Experimental Study on Plastic Waste Fuel Combustion

OHIRA, Tomoaki / 大平, 智章

(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

Experimental Study on Plastic Waste Fuel Combustion in High Temperature Atmosphere

高温空気中における廃棄物プラスチック燃料の燃焼特性の解明に関する実験的研究

指導教授：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修士課程

06R1105

大平　智章

Ohira Tomoaki

Abstract

The experimental study of solid waste fuels has been performed to throw light on some fundamental features of plastics fuels in high temperature environments to realize the flame stabilization and low pollutant substances. The polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are used for the present study as representative fuels of plastics because these plastics occupy about a half of total Japanese plastic production.

From the observation on combustion behavior of PE, PP and PVC, it can be summarized as follows that,

(1) There are three stages of combustion behavior of the plastic waste fuels, that is: ignition delay, flaming duration and char combustion. However it is impossible to observe the char combustion for PE and PP.

(2) The radiative heat transfer is the dominant factor to determine the ignition delay.

(3) The apparent activation energies for ignition estimated from the Arrhenius equation type are 28 kJ/mol for PE, 42 kJ/mol for PP and 68 kJ/mol for PVC.

(4) For PVC, the stationary combustion may be established above 970K of the ambient temperature.

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1. Introduction

In recent year, the progress of science and technology has brought us a convenient and comfortable life style. On the contrary the environmental problems in the terrestrial scale of the lack of energy and resources, the acid rain, the ozone layer depletion, the global warming and desertification, a large quantity of waste produced by mass production and consumption are disposed, especially, by incinerator.

Therefore, it is strongly required to develop a useful technique for the waste fuel combustion immediately. Moreover, in Japan it is reported that, by the 2010 the power generation from the combustion of solid waste aims to achieve about 4 million kJ electric powers.

But there are some problems on waste fuel combustion, that are,

- Flame stabilization to prevent the irregular combustion.
- Reduction of pollutant substances.

Thus, it is required to reveal the fundamental combustion properties of waste fuel in high temperature environments. Then the plastic waste is paid attention. Plastic is used in a lot of things in our life. For example, packaging, containers, machine components and so on. And plastic is made from natural resources and it has a high calorific value. Thus, the experiments have been carried out to reveal the fundamental combustion properties of plastics such as polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC) and they are occupied about 60% of total Japanese plastic production [1]. Figure 1 shows the production ratio of plastic resin in Japan in 2006.

The combustion behaviors of plastic fuels are examined in a high temperature environment of electric furnace in the temperature range from 873K to 1673K.

The objectives for the study are as follows.

1. To examine the fundamental combustion behavior such as ignition delay, flaming duration and char combustion in the high temperature environments to examine.
2. To examine the ignition mechanism of the plastic by observing the ignition behavior in the high temperature environments.
3. To investigate the optimum conditions of flame stabilization of plastic in the high temperature environments.

2. Experimental Apparatus and Procedure

2-1. Test apparatus

Figure 2 shows the experimental setup of the test assembly employed for the study. The test assembly, which is the rectangular shape of 900 mm ×350 mm ×950 mm in size and 40kg in weight, consists of electric furnace, a temperature control equipment, an air cylinder, an air tank, an electro-magnetic valve, an air compressor, an electromagnetic scale and an 8-mm digital video camera (SONY Co. Model DCR-TRV240). The electric furnace is rectangular shape 150×110mm in the inside dimension as shown in Fig.3. The electric furnace is composed of siliconit heating rods and the maximum temperature that can be reached by the electric furnace is about 1673K. The temperature profile located in the central part of electric furnace is measured by R-type thermocouple.

2-2. Test Fuels

The fuels adopted for the present study as representative plastics in practical use are the polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC). The configuration of the test fuels is sphere. The diameters of PE and PP are 4.0, 5.6 and 9.5mm, and the diameter of PVC is 5.5mm. Figure 4 shows the test piece of PE, diameter is 5.6mm.

Table 1 shows the physical properties of each fuel. From this figure, densities, melting points and degradation temperatures are comparable. And thermal conductivities, specific heats and lower calorific values have big deference [2].

The test fuels are processed by a drill to make a hole of 0.5mm in diameter, and they are attached at the tip of the fine quartz fiber.

2-2-1. Description of the polyethylene (PE)

Polyethylene is a polymer consisting of long chains of the monomer ethylene (IUPAC name ethene). The recommended scientific name 'polyethene' is systematically derived from the scientific name of the monomer. In certain circumstances it is useful to use a structure–based nomenclature. In such cases IUPAC recommends poly(methylene). The difference is due to the 'opening up' of the monomer's double bond upon polymerisation.

In the polymer industry the name is sometimes shortened to PE, in a manner similar to that by which other polymers like polypropylene and polystyrene are shortened to PP and PS, respectively. In the United Kingdom the polymer is commonly called polythene, although this is not recognised scientifically.

The ethene molecule (known almost universally by its common name ethylene), C_2H_4 is CH_2=CH_2, Two CH_2 groups connected by a double bond.

Polyethylene is created through polymerization of ethene. It can be produced through radical polymerization, anionic addition polymerization, ion coordination polymerization or cationic addition polymerization. This is because ethene does not have any substituent groups that influence the stability of the propagation head of the polymer. Each of these methods results in a different type of polyethylene [3].

2-2-2. Description of the polypropylene (PP)

Most commercial polypropylene has an intermediate level of crystallinity between that of low density polyethylene (LDPE) and high density polyethylene (HDPE); its Young's modulus is also intermediate. Although it is less tough than HDPE and less flexible than LDPE, it is much less brittle than HDPE. This allows polypropylene to be used as a replacement for engineering plastics, such as ABS. Polypropylene is rugged, often somewhat stiffer than some other plastics, reasonably economical, and can be made translucent when uncolored but not completely transparent as polystyrene, acrylic or certain other plastics can be made. It can also be made opaque and/or have many kinds of colors. Polypropylene has very good resistance to fatigue, so that most plastic living hinges, such as those on flip-top bottles, are made from this material. Very thin sheets of polypropylene are used as a dielectric within certain high performance pulse and low loss RF capacitors.

Polypropylene has a melting point of about 440K. Many plastic items for medical or laboratory use can be made from polypropylene because it can withstand the heat in an autoclave. Food containers made from it will not melt in the dishwasher, and do not melt during industrial hot filling processes. For this reason, most plastic tubs for dairy products are polypropylene sealed with aluminum foil (both heat-resistant materials). After the product has cooled, the tubs are often given lids of a cheaper (and less heat-resistant) material, such as LDPE or polystyrene. Such containers provide a good hands-on example of the difference in modulus, since the rubbery (softer, more flexible) feeling of LDPE with respect to PP of the same thickness is readily apparent. Rugged, translucent, reusable plastic containers made in a wide variety of shapes and sizes for consumers from various companies such as Rubbermaid and Sterilite are commonly made of polypropylene, although the lids are often made of somewhat more flexible LDPE so they can snap on to the container to close it. When liquid, powdered, or similar consumer products come in disposable plastic bottles which do not need the improved properties of polypropylene, the containers are often made of slightly more economical polyethylene, although transparent plastics such as polyethylene terephthalate are also used for appearance. Plastic pails, car batteries, wastebaskets, cooler containers, dishes and pitchers are often made of polypropylene or HDPE, both of which commonly have rather similar appearance, feel, and properties at ambient temperature.

MFI (Melt Flow Index) identifies the flow speed of the raw material in the process. It helps to fill the plastic mold during the production process. The higher MFI increases, the weaker the raw material gets.

It also has Copolymer and Random Copolymer. Copolymer helps stiffness of the PP (Polypropylene). Random Copolymer helps transparent look.

Copolymer is more expensive than Homopolypropylene. Random Copolymer is even higher than copolymer PP.

A rubbery PP can also be made by a specialized synthesis process, as discussed below. Unlike traditional rubber, it can be melted and recycled, making it a thermoplastic [4].

2-2-3. Description of the polyvinyl chloride (PVC)

Polyvinyl chloride, (IUPAC Polychloroethene) commonly abbreviated PVC, is a widely used thermoplastic polymer. In terms of revenue generated, it is one of the most valuable products of the chemical industry. Around the world, over 50% of PVC manufactured is used in construction. As a building material, PVC is cheap, durable, and easy to assemble. In recent years, PVC has been replacing traditional building materials such as wood, concrete and clay in many areas. Despite the fact that PVC production negatively affects the natural environment and human health, it is still widely used.

There are many uses for PVC. As a hard plastic, it is used as vinyl siding, magnetic stripe cards, window profiles, gramophone records (which is the source of the term vinyl records), pipe, plumbing and conduit fixtures. The material is often used in Plastic Pressure Pipe Systems for pipelines in the water and sewer industries because of its inexpensive nature and flexibility. PVC pipe plumbing is typically white, as opposed to ABS, which is commonly available in gray as well as white.

It can be made softer and more flexible by the addition of plasticizers, the most widely-used being phthalates. In this form, it is used in clothing and upholstery, and to make flexible hoses and tubing, flooring, to roofing membranes, and electrical cable insulation [5].

