

# 废塑料油在船用柴油机上的燃烧特性及适用性研究

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**摘要:**目前,世界上发达国家废塑料油(WPD)的生产技术已日趋成熟,如何将废塑料油(WPD)运用在各种发动机上已成为当务之急。本文通过一系列实验对废塑料油(WPD)在船用柴油机上的适用性作了一些研究,并通过加入水及控制着火延时来控制氮化物(NO<sub>x</sub>)、碳化物(CO<sub>x</sub>)及固体颗粒的生成量。希望不久的将来废塑料油(WPD)能在船用柴油机上真正得到实际运用。

**关键词:**废塑料油;船用柴油机;固体颗粒;氮化物;碳化物

## Application of Waste Plastic Disposals to Marine Diesel Engines

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**Abstract:**This paper illustrates a new test and result of WPD oil applied to marine diesel engines. In recent years, we must make an effort to develop an advanced technique for recycling waste plastics in order to utilize scrapped plastics as fuel for diesel engine. It is very important and necessary for us to cope with the increasing calorific value and the growing need of environment protection. The experiment fuel oil was obtained by mixing of diesel oil, WPD and water.

**Key words:** WPD; diesel engine; particulate matter; NO<sub>x</sub>; CO<sub>x</sub>

能源是工业的血液,然而地球上的能源是有限的、不再生的,当人类使用完石油、煤炭之前必须找到一种替代能源,这已成为当代科学研究的一个重大课题。随着科学技术的发展,将废塑料回收再利用,使之成为废塑料油(WPD)已不是幻想。它既是一种很好的替代能源,同时符合环保发展的需要。目前,世界上每天大约产生12900万吨废塑料<sup>[1]</sup>,其中的60%(相当于6900万吨)可以被回收再利用,生产废塑料油(WPD)<sup>[1]</sup>。如果用20万吨的油轮来装的话,大约得用350艘。因此,WPD再利用不但解决了环保问题,而且是一种很好的能源替代成品。作为一种新能源,WPD不但可以使用在汽车上,而且能使用在柴油机上。本文的研究目的就是研究WPD在船用柴油机上的适用性。为此,通过一系列实验,作者对应用WPD的柴油机的工作状况、排气中NO<sub>x</sub>、CO<sub>x</sub>及固体颗粒的生成量进行了比较分析研究。

### 1. WPD 特性

将废塑料在400℃~500℃通过一系列复杂的物理、化学反应,就能够生成WPD。表1为WPD的各种理化特性,从表1可以看出,WPD的主要化学成分为苯乙烯聚合物,约占WPD体积的60%。图1分别为苯乙烯单体、苯乙烯二聚物、苯乙烯三聚物的化学分子式结构图<sup>[1]</sup>。

### 2. 实验方法及装置

为了对柴油机的运转性能、燃烧状况及排气成分如NO<sub>x</sub>、CO<sub>x</sub>及固体颗粒等进行分析、比较。将WPD与船用柴油、重油按一定比例混合使用,分别用WPD/D.O.及WPD/F.O.表示。柴油的闪点值为60℃左右,当WPD/D.O.混合率增加时,混合油的闪点值随之下降,当混合率为40%时,闪点值下降50%。同时两者之间不同的粘度、密度对混合油及排气成分有影响,还影响着爆发压力、着火角<sup>[2]</sup>。图2为两者在不同混合率下测得的示功图,十分明显地说明了混合率对上述参数的影响。

为了能使WPD混合油在柴油机上正常使用,并对混合油的燃烧状况及废气的成分有所了解,首先在作者简介:魏海军(1971~)男,浙江上虞人,讲师,主要从事船舶柴油机尾气的检测、削减等方面的研究。

开口炉中进行了中间燃烧试验。本实验的柴油机为 YANMAR NF19 型单缸四冲程柴油机，其额定功率为 11.8kW，额定转速为 2200rpm。在实验过程中保持柴油机的转速、功率不变。

表 1 WPD 特性及成分

项目	单位	含量	
密度 (15℃)	g/cm <sup>3</sup>	0.939	
粘度 (30℃)	cSt	1.189	
闪点	℃	30.5	
成分	苯乙烯单体	%	63.9
	苯乙烯二聚物	%	11.5
	苯乙烯三聚物	%	5.7
		%	2.2
	乙烯苯	%	1.4
	α-甲基	%	2.2
	其他	%	13.1

