3 + 3 \times 79/21)} = 0.070 \quad (2)$$

V_f and V_a are DME and air volume respectively.

On the other side, air-fuel ratio by Dalton’s law is expressed as

$$\frac{V_f}{V_a} = \frac{P_f}{P_t - P_f} \quad (3)$$

P_f is DME partial pressure and P_t is mixture total pressure. Equivalence ratio ϕ is defined as fuel-air ratio divided by theoretical fuel-air ratio. Therefore, ϕ is reexpressed as follows.

$$\phi = \frac{(V_f / V_a)}{(V_f / V_a)_t} = \frac{P_f / (P_t - P_f)}{0.070} \tag{4}$$

Led by equation (3), DME partial pressure is

$$P_f = \frac{0.070\phi}{1 + 0.070\phi} P_t \tag{5}$$

Air partial pressure, P_a, equals to mixture total pressure minus DME fuel partial pressure.

$$P_a = \left(1 - \frac{0.070\phi}{1 + 0.070\phi} \right) P_t \tag{6}$$

Making mixtures at each equivalence ratio is based on this theory.

2-3-2 Mixing process

1) Suck out air in store tank with vacuum pump.
2) Send dried air into the tank until internal pressure gets higher than atmospheric pressure.
3) Open the inlet valve and let extra air out. Internal pressure is made to be equal to atmospheric pressure.
4) Send DME fuel into the tank little by little until desired pressure value which was calculated by formulation (5).

5) Send dried air into the tank until desired total pressure.
6) Turn on mixing fan in the tank for 30 minutes.

2-4 Experimental process

1) Make mixture at desired equivalence ratio according to the way shown in 2-3-2.
2) Evacuate the combustion bomb then send the mixture until internal pressure gets desired value.
3) Set the experimental assembly in air drag shield. Hang them on polypropylene rope at the top of falling tower.
4) Connect high speed camera, ignition device, computer and D.C. power supply using computer or electric cables.
5) Start up Phantom 590 analyzer and make it state of “waiting for trigger”.
6) Turn on D.C. power supply and turn off the room light.
7) By cutting polypropylene rope, let the assembly fall freely.
8) On analysis of captured photographs data, calculate flame propagation speed and burning velocity.

Chapter 3 Experimental results and observations

3-1 Combustion behavior

3-1-1 Under normal gravity

Figure 9 is direct photographs of DME-air mixtures at various equivalence ratios under normal gravity and atmospheric pressure. White circle, yellow circle, and center red point indicate inner wall of combustion bomb, flame front, and ignition point respectively.

The flame shape of such slow burning velocity mixtures (photograph (a) [5]) is subjected to marked influence of buoyancy effect, and hence the flame overall lifts above the center of bomb. The propagation looks like “jellyfish shape”. In the case of photograph (b), the flame shape is subjected to a little influence of buoyancy effect, and hence the flame lifts rather upward. The propagation takes on spheroid. In the case of photograph (c), the flame shape is subjected to little influence of buoyancy effect, and hence the flame propagates to spherical symmetry. These variations of the flame shape in each equivalence ratio at DME-air mixtures are very much similar to propane-air mixtures.

3-1-2 Under micro-gravity

Sequential photographs on combustion behavior of DME-air mixtures at 0.65 equivalence ratio under normal and micro-gravity are shown in Fig.10. White circle, red circle, and center yellow point indicate inner wall of combustion bomb, flame front, and ignition point respectively.

In the case of under normal gravity, the flame is lifted up and deformed to spheroidal shape for the reason explained in 3-1-2.

On the other hand, under micro-gravity, the flame propagates to perfectly spherical symmetry although it is area to distort the flame shape under normal gravity.

3-2 Flame radius

Figure 11 shows ratio of upward and downward flame radiuses against time from ignition at equivalence ratio ϕ=0.65, atmospheric pressure. Blue line is based on result under normal gravity experiment and red one is on result under micro-gravity. As it shows, under normal gravity environment, it is obvious that upward flame radius is much longer than downward one because the flame is lifted by buoyant force. On the contrary, under micro-gravity, the ratio is almost equal to 1. In another expression, spherical flame propagation can be realized even at lean mixture such as equivalence ratio ϕ=0.65.

3-3 Flame speed

Figure 12 indicates flame propagation speed of DME-air mixture at various equivalence ratios and mixture pressures. The experiment was carried out under micro-gravity for mixtures at equivalence ratio ϕ=0.65 and 0.7. For the other mixtures, it was carried out under normal gravity. As it shows, the maximum flame speed appears at equivalence ratio ϕ=1.1 and flame speed decreases as equivalence ratio goes to lean or rich side at each mixture pressure.

In case of same equivalence ratio, the flame speed decreases as pressure increases. So it can be said that pressure effect is not related to equivalence ratio.

3-4 Burning velocity

The burning velocity S_u is then given by

$$S_u = \frac{\rho_b}{\rho_u} S_f = \frac{T_u}{T_b} S_f \times I \tag{7}$$

where ρ_b and ρ_u are mean density of burnt and unburnt mixture. T_u and T_b are temperature of unburnt mixture and adiabatic flame temperature in isobaric change and I is correction factor.

Figure 13 is model of flame temperature. Temperature distribution is assumed to be linear and burnt gas temperature equals to adiabatic flame temperature.

The correction factor I [6] based on the model is given by

$$I = \frac{1}{r^3{}_b}\left[\left(r_b - \delta\right)^3 + \frac{3T_b r^3{}_b \delta}{T_b - T_u} \ln\frac{T_b}{T_u} \right] \tag{8}$$

where r_b is flame radius and δ is flame thickness. In this research, flame radius value is fixed at 20 mm.

Flame thickness δ is given by

$$\delta = \frac{2\overline{\lambda}}{S_u \overline{c_p} \rho_u} \tag{9}$$

where $\overline{\lambda}$, and $\overline{c_p}$ are mean thermal conductivity and mean isopiestic specific heat of flame front and ρ_u is unburnt gas density.

Figure 14 and Figure 15 show correction factor I and flame thickness δ calculated from Eq.(8) and (9). Obviously, in rich or lean side, the values much differ from the values of stoichiometric mixture.

Corrected burning velocity S_u is calculated by Eq.(7), (8) and (9). The process is as follows.

1) Based on experimental data, calculate non corrected burning velocity S_u using Eq.(6).
2) Calculate flame thickness δ by substitution S_u calculated from 1) for S_u in Eq.(9).
3) Calculate correction factor I by substitution δ calculated from 2) for δ in Eq.(8).
4) Calculate corrected burning velocity S_u by substitution I calculated from 3) for I in Eq.(7).
5) Compare corrected burning velocity with non corrected burning velocity. If they have difference, substitute the corrected burning velocity S_u for S_u in Eq.(9). Then go through the process 2) ~ 4) again.
6) Repeat process 5) until S_u of stage 2) is equal to S_u which was calculated in stage 4)

The results of the calculation converge on a certain value. In this research, the calculation was repeated 10 times for each data using Microsoft Excel to calculate mean burning velocity.

Figure 16 shows the calculated burning velocity of DME-air mixture by these functions for various equivalence ratios and pressures.

In this research, the maximum and minimum burning velocities of DME-air mixture, under atmospheric pressure, are 44.2 cm/sec at ϕ=1.1 and 16.5

cm/sec at ϕ=0.65. For fixed equivalence ratio mixtures, the maximum value of burning velocity decreases as pressure increases. Figure 17 indicates burning velocity of DME-air mixture compared with Methane and Propane-air mixtures under atmospheric pressure [7] [8].

In case of comparison of these different fuel-mixtures, the velocity of DME-air mixture is much higher than that of Methane, and Propane-air mixtures in rich side but little lower in lean side.

Figure 18 shows decreasing trend of burning velocity of DME-air mixture at various equivalence ratios and mixture pressures. Burning velocity at each equivalence ratio mixture decreases about 4.6 cm/sec as the pressure increase 0.1 MPa.

Chapter 4　Conclusions

Experiments have been carried out to investigate the combustion characteristics of DME fuel-air mixtures using a spherical flame in a closed bomb under micro-gravity achieved in a freely falling chamber. The values of burning velocity and pressure effect have been obtained. The main conclusions are as follows

1) The maximum and minimum burning velocities of DME-air mixture, under atmospheric pressure, are 44.2 cm/sec at equivalence ratio ϕ=1.1 and 16.5 cm/sec at ϕ=0.65
2) Burning velocity of DME-air mixture is much higher than that of Methane and Propane-air mixtures in rich side but little lower in lean side under atmospheric pressure.
3) Burning velocity at each equivalence ratio mixture decreases about 4.6 cm/sec as the pressure increases 0.1 MPa.

Acknowledgement

The author would like to thank Professor S.OKAJIMA for his guidance and encouragement through my whole study. He also gave me wonderful chances such as making presentations at domestic and international conferences and he made my school days so meaningful. The author would like to express his appreciation to Professor T.KAWAKAMI for his helpful suggestions and kind teachings in his class. Finally, the author is deeply indebted to his friends belong the laboratory and the family supported his student life.