2-3. Experimental Procedure

1. A faucet is turned on and the cooling water is circulated around the electric furnace.
2. The temperature control equipment is powered up and the temperature of the electric furnace is regulated.
3. An air tank is filled up the air from an air compressor.
4. An air cylinder is filled up the air from an air tank.
5. The room temperature and the atmospheric pressure in the experimental laboratory are measured.
6. The mass of the test fuel is measured by using an electromagnetic scale.
7. The digital video camera is turned on.
8. The test fuel is supported at the tip of the fine quartz fiber. And it is fitted in at the end of the air cylinder.
9. The air cylinder is turned on power and introduced in to the electric furnace. As soon as introducing, the air cylinder is operated by the compressed air from air tank, and the test fuel is shifted to the center position of the electric furnace. Then the combustion of the test fuel starts.
10. The combustion behavior of the test fuel is observed by taking the direct photographs with 8-mm digital video camera. And the burning time is measured by using the image analysis software (TMPGEnc).
11. The mass of the test fuel is measured by using an electromagnetic scale.

The experiment has been carried out as the parameters of the ambient temperature of the electric furnace and the diameter of the test fuel. The range of ambient temperature in the electric furnace is 873K to 1673K.

3. Results and Discussions

3.1 Combustion Behavior

Generally, for solid fuel combustion, the combustion process consists of three kinds of phases, that is, ignition delay, flaming duration (luminous diffusion flame) and char combustion period.

Figure 5 shows the combustion behavior of PE. The initial diameter is 5.6mm. And ambient temperature of the electric furnace is 1273K. From this figure, in the first phase, after the test fuel is introduced into the electric furnace, the ignition occurs after a time delay. It calls ignition delay. The burning process initiates when the flame can be appeared. And then, luminous diffusion flame is established. However, in the combustion process of PE, the observation of all of the combustion behavior including the luminous diffusion flame cannot readily done because the plastic fuel begin to stream down while being melted before the combustion process of the luminous diffusion flame is completed.

Figure 6 shows the combustion behavior of PP. The initial diameter is 5.6mm and ambient temperature of the electric furnace is 1273K. The combustion behavior of PP also looks very similar to PE. For PP it is also possible to observed the ignition delay and flaming duration.

Figure 7 shows the combustion behavior of PVC. The initial diameter is 5.5mm. And ambient temperature of the electric furnace is 1273K. For PVC, it is observed all the three combustion phases that is, the ignition delay (phase one), flaming duration (phase two) and char combustion (phase three).

For the combustion phases of plastic fuels, there are three kinds of combustion phases, that is, (1) gradual heating of plastic fuels leading to ignition, (2) combustion of plastic fuels with a luminous flame envelop and (3) char combustion.

In the first phase, the partially evaporated volatile contents tend to escape from the plastic sphere eventually leading to build-up of an ignitable mixture at the surface.

In the second phase, after the ignition, the diffusion flame of plastic fuels is established and the volatile matter of plastic fuels gets exhausted during this combustion phase.

In the third phase, the char combustion occurs at the surface of plastic fuels due to the diffusion of oxygen towards the surface of the plastic fuels, because there is a scarce volatile composition from the plastic fuels after the duration of the luminous diffusion flame. Especially, the char porous substances are mainly composed of the fixed carbon and ash [6][7].

3.1.1 Ignition Delay

Figure 8 shows the ignition delay versus the ambient temperature of electric furnace as a parameter of initial diameter of PE. The ignition delay is defined as a time interval from the introduction of plastic fuel into the electric furnace to the appearance of luminous diffusion flame. From this graph it can be seen that the ignition delay significantly decreases with the increasing ambient temperature and an increase of the diameter leads to the increase of the ignition delay. Additionally, figure 9 shows the case of PP and figure 10 for PVC. From the graphs the ignition delay of PP and PVC it denotes same tendency of PE.

Assuming that the test fuel is simplified steady model, such as there is no temperature gradient inside the plastic fuel, namely the temperature of the fuel is constant, the fuel ignite quickly after reaching the ignition temperature T_{ig} and the Nusselt's number is about 2 (formula (1)),

$$Nu = \frac{hD_0}{k} \approx 2 \tag{1}$$

where h is a heat transfer coefficient of surface of the plastic fuel, D_0 is the initial diameter of the plastic fuel and k is the thermal conductivity of air, the theoretical ignition delay τ_{th} is expressed following formula,

$$\tau_{th} = \tau_1 + \tau_2 \tag{2}$$

where τ_1 is the time required for the plastic fuel to be heated to the ignition temperature T_{ig} and τ_2 is the time required for the plastic fuel to be heated to vaporization.

Then, the heat balance of the plastic fuel can be evaluated as following equation,

$$\left(\frac{\pi}{6}\right) D_0^3 \rho c \frac{dT_p}{d\tau_1} = \pi D_0^2 h \left(T_a - T_p\right) \tag{3}$$

$$\left(\frac{\pi}{6}\right) D_0^3 \rho L = \pi D_0^2 h \left(T_a - T_m\right) \tau_2 \tag{4}$$

where T_a is the ambient temperature, ρ is the density of the plastic fuel, c is the specific heat of the plastic fuel, T_p is the temperature of the plastic fuel, L is the evaporation heat of the plastic fuel and T_m is the boiling point of the plastic fuel.

Eqn (3) can be integrated from the initial temperature T_0 until T_{ig} to yield τ_1

$$\tau_1 = \frac{D_0^2 \rho c}{12k} \ln \frac{T_a - T_0}{T_a - T_{ig}} \tag{5}$$

rearrange eqn (4) to yield τ_2

$$\tau_2 = \frac{D_0^2 \rho}{12k} \frac{L}{T_a - T_m} \cdot \tag{6}$$

From eqn (2)

$$\tau_{th} = \frac{\rho D_0^2}{12k} \left[c \ln \frac{T_a - T_0}{T_a - T_{ig}} + \frac{L}{T_a - T_m} \right] \tag{7}$$

$$\therefore \tau_{th} \propto D_0^2 , \tag{8}$$

namely the theoretical ignition delay τ_{th} is proportional to the squared initial diameter of the plastic fuel $D_0{}^2$ [8].

Figure 11 shows the ignition delay versus the squared diameter of plastic sphere as a parameter of the ambient temperature of PE. The ignition delay is increasing according to the increase of the squared diameter of the plastic sphere or the surface area. In case of the droplet combustion, the increase tendency is proportion to the squared diameter; however in this solid plastic case the increase tendency does not be proportional to the squared diameter of the plastic sphere. Figure 12 shows in the case of PP and it denotes same tendency of PE.

The relation between the ignition delay τ and ambient temperature of the electric furnace T is assumed to be following formula,

$$\tau = \alpha \times T^{\beta} \tag{1}$$

taking its natural logarithm gives following formula,

$$\ln \tau = \ln \alpha + \ln T^{\beta} \tag{2}$$

$$\ln \tau = \beta \ln T + \ln \alpha \tag{3}$$

suppose that $lnT=X$ and $ln\tau=Y$, equation (3) becomes as following formula,

$$Y = \beta X + C \tag{4}$$

the relation between the ignition delay τ and ambient temperature of the electric furnace T could be leaded by measuring the slope of the line β in a graph. In Fig. 13 shows the logarithmic plot of the ignition delay against the ambient temperature to examine the heat transfer mechanism for ignition in the electric furnace. From this graph, the slope of the line β is -4 and one can derive an empirical equation (5) for ignition delay τ with ambient temperature T of electric furnace.

$$\tau \propto T^{-4} \tag{5}$$

Where the radiative heat flux q_r is given by the following formula, the Stefan-Boltzmann's law,

$$q_r = \sigma T^4 \tag{6}$$

where σ is the Stefan-Boltzmann constant (=5.67×10^{-8} [W/(m$^2 \cdot$K^4)]). From the equation (6), the radiative heat flux q_r is proportion to fourth power of the ambient temperature T. From the equation (5) and (6), the ignition delay τ may be expressed as the following equation,

$$\tau \propto \frac{1}{T^4} \propto \frac{1}{q_r} \tag{7}$$

The equation (7) once again confirms that the radiant heat transfer is the dominant process in the ignition of the plastic fuels [9][10].

Figure 14 shows the semi-logarithmic graph with the ignition delay. From a result of Fig. 14, τ is expressed by following formula of Arrhenius type [11],

$$\tau \propto \exp\left(E/RT\right) \tag{8}$$

where E is an apparent activation energy for ignition, R is a gas constant and T is temperature. The slope of the line in Fig. 14 gives the apparent activation energy for the ignition of plastic fuels. Table 2 shows the apparent activation energies of plastic fuels obtained from equation (8) and Fig. 14. These apparent activation energies are approximately 28kJ/mol, 42 kJ/mol and 68 kJ/mol for PE, PP and PVC, respectively. And on the right, there are illustrated values for famous gases such as the methane, ethane and propane. There are two types of ignition delay that are the physical delay τ_1 and the chemical delay τ_2. τ_1 is a result from the physical heating process. And τ_2 is a result from the chemical process. From Table 2, as compared with the values of famous gases, the apparent activation energies for ignition of plastic fuels are very small. It is predicted that the physical heating process on the combustion of plastic fuels plays a very important role [12].

3.1.2 Framing Duration

In Fig. 15 is shown the variation of flaming duration with ambient temperature of electric furnace for PVC. The flaming duration is defined as the time interval in which the luminous flame is continuously maintained. From this graph, it is seen that above 970K of ambient temperature of electric furnace the flaming duration gradually decreases with increasing ambient temperature. Anyway below 970K its duration increases steeply with the increasing ambient temperature. This fact probably indicates that, below 970K there is not enough amounts of the combustible volatiles to maintain the flame. On the contrary, above 970K the increment of the ambient temperature may lead to increase the combustible volatiles and to accelerate a reaction.

3.1.3 Total Burning Time

Figure 16 shows the total burning time of PVC against the ambient temperature of the electric furnace. The total burning time includes all the three combustion phases – ignition delay, flaming duration and char combustion. As can be seen from this graph, the increment of the ambient temperature may lead to decrease of the total burning time. That is to say the ambient temperature has a significant effect on each combustion phases.

3.1.3 Average Mass Burning Rate

Figure 17 shows the average mass burning rate of PVC during flaming duration against ambient temperature. The average mass burning rate $\dot{m}_a$ is defined the mass reduction rate during the flaming duration. And it is expressed by following formula

$$\dot{m}_a = \frac{m_{ID} - m_{FD}}{t_{FD}} \tag{9}$$

where m_{ID} is the mass of the ignition delay, m_{FD} is the mass after the flaming duration and t_{FD} is the flaming duration.

As can be seen from this graph, above 970K of the ambient temperature, the average mass burning rate increases in proportion to the ambient temperature. It is predicted that the stationary combustion may be established above 970K of the ambient temperature.

4. Conclusion

Experiments have been conducted to elucidate the combustion characteristics of plastic fuel in detail. The main results obtained for the study are as follows:

1. After the plastic fuel is introduced into the electric furnace, the ignition occurs after a time delay, and then luminous diffusion flame is established. After that we can observe the char combustion period for PVC only, though its period does not exist for PE and PP.
2. The radiative heat transfer from high temperature environment to plastic sphere in electric furnace is the dominant factor to determine the ignition delay.
3. The apparent activation energies estimated from the Arrhenius equation type are 28 for PE, 42 for PP and 68 kJ/mol for PVC, respectively. This fact may predict that the heating process on combustion of plastics fuel plays a very important role.
4. For PVC, the stationary combustion may be established above 970K of the ambient temperature.

Acknowledgement

I am indebted to the participants in the studies for their gracious cooperation. I wish to acknowledge the continuing guidance and encouragement of Prof. S. Okajima and Prof. T. Kawakami. I am grateful to the staff of Workshop Center of Hosei University and Jindrich Ziegelheim, Hosei University for their considerable assistance. I am also pleased to acknowledge the hospitality and encouragement of the members of Heat Dynamics Research Laboratory.

References

1. **社団法人　プラスチック処理推進協会：プラスチックリサイクルの基礎知識、**pp11 (2007)
2. **北條　英光ら：プラスチック材料活用事典、産業調査会、**pp864,865 (2001)
3. **北條　英光ら：プラスチック材料活用事典、産業調査会、**pp877 (2001)
4. **北條　英光ら：プラスチック材料活用事典、産業調査会、**pp878 (2001)
5. **北條　英光ら：プラスチック材料活用事典、産業調査会、**pp879 (2001)
6. A. Okajima: Experimental Investigation on Combustion of Solid Waste Fuels in High Temperature and Low Oxygen Atmosphere　**高温低酸素雰囲気中での廃棄物固体低質燃料の燃焼に関する実験的研究、２００５年度　法政大学大学院工学研究科機械工学専攻　学位（博士）論文、**pp42,43
7. **藤井　直人、青田　峰朋、岡島　明子、岡島　敏：第４３回燃焼シンポジウム講演論文集、**pp.472-473 (2005).
8. **岡島　敏、山口　修次、阿部　和利：球状高分子材料の点火と燃焼、別刷　法政大学工学部研究集報** Bulletin of the College of

Engineering, Hosei University　Vol. 17, pp87-95 (1981)

9. 岡島　明子、棚網　祐介、岡島　敏、日本機械学会論文集　別冊７１巻　７０２号　B 編、pp.322-327(2005).
10. 高山　靖宏、高温・低酸素雰囲気中での固体廃棄物低質燃料の基本的燃焼特性に関する研究、２００３年度　修士論文、pp14,15
11. 新岡　嵩、河野　道方、佐藤　順一、燃焼現象の基礎、オーム社(2006).
12. A.Okajima, B.N.Raghunandan, S.Okajima: 4th International High Energy Material Conference, Vol. 4, pp. 286-294(2003).

Publication Papers

(1) **論文題名：同軸流** DME **火炎の燃焼特性の解明に関する実験的研究**

発表者：大平智章、岡島敏

論文発表年月：2006 **年** 3 **月**

論文発表誌名：北陸信越支部 第 4**３期総会・講演会 講演論文集**

(2) **論文題名：高温空気中での廃棄物プラスチックの燃焼特性の解明に関する研究**

発表者：大平智章、岡島敏

論文発表年月：2006 **年** 12 **月**

論文発表誌名：第 44 **回燃焼シンポジウム 講演論文集**

(3) **論文題名：高温空気中での廃棄物プラスチックの燃焼性の解明に関する実験的研究**

発表者：大平智章、岡島敏

論文発表年月：2007 **年** 9 **月**

論文発表誌名：日本機械学会 2007 **年度年次大会 講演論文集**

(4) **論文題名：高温空気中での廃棄物プラスチック材料の燃焼特性の解明に関する研究**

発表者：<u>大平智章</u>、岡島敏

論文発表年月：2007 **年** 12 **月**

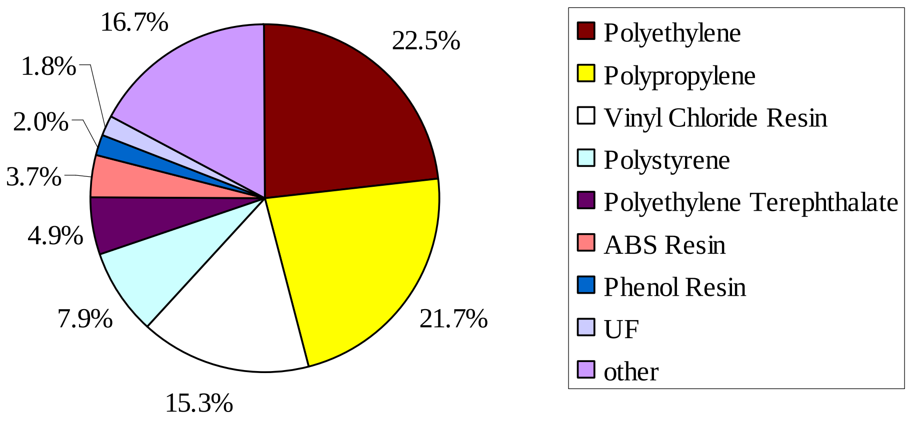
論文発表誌名：第 45 **回燃焼シンポジウム 講演論文集**

(5) **論文題名：**Experimental Investigation on Plastic Waste Fuel Combustion in High Temperature Environments

発表者：<u>大平智章</u>、笹川健太、岡島明子、岡島敏

論文発表年月：2007 **年** 12 **月**

論文発表誌名：Ⅵ International HIGH ENERGY MATERIALS CONFERENCE & EXHIBIT-2007



From The Japan Plastics Industry

Fig.1. The Production Ratio of Plastic Resin in Japan in 2006.