February, 2008
Hosei University Graduate School
Kenta SASAGAWA

References

1) International Energy Agency: World energy outlook 2002, Organization for Economic (2002)

2) 九州 DME 研究会 HP： http://www.kyudme.jp/

3) 日本化学会(編)：化学便覧　基礎編(3 版), 丸善, 1984

4) S. Okajima, K. Inuma, S. Kumagai : Measurement of slow burning velocities and their pressure dependence using a zero-gravity method, 20th Symposium on Combustion, The Combustion Institute, pp.1951-1956, 1984

5) 野村浩行：「微小重力法による DME 燃料－空気混合気の燃焼特性の解明に関する研究」,法政大学大学院 2005 年度工学研究科機械工学専攻修士論文集 2006-3

6) 岡島敏, 江川哲司, 日本機械学会論文集(B 編), 53 巻, 1987

7) G. E. Andrews, D. Bradley: The burning velocity of methane-air mixtures (Methane-air mixtures burning velocity as function of equivalence ratio at atmospheric pressure, using bomb/hot-wire and corrected density ratio techniques), Combustion and Flame. Vol. 19, pp. 275-288. 1972

8) G. Yu, C.K. Law, C.K. Wu: Laminar Flame Speeds of Hydrocarbon + Air Mixtures with Hydrogen Addition, Combustion and Flame Vol.63, pp.339-347, 1986

Conferences

1) 笹川健太, 岡島敏；「DME－プロパン－空気希薄混合気燃焼における火炎挙動の微小重力観察」　日本機械学会関東支部第12回講演会論文集, pp397-398, 2006-3

2) A. Nakamura, K. Sasagawa, Y. Aoyama, S.Okajima; Combustion Characteristics at Lean Side of DME-Propane-Air Mixtures using Microgravity Technique, 31st International Symposium on Combustion, pp.394,2006-8

3) 笹川健太, 中村昭夫, 岡島敏；「球状火炎法によるＤＭＥ－プロパン－空気希薄混合気の燃焼特性の解明に関する研究」日本機械学会2006年度年次大会講演論文集,　pp227, 2006-9

4) 笹川健太, 岡島敏；「微小重力下における高圧雰囲気中でのDME-空気混合気の燃焼特性の解明に関する研究」　第44回燃焼シンポジウム講演論文集, pp144-145, 2006-12

Table 1 Physical properties of DME

	DME	Methane	Propane	Methanol	Light oil
Chemical formula	CH_3OCH_3	CH_4	C_3H_8	CH_3OH	
Boiling point [℃]	-25.1	-161.5	-42	64.6	180～360
Liquid density [g/cm^3,20℃]	0.67		0.49	0.79	0.84
Vapor pressure [atm, 25℃]	6.1	246	9.3		
Ignition point [℃]	235	650	470	450	250
Flammability limit [vol.%]	3.4～17	5～15	2.1～9.4	5.5～36	0.6～7.5
Cetane number	55～60	0	5	5	40～55
Lower calorific value [kcal/kg]	6900	12000	11100	4800	10200
Higher calorific value [kcal/m^3]	14200	8600	21800		

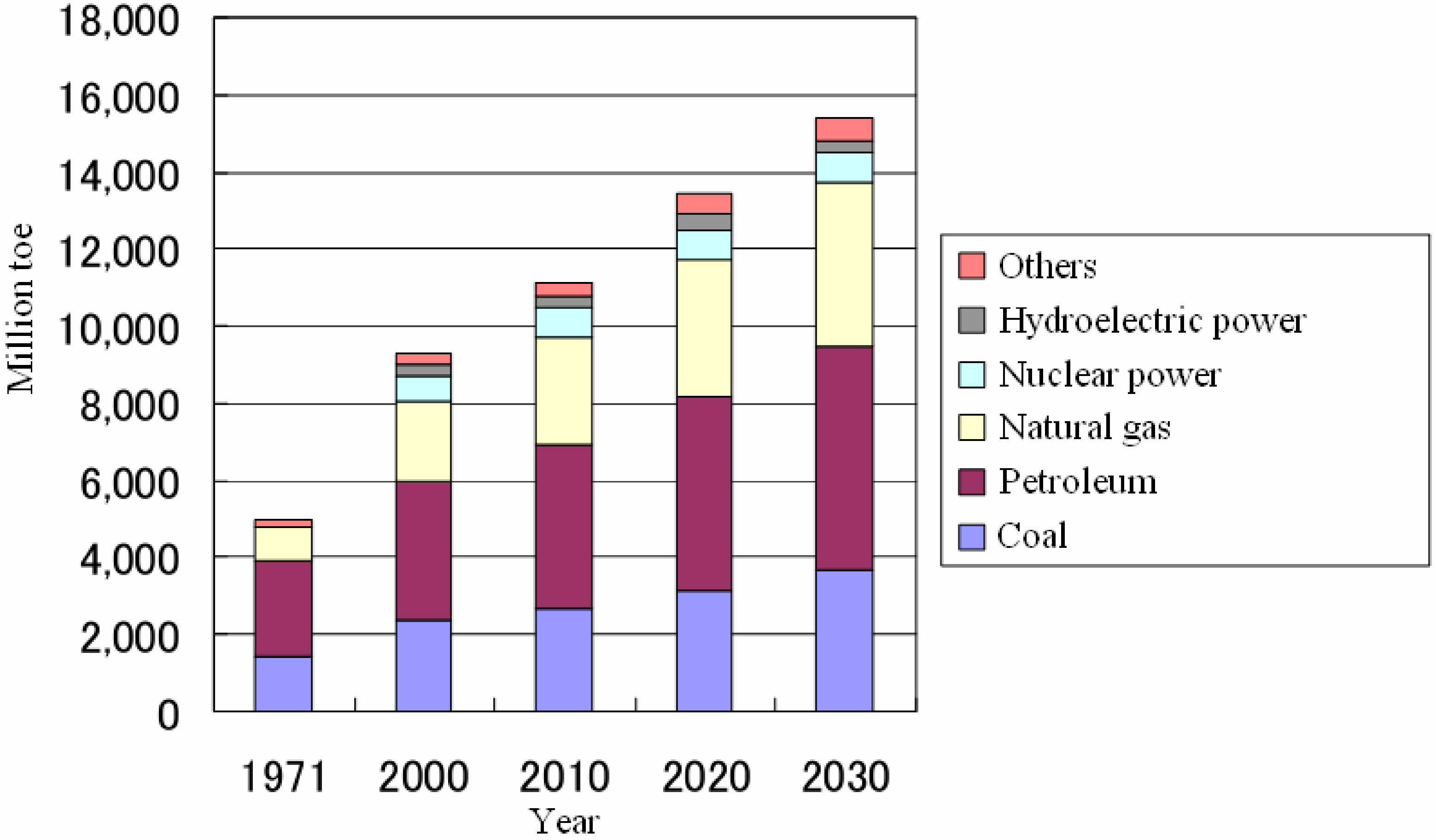
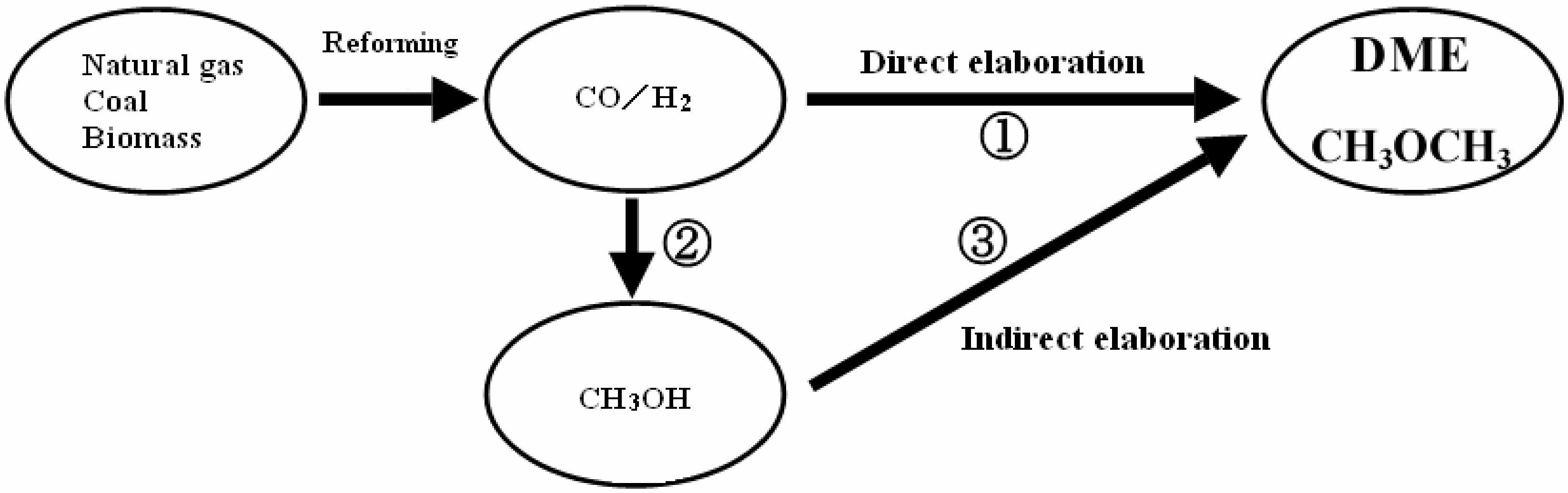