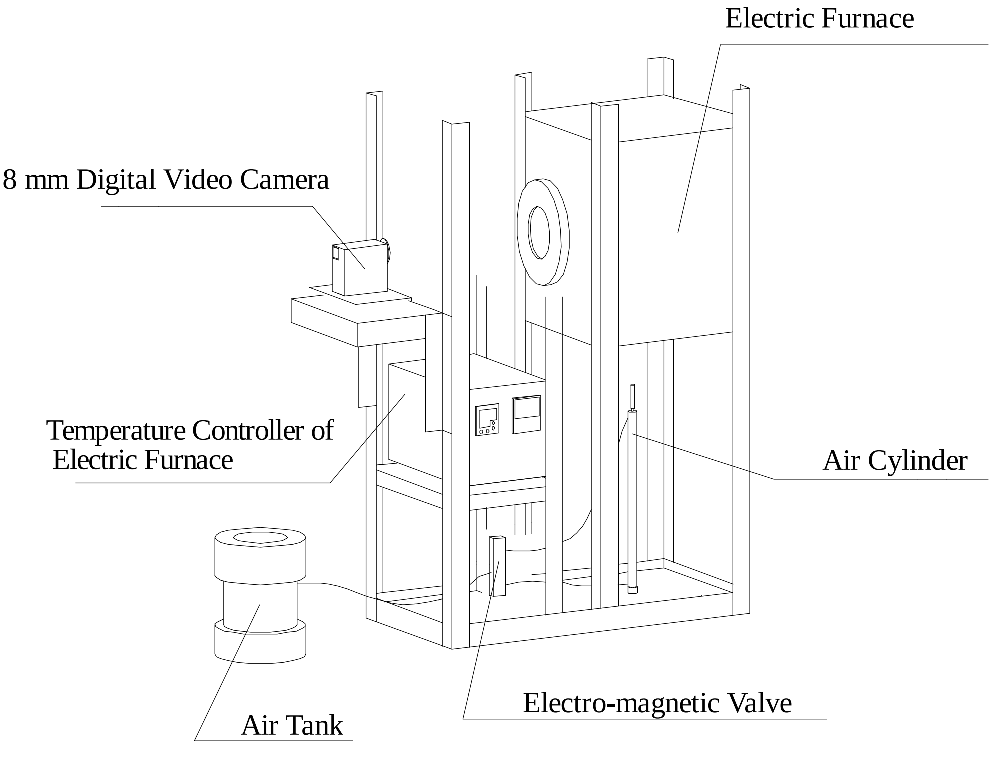


Fig.2. Experimental Set-up of Test Assembly.

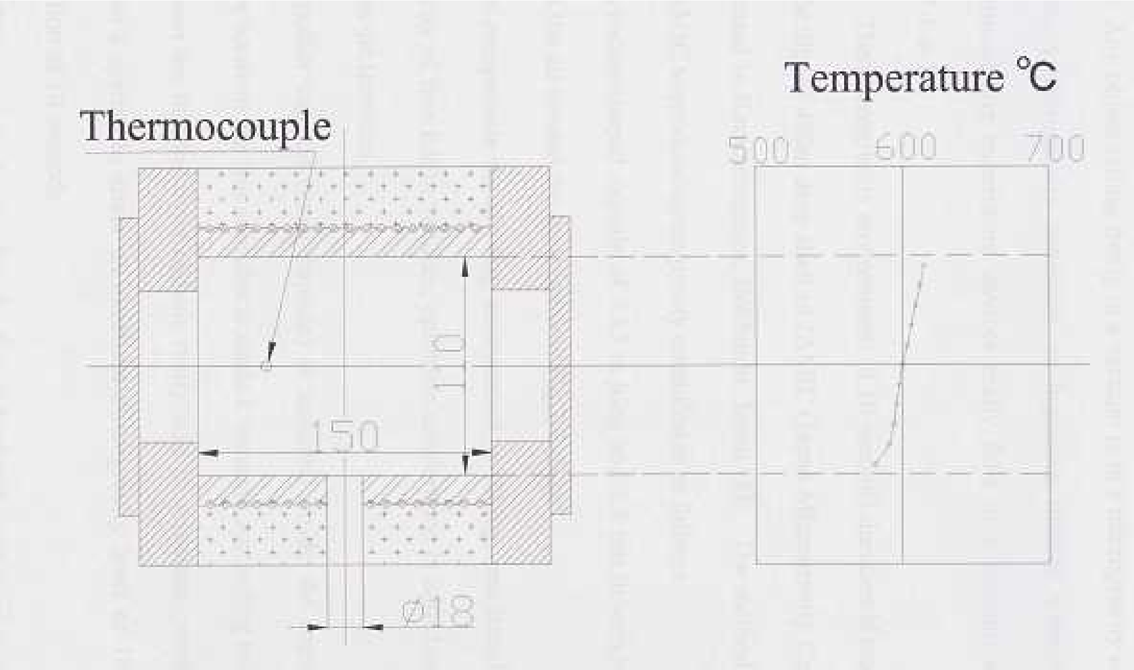
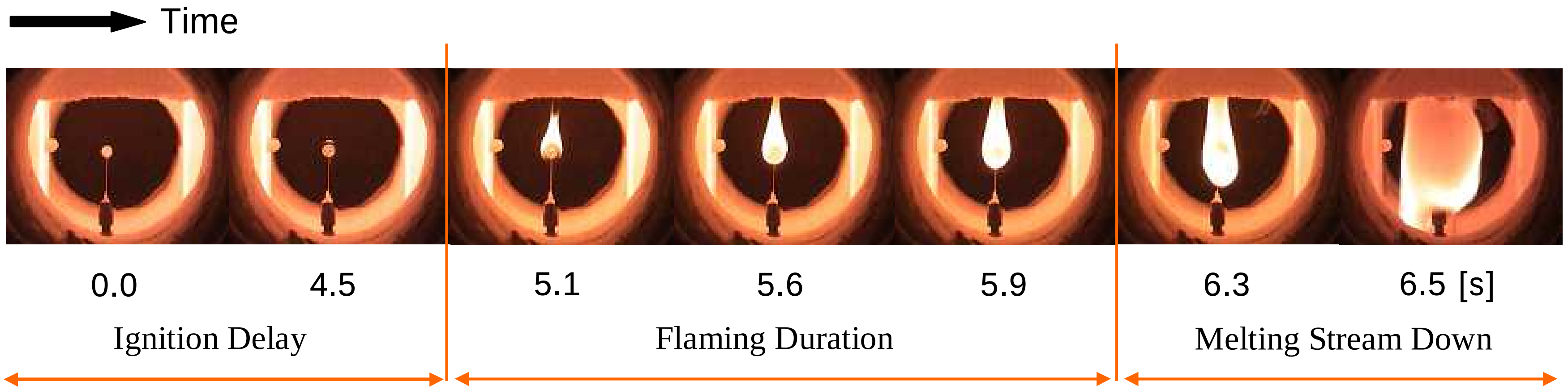


Fig.3. Electric Furnace and Temperature Profile.

Fig.4. Test Piece of PE.

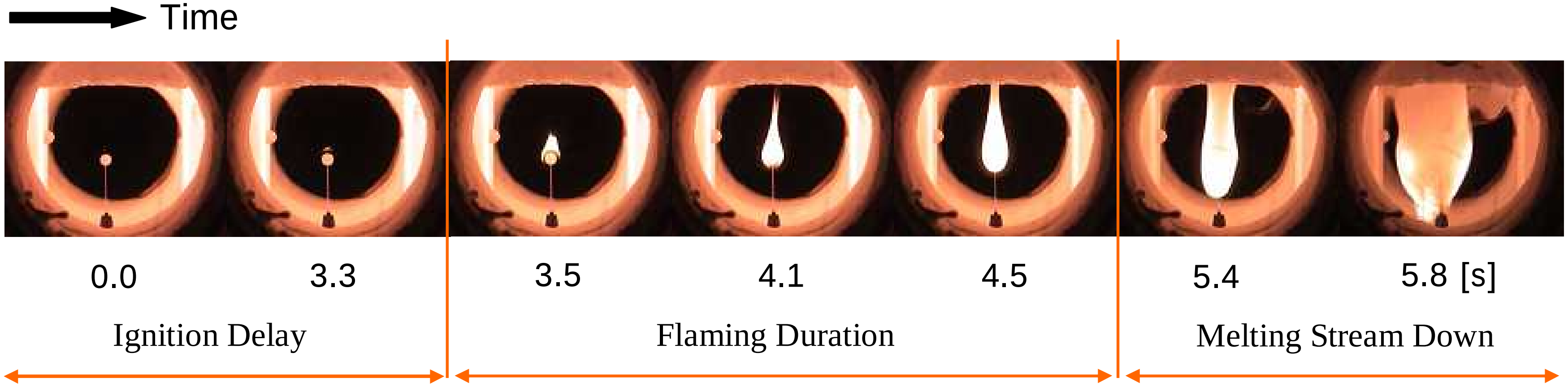
Table 1. The Physical Properties of PE, PP and PVC.

	Polyethylene (PE) **$[\mathrm{-CH2-CH2-}]_n$**	Polypropylene (PP) **$[\mathrm{-CH2-CH(CH3)-}]_n$**	Polyvinyl Chloride (PVC) **$[\mathrm{-CH2-CH(Cl)-}]_n$**
Density [$\mathrm{g/cm^3}$]	0.91-0.935	0.90-0.91	1.18-1.54
Melting Point [K]	378-398	438-443	341
Degradation Temperature [K]	363-403	378-398	323-353
Thermal Conductivity [$1/10^2$W/(m K)]	8-12.4	2.8	3-5
Specific Heat at Constant Pressure [kJ/(kg K)]	0.55	0.46	0.25-0.5
Lower Calorific Value of Combustion [MJ/kg]	46.2	43.9	18.0



PE (D=5.6mm)   1273K

Fig.5. Combustion Behavior of PE.



PP (D=5.6mm) 1273K

Fig.6. Combustion Behavior of PP.

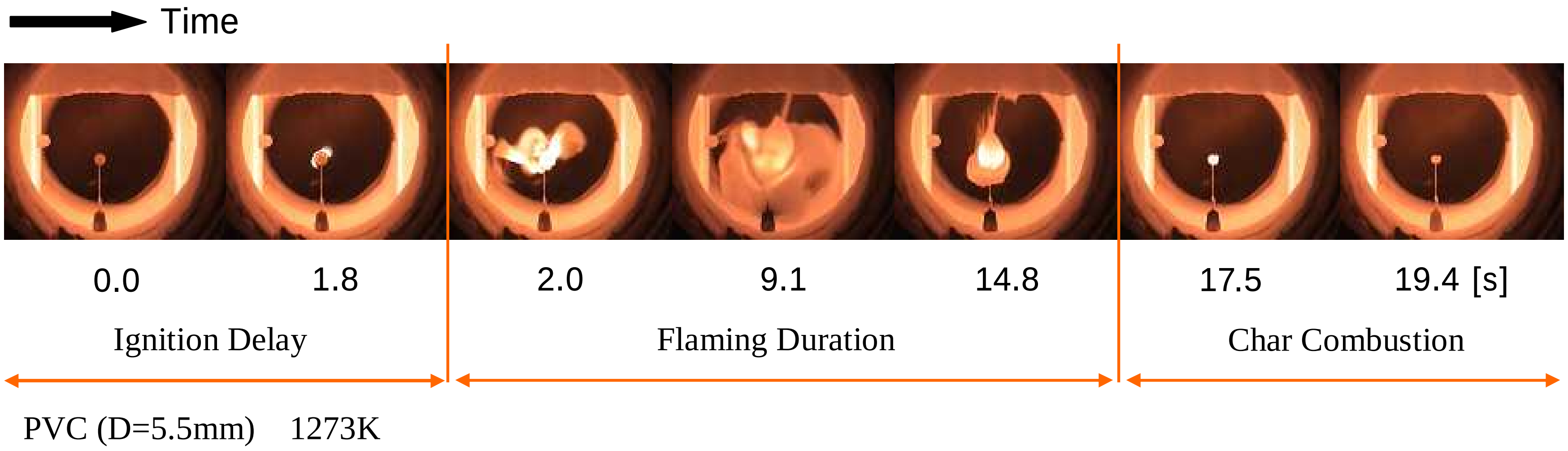


Fig.7. Combustion Behavior of PVC.

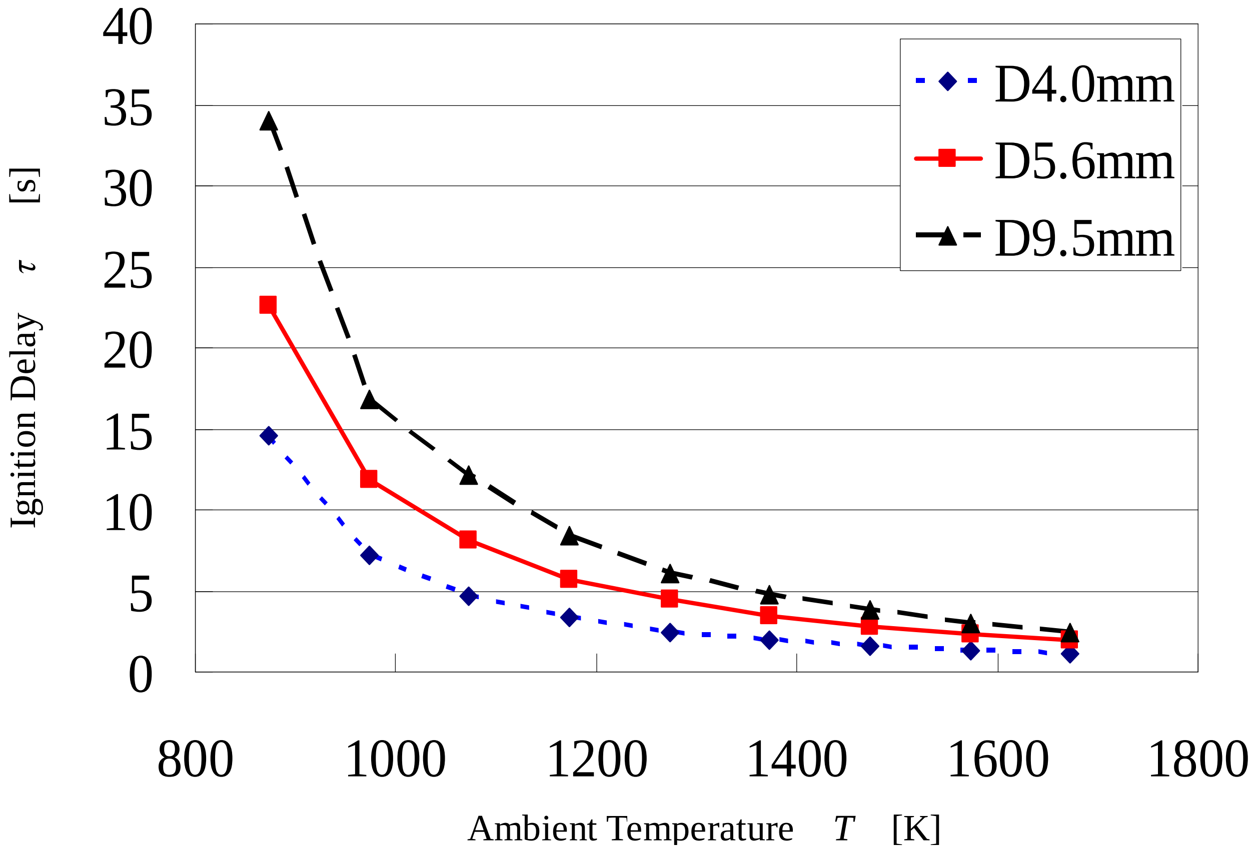


Fig.8. Ignition Delay of PE.

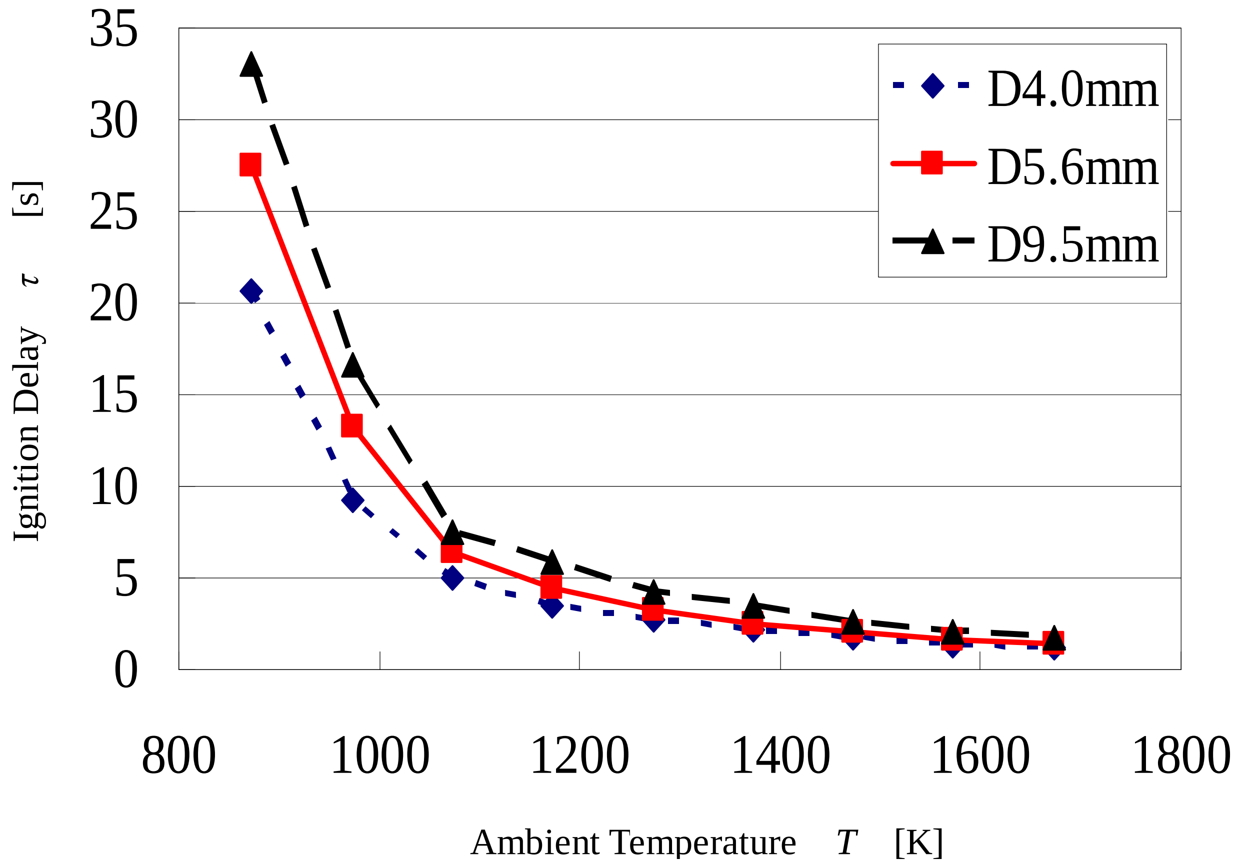


Fig.9. Ignition Delay of PP.