Fig.1 Energy demand prediction



② $2CO+4H_2 \rightarrow 2CH_3OH$

① $3CO+3H_2 \rightarrow CH_3OCH_3+CO_2$

③ $2CH_3OH \rightarrow CH_3OCH_3+H_2O$

Fig.2 Manufacturing process of DME

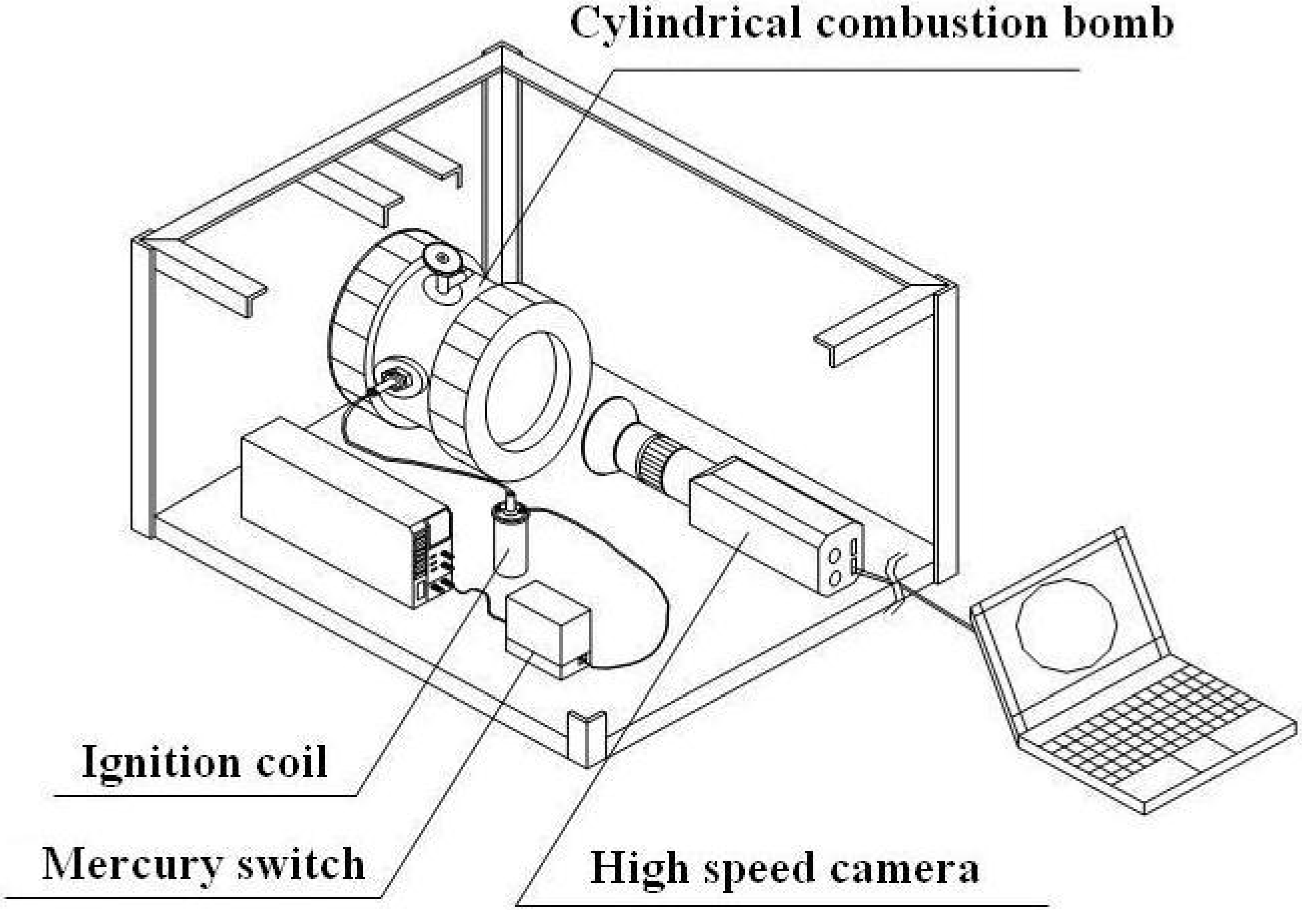


Fig.3 Outline of test assembly

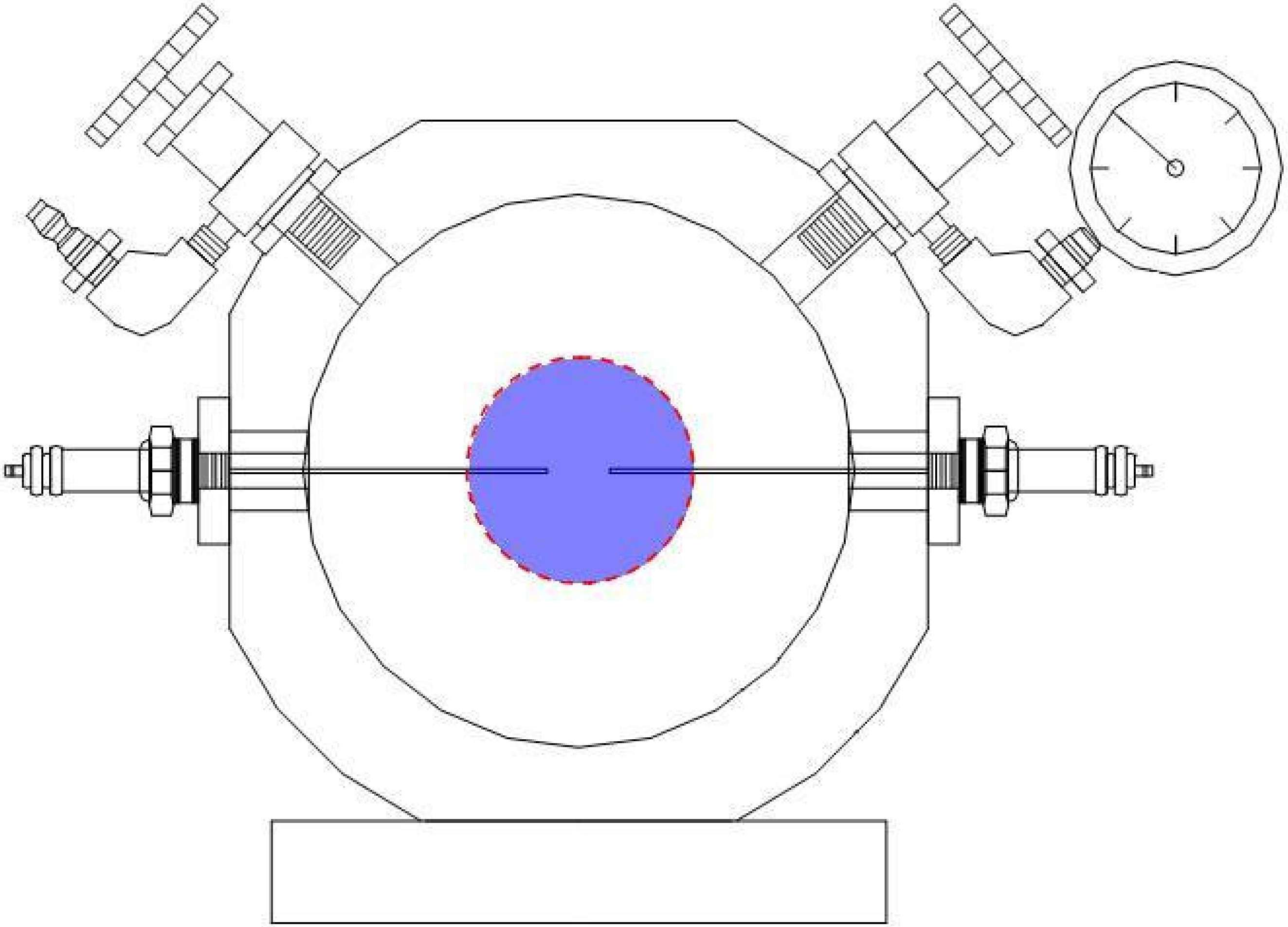


Fig.4 Cylindrical combustion bomb

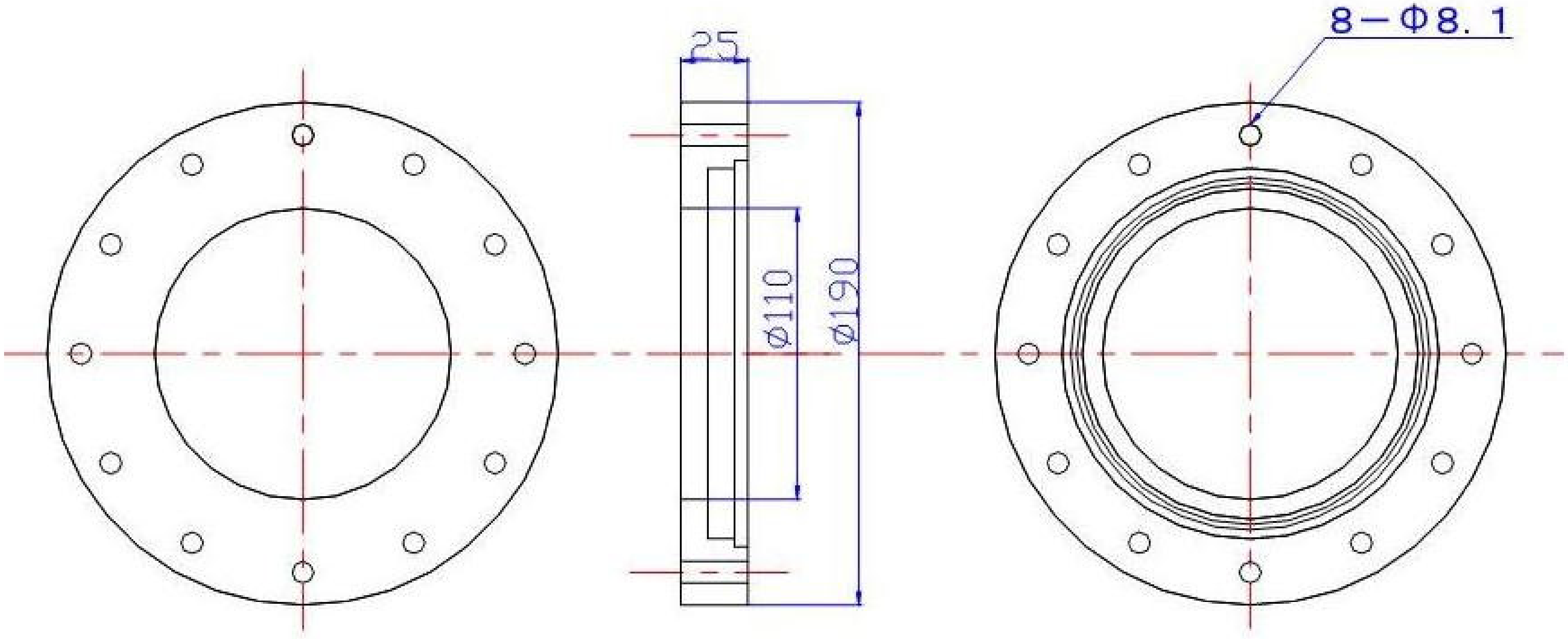


Fig.5 Manufacturing drawing of cylindrical combustion bomb (Side view)