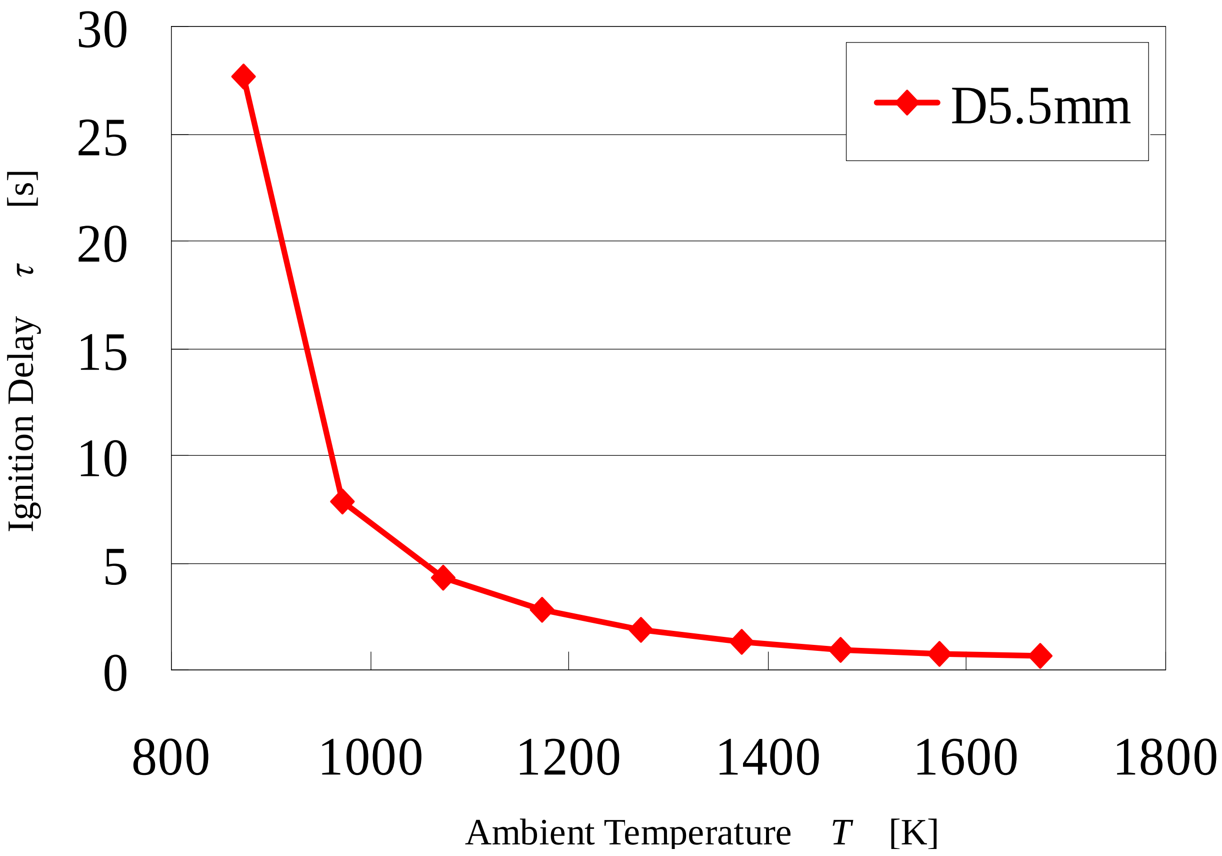


Fig.10. Ignition Delay of PVC.

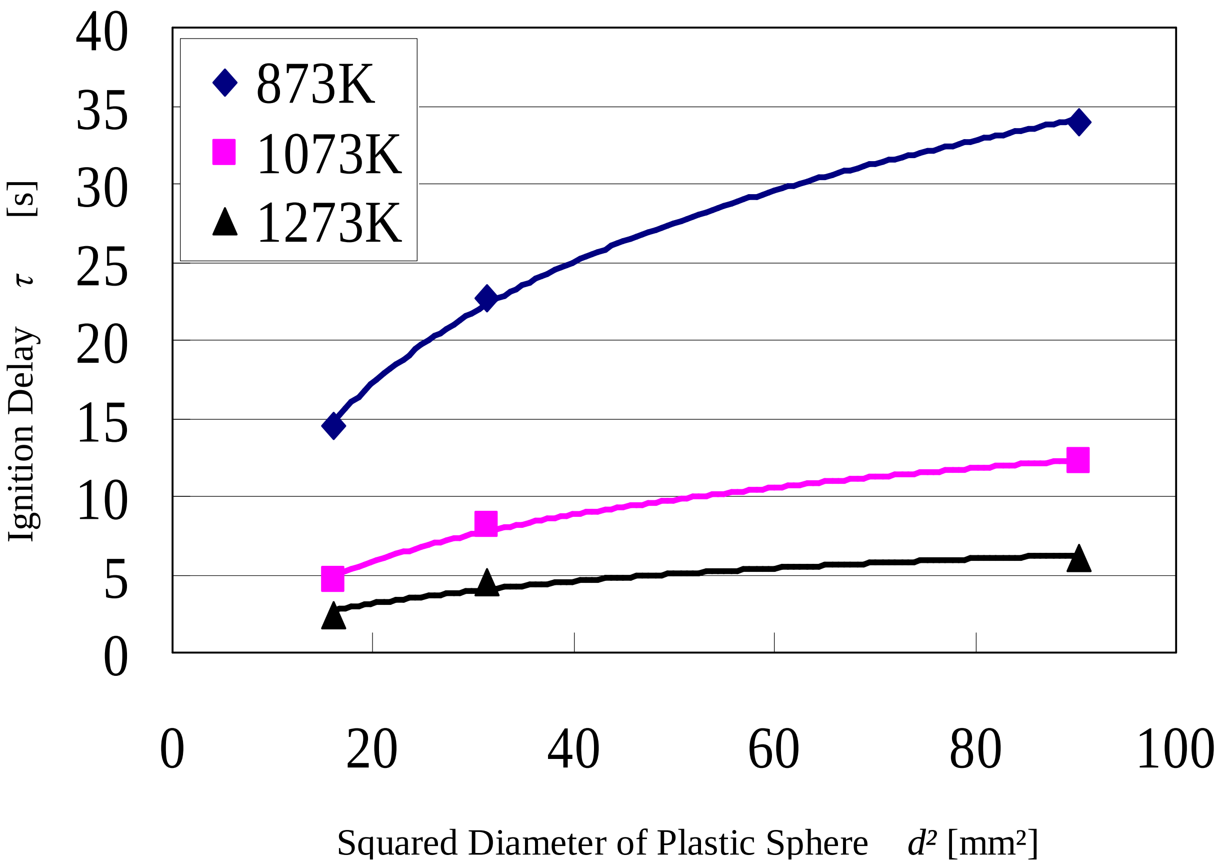


Fig.11. Relation Between Squared Initial Diameter and Ignition Delay of PE.

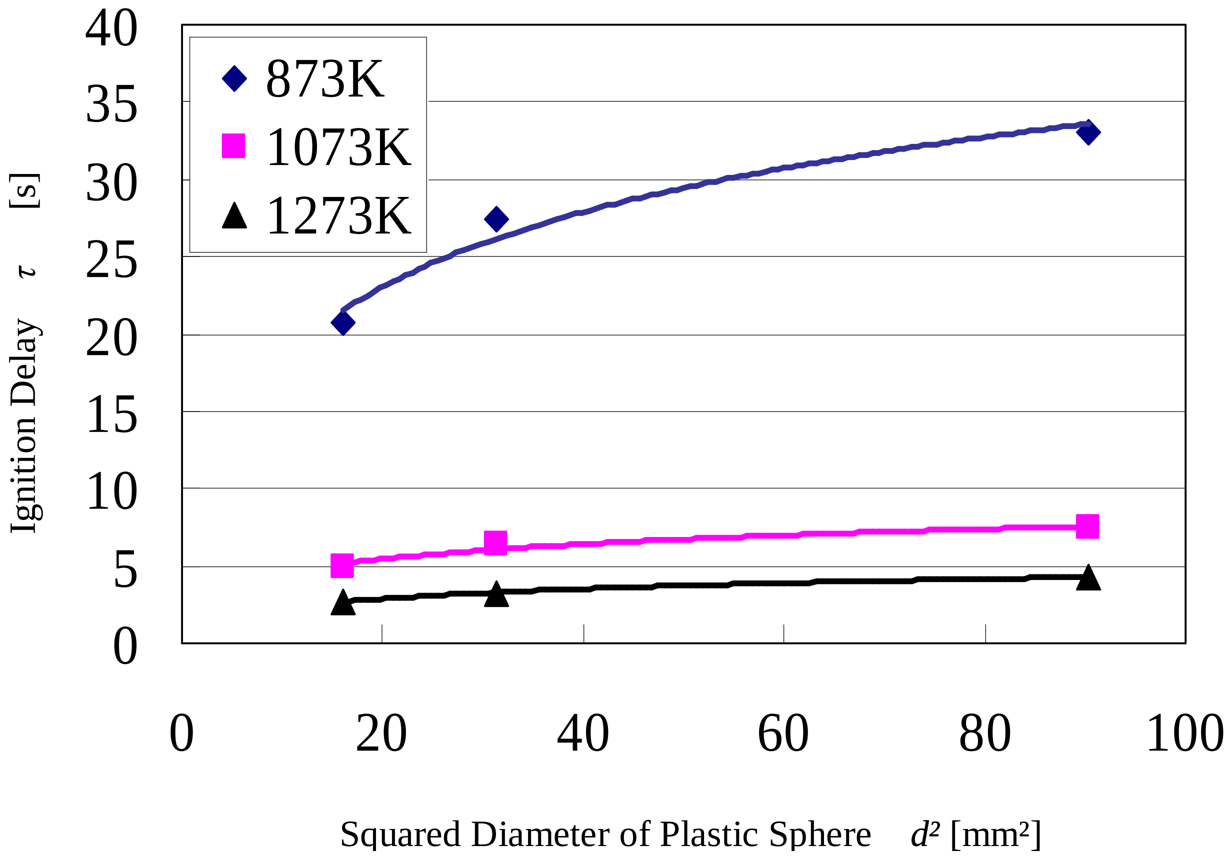


Fig.12. Relation Between Squared Initial Diameter and Ignition Delay of PP.

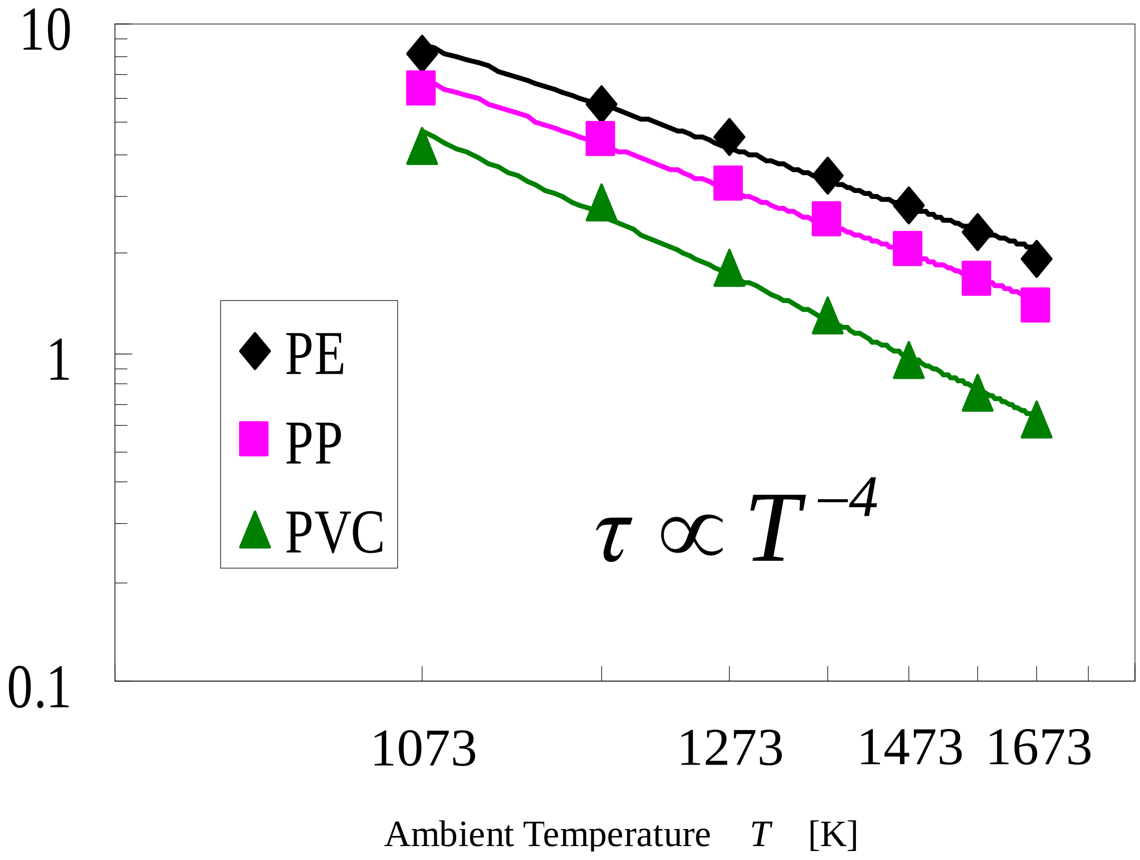


Fig.13. Log-Plot of Ignition Delays of PE, PP and PVC.

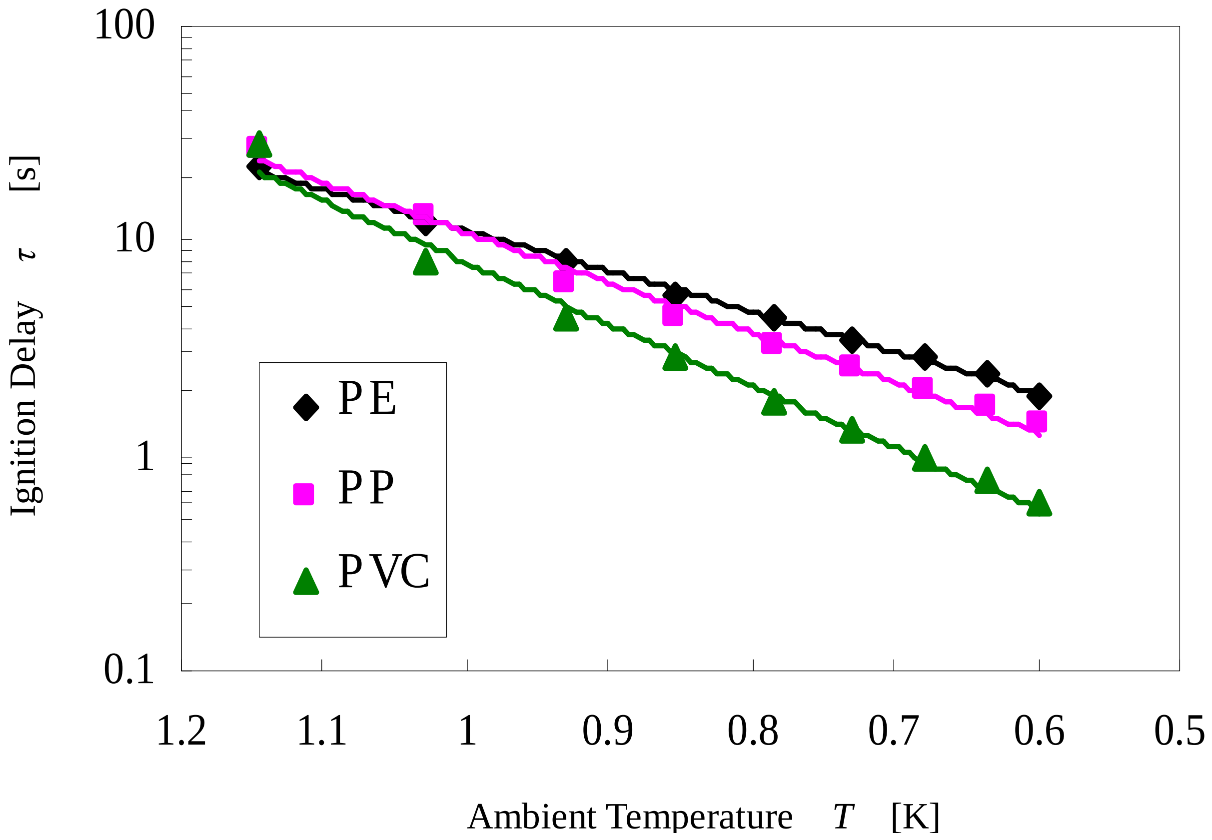


Fig.14. Semi-Logarithmic Graph with the Ignition Delay.

Table 2. Activation Energies.