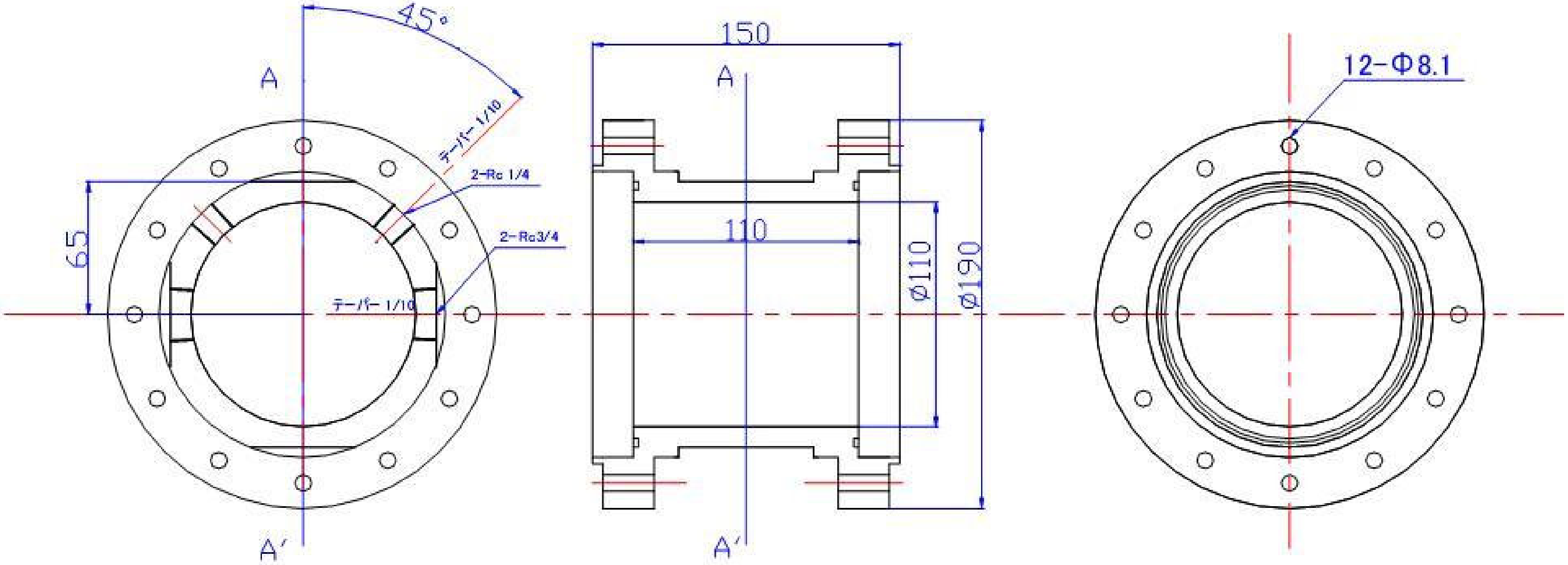


Fig.6 Manufacturing drawing of cylindrical combustion bomb (Front view)