E [kJ/mol]			
PE	28	Methane	121
PP	42	Ethane	205
PVC	68	Propane	176

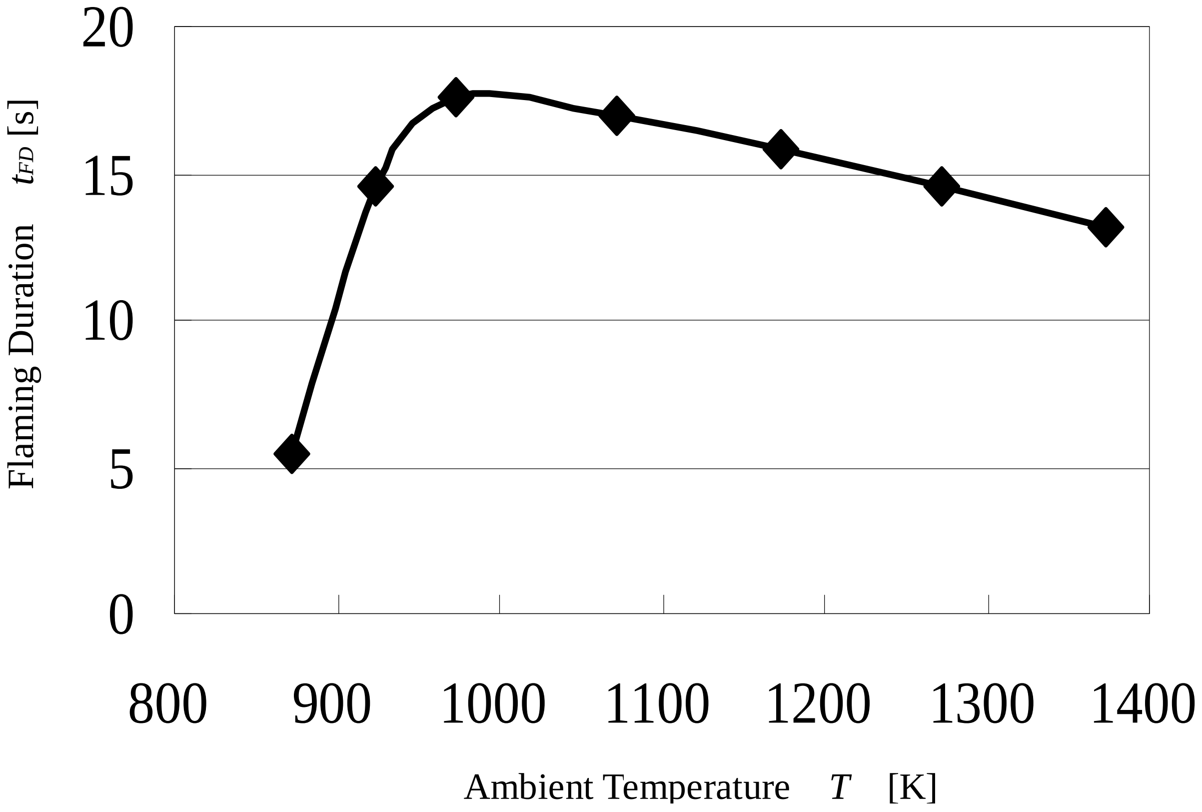


Fig.15. Flaming Duration of PVC.

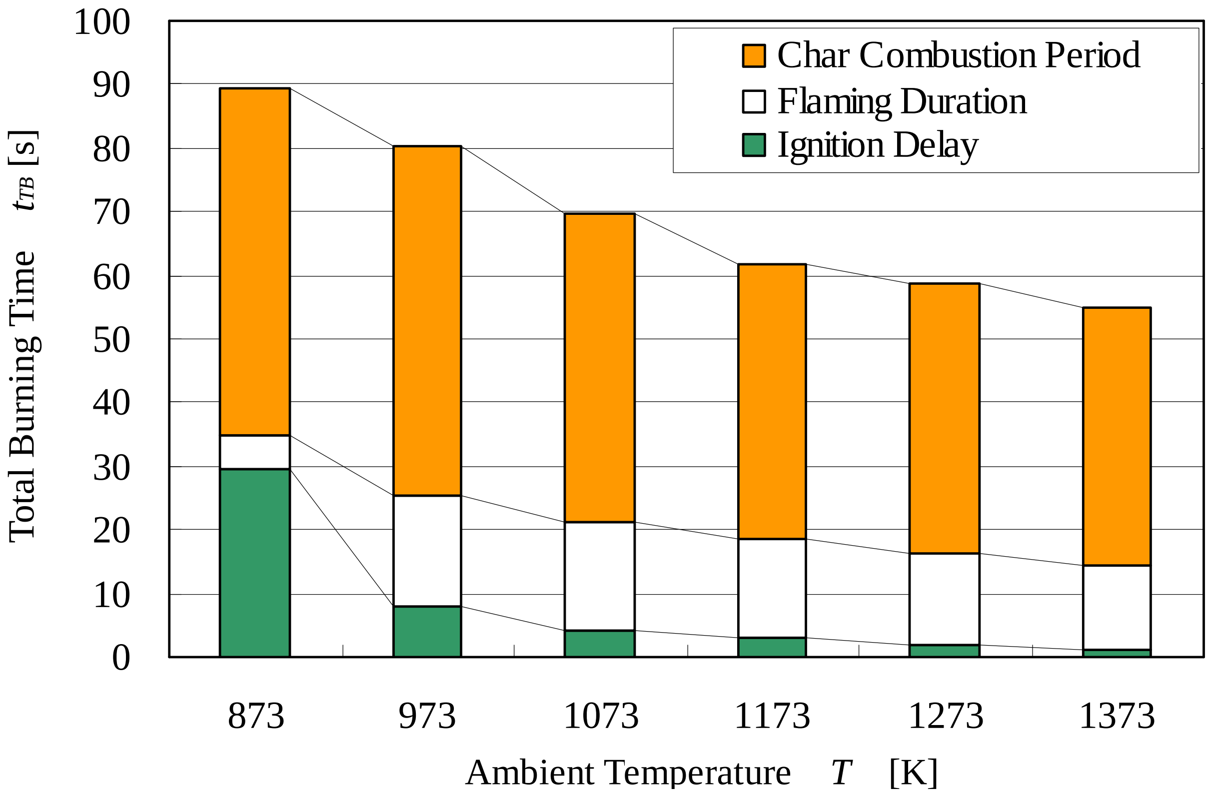


Fig.16. Total Burning Time of PVC.

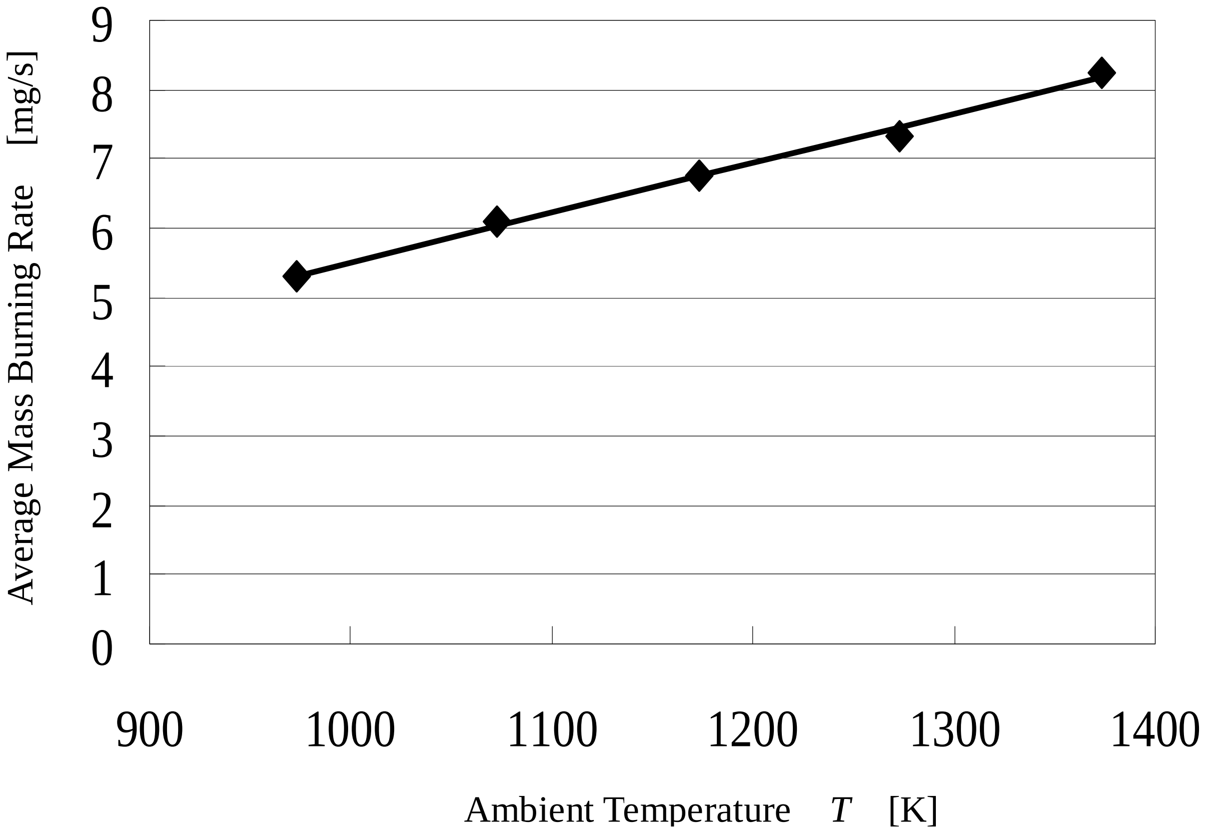


Fig.17. Average Mass Burning Rate of PVC.