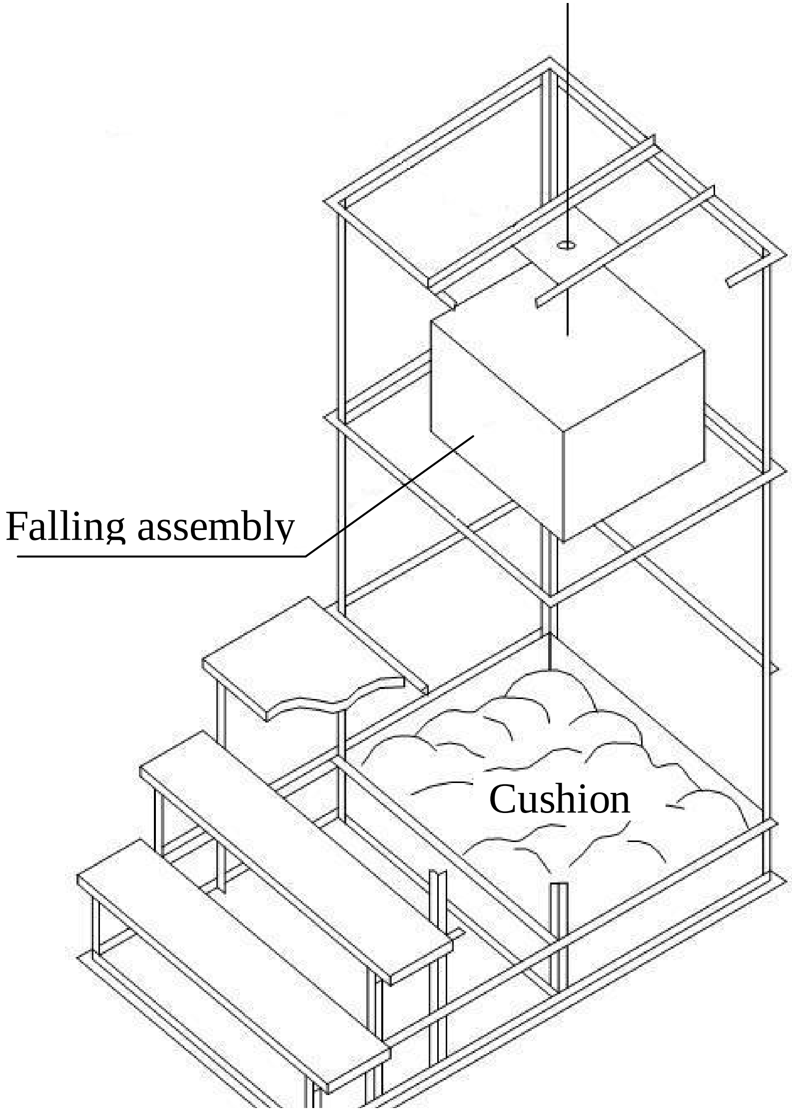


Fig.7 Falling tower

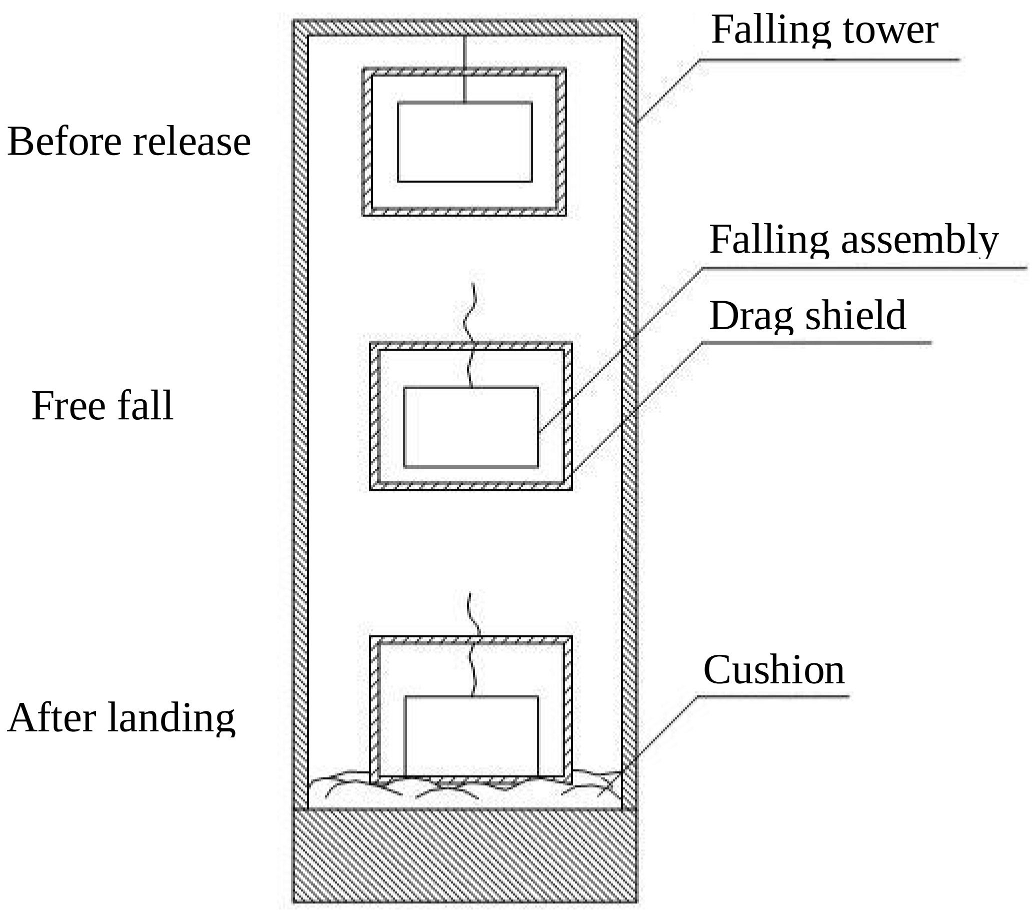
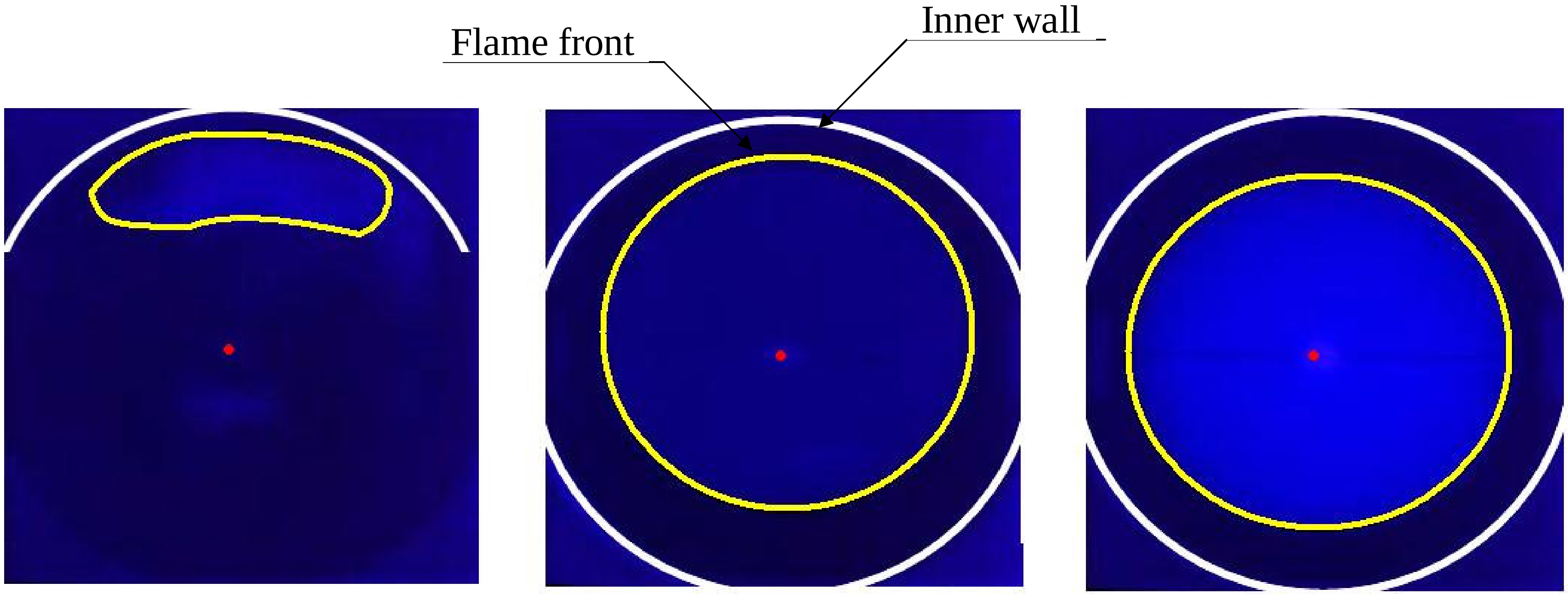
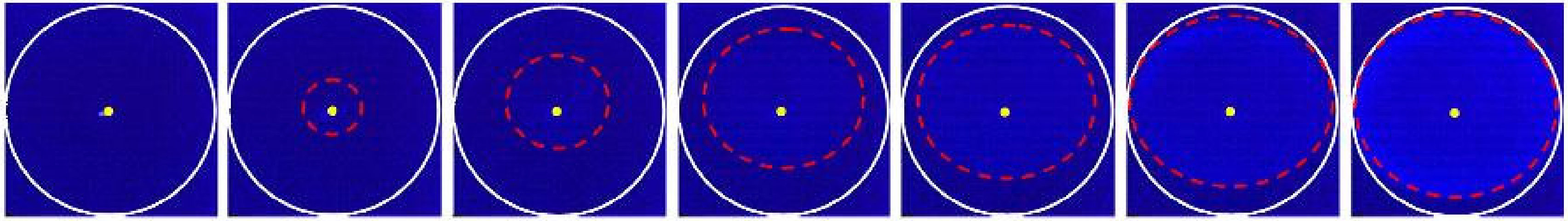


Fig.8 Falling tower and air drag shield

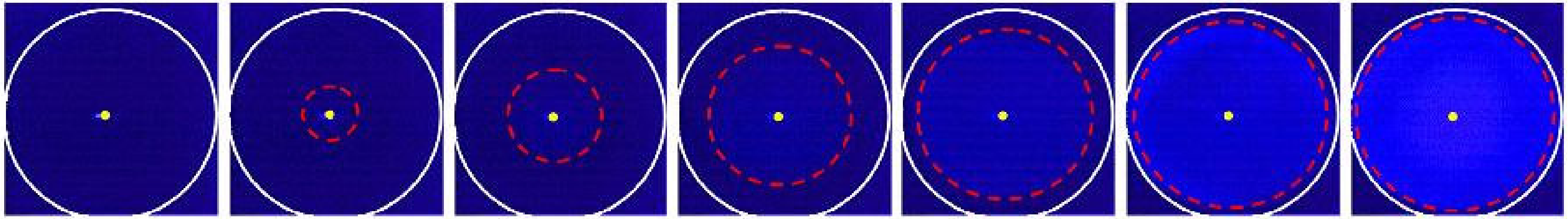


(a) ϕ =0.55 (b) ϕ =0.65 (c) ϕ =0.8

Fig.9 One-shot photographs of DME-air mixtures at various equivalence ratios under normal gravity



(a) Normal gravity ϕ =0.65, *T*=298K, *P*=0.1MPa (Frame interval: 0.02 sec)



(b) Micro-gravity ϕ =0.65, *T*=298K, *P*=0.1MPa (Frame interval: 0.02 sec)

Fig.10 Sequential photographs of DME-air mixtures under normal and micro gravity

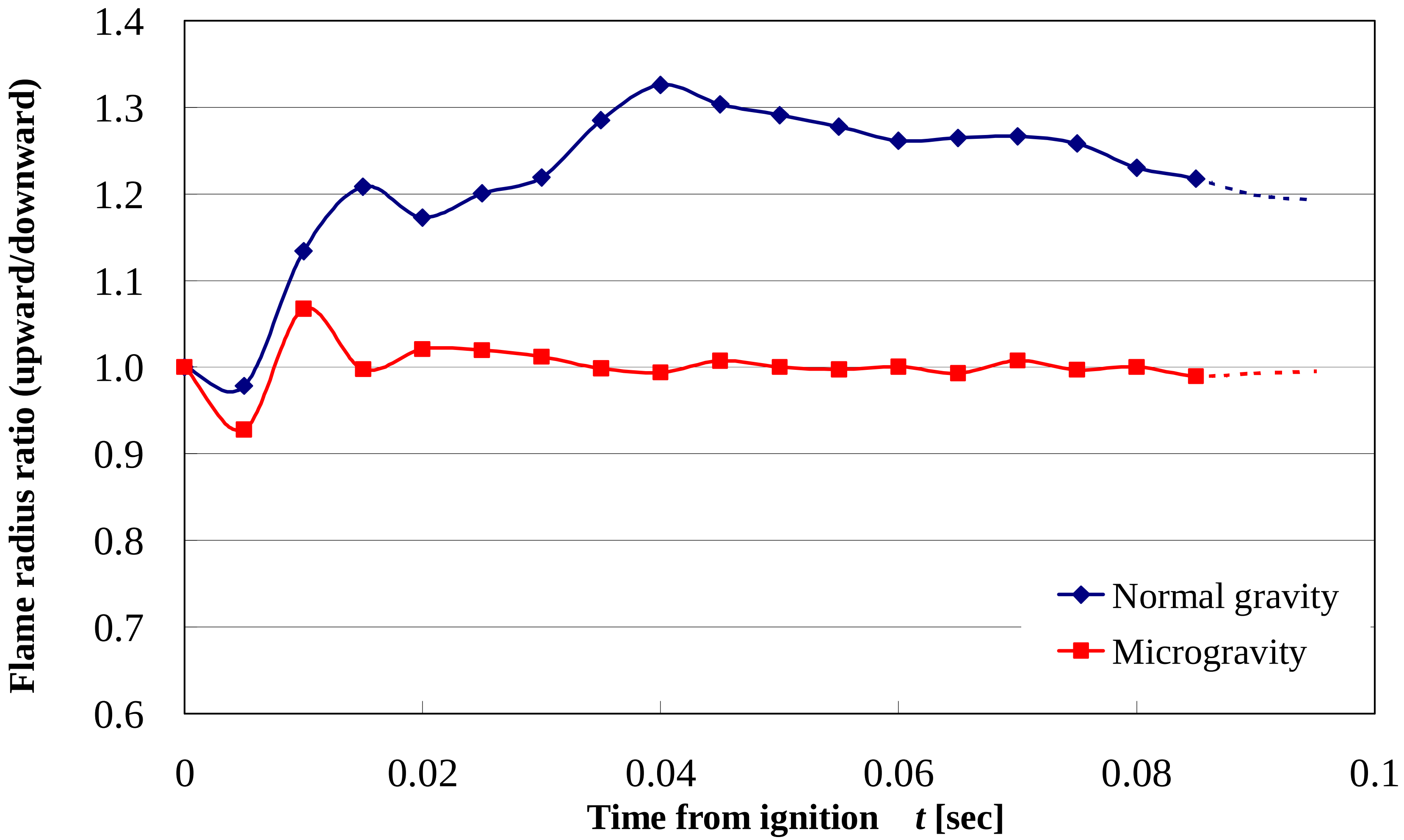


Fig.11 **Flame radius ratio of DME-air mixture at ϕ =0.65, atmospheric pressure**

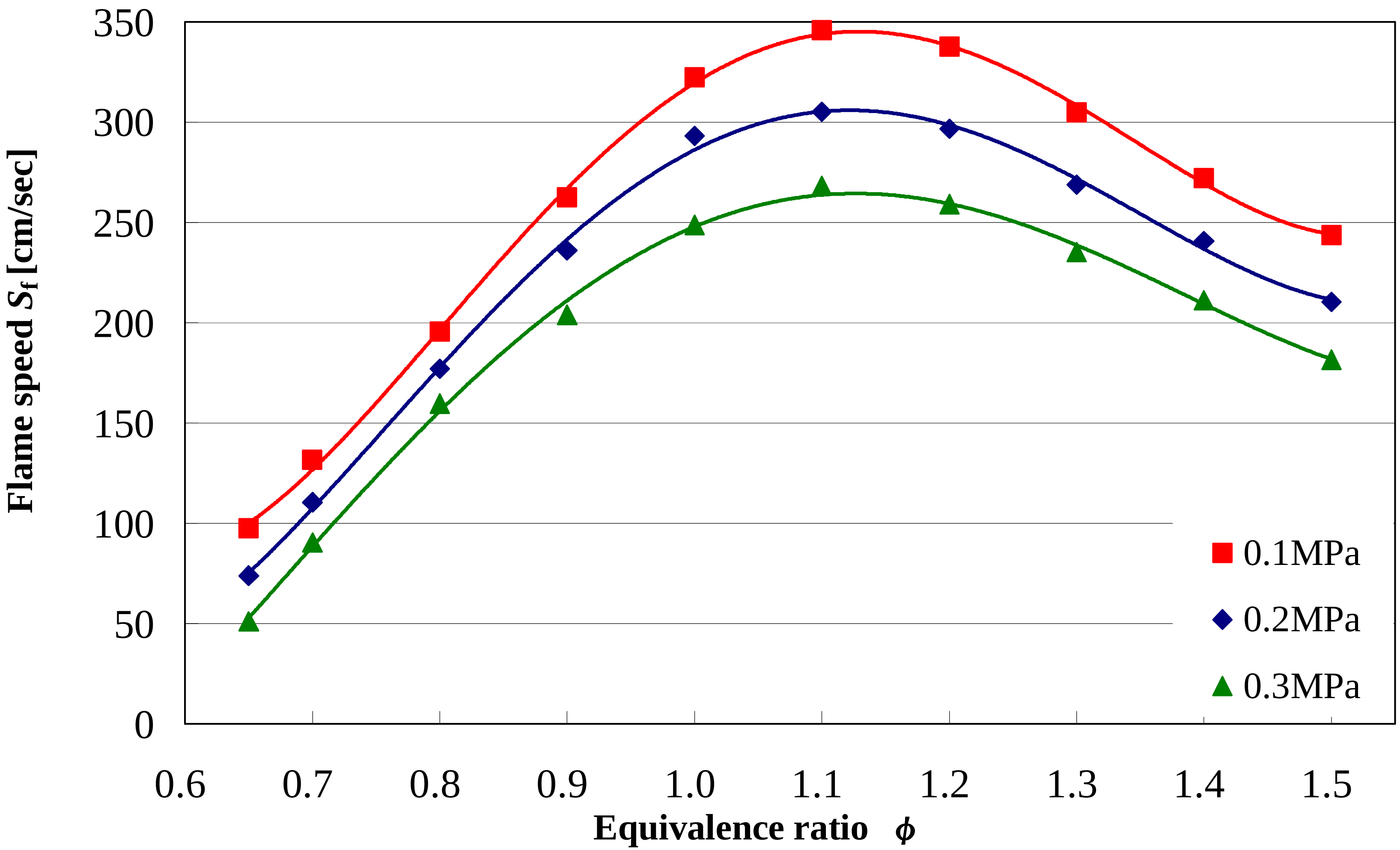


Fig.12 Flame speed of DME-air mixtures at various equivalence ratios and mixture pressures

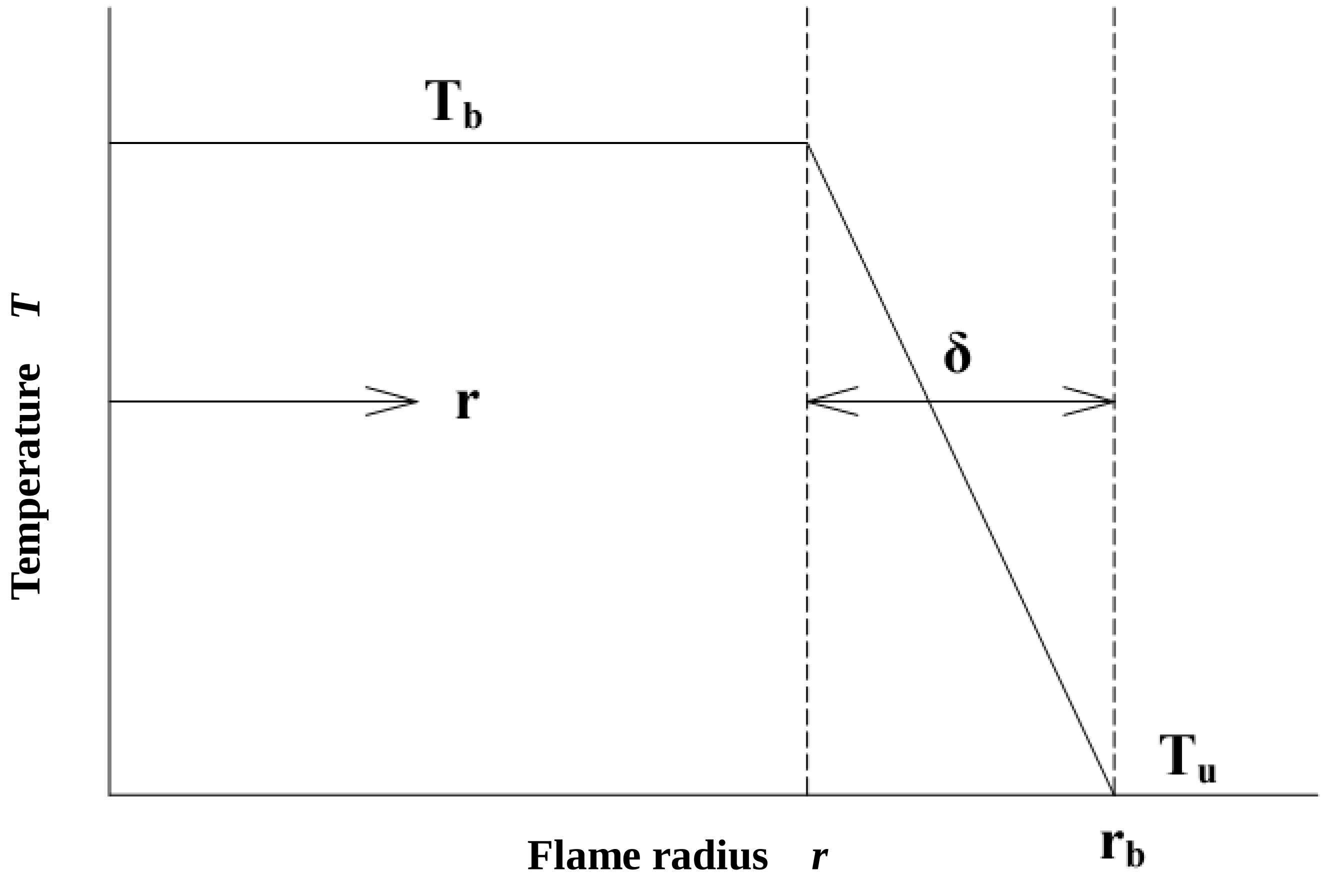


Fig.13 Flame temperature model

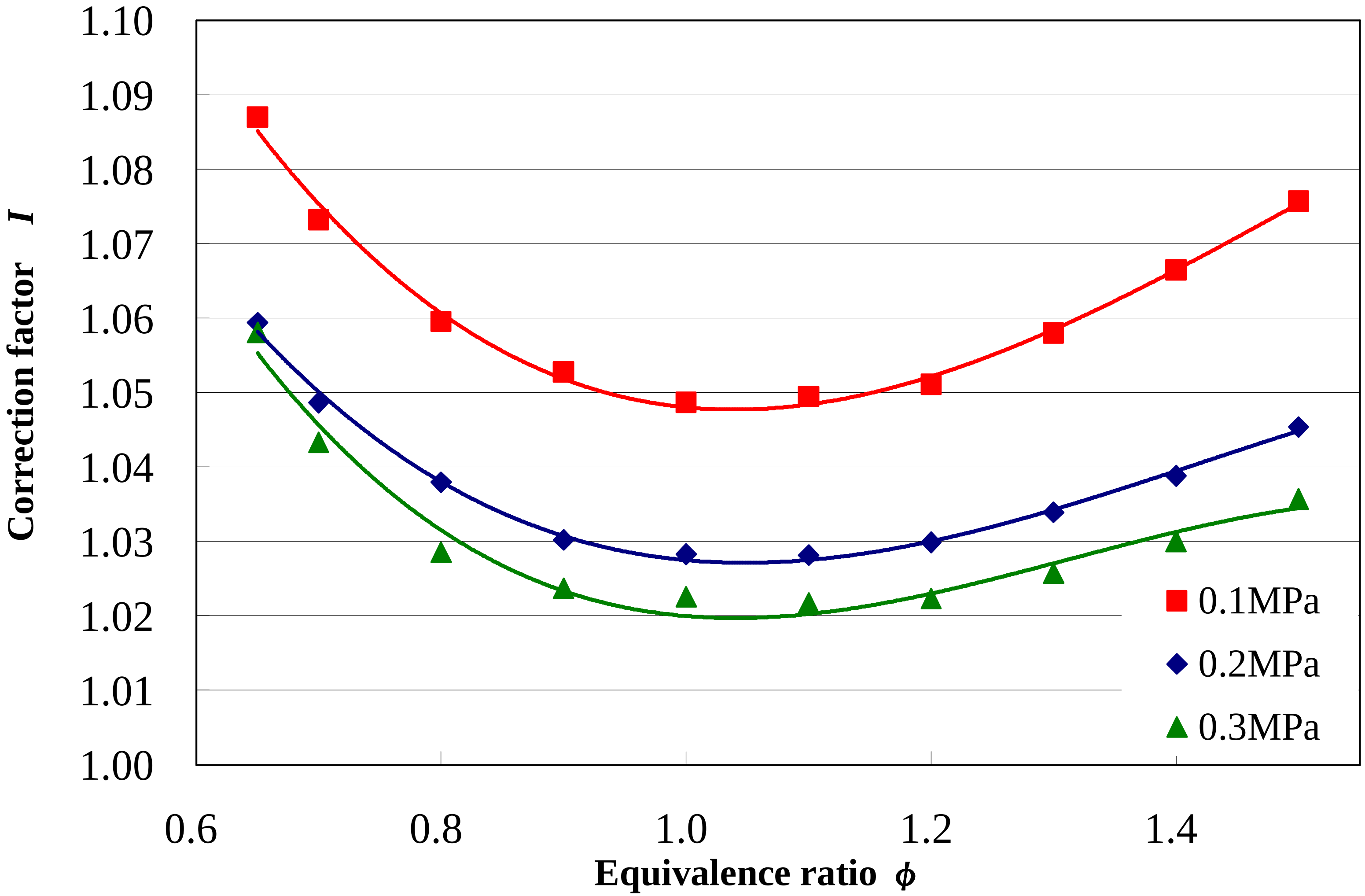


Fig.14 **Correction factor *I* of DME-air mixture**

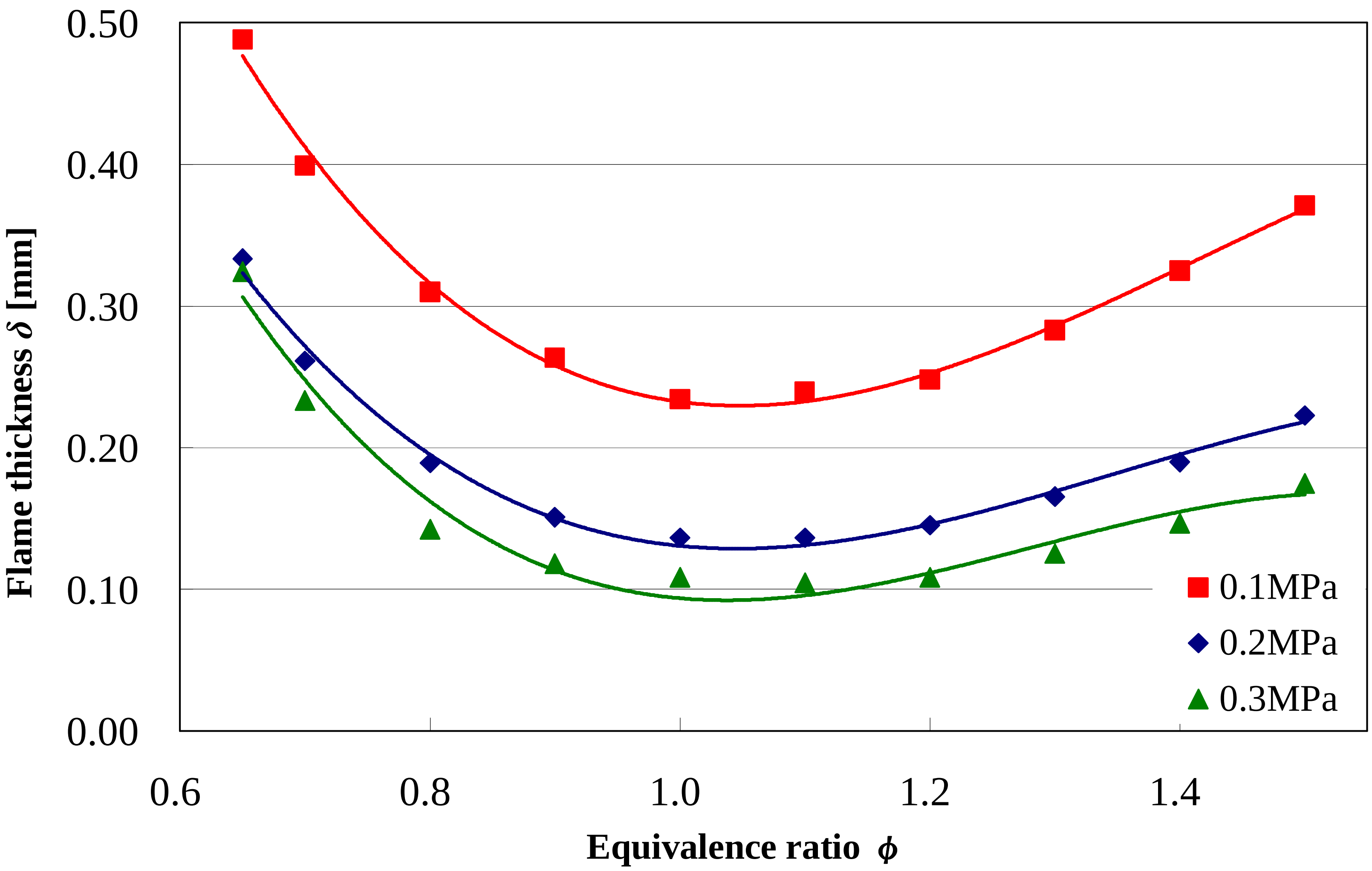


Fig.15 Flame thickness δ of DME-air mixture

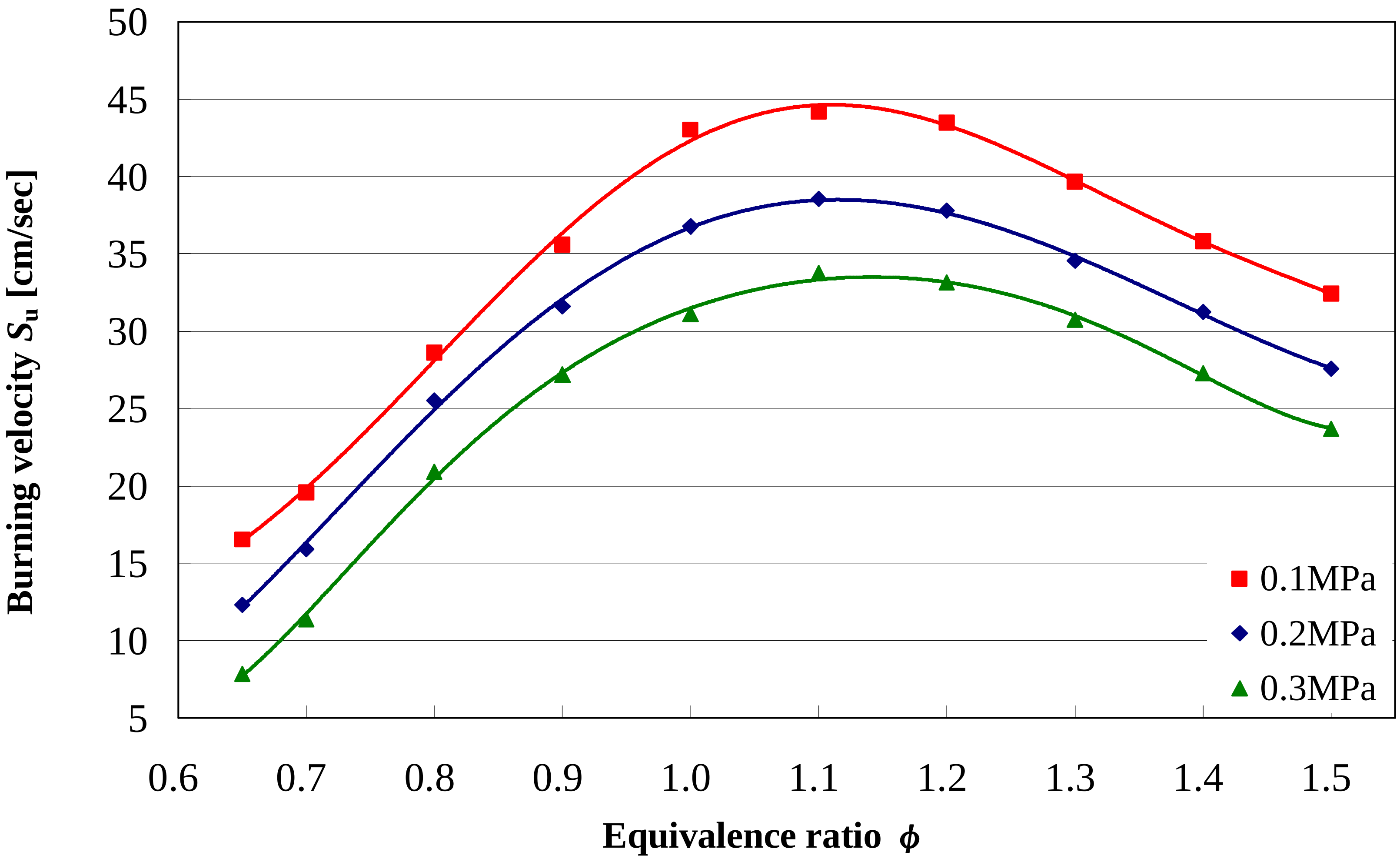


Fig.16 Burning velocity of DME-air mixtures at various equivalence ratios and mixture pressures

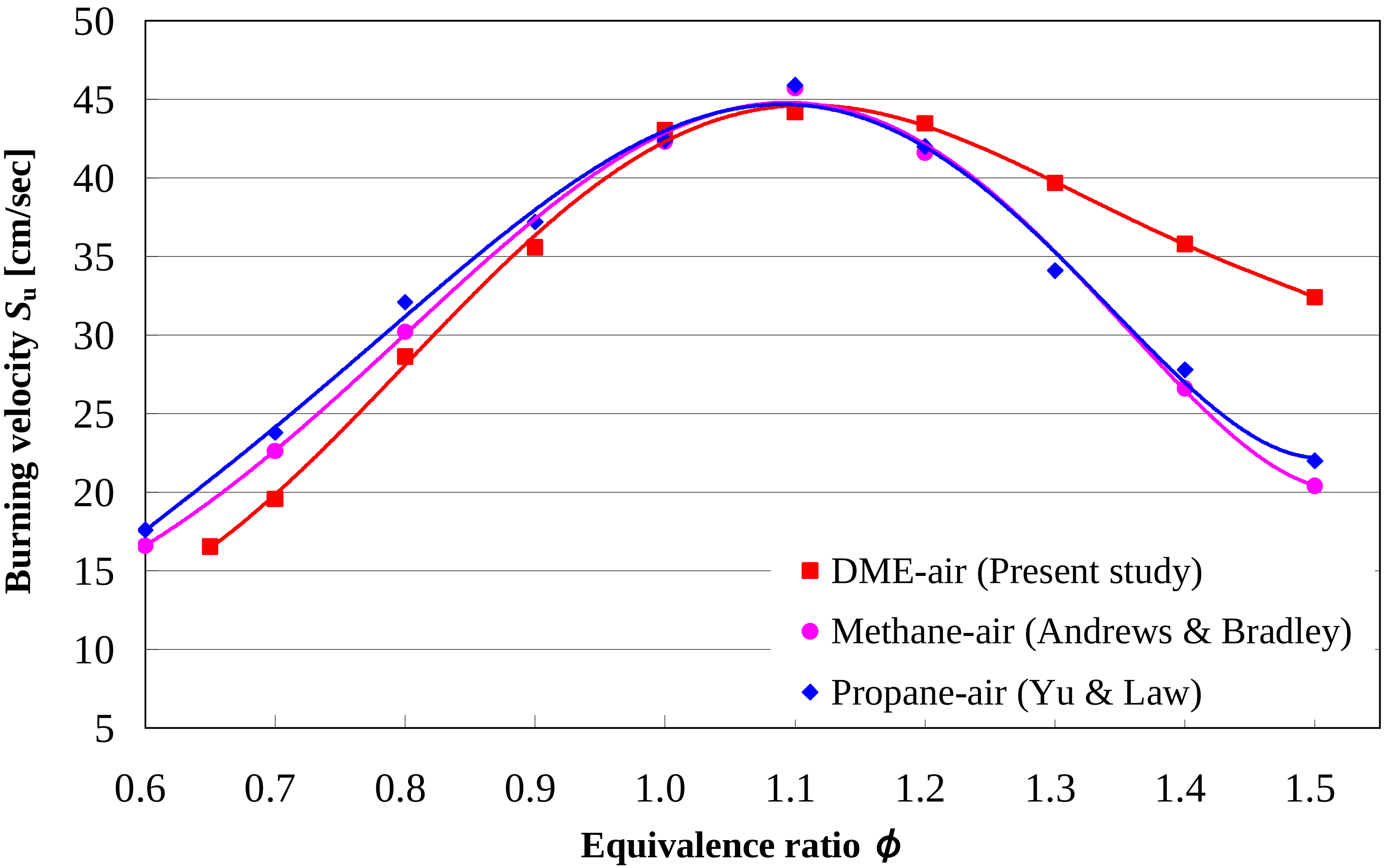


Fig.17 Burning velocity of DME, Methane, Propane-air mixtures at various equivalence ratios, atmospheric pressure

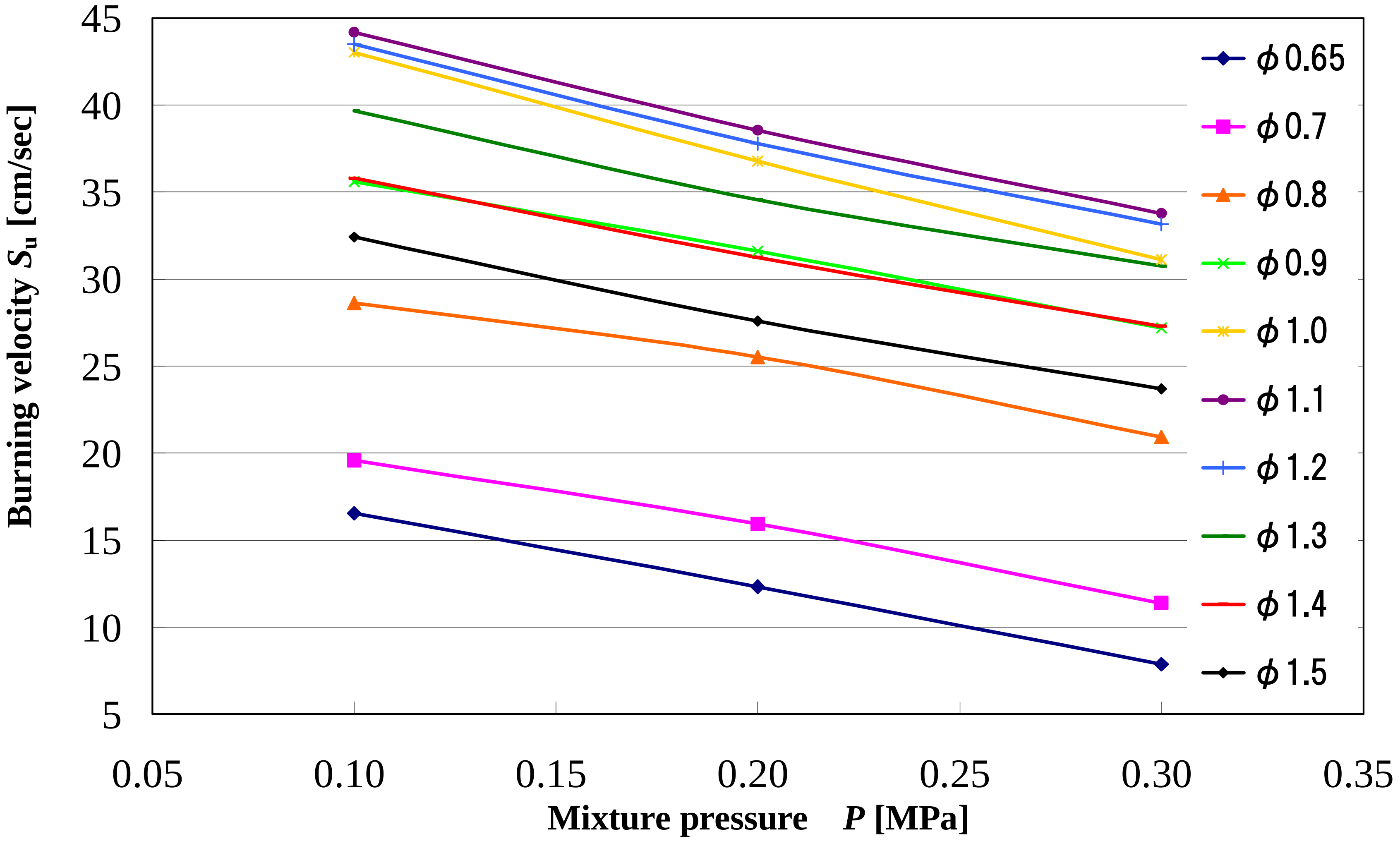


Fig.18 Decreasing trend of Burning velocity of DME-air mixture