#### 4. 实验结果及分析

##### 4.1 开口炉试验

为了使在开口炉中的燃烧更接近柴油机的运转状况，将油枪油头的压力设定为 11.27MPa，WPD/D.O. 的混合率在 0%~100%之间进行实验，结果发现燃烧时间由 130ms 减少到 80ms，着火滞后期由 6ms 减少到 3ms，NO<sub>x</sub> 生成量由 20ppm 减少到 7ppm。

##### 4.2 柴油机上实验

##### 4.2.1 WPD 混合柴油

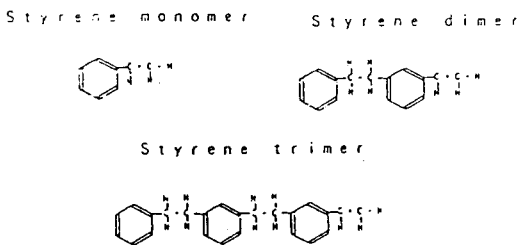


图 1 苯乙烯单体、苯乙烯二聚物、苯乙烯三聚物的化学分子式结构图。

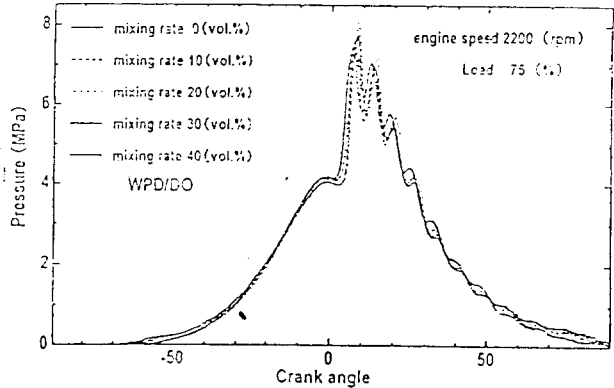


图 2 不同混合率下的示功图

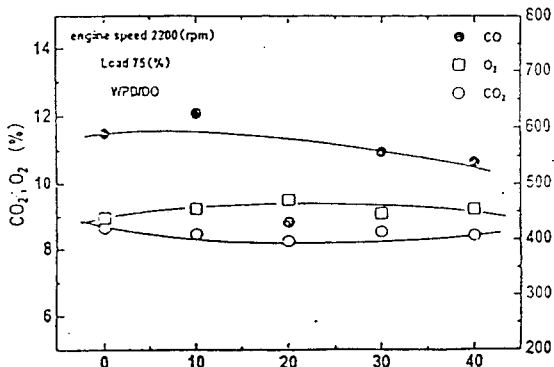


图 3 CO<sub>x</sub> 生成量与混合率的关系图

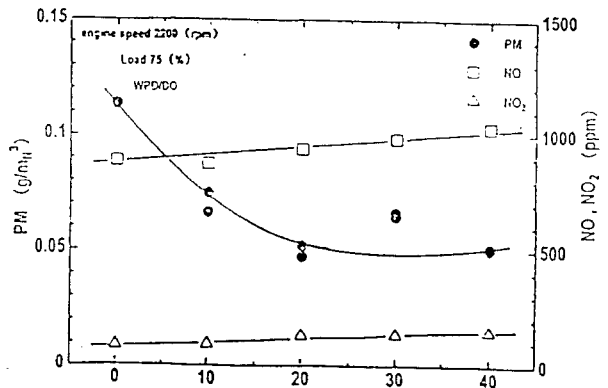


图 4 NO<sub>x</sub> 及固体颗粒生成量与混合率的关系图

从图 2 可以看出,随着混合率的上升,着火滞后和爆发压力随之增加,而燃烧终点几乎没有变化。在混合率为 10% 时,排烟温度大约下降 10%,但随着混合率的上升不再发生明显变化。图 3、4 为  $CO_x$ 、 $NO_x$  及固体颗粒生成量与不同混合率之间的关系图。随着混合率的上升,由于爆发压力的增加,从而使得  $NO_x$  的生成量也明显上升,特别是  $NO_2$  (约占  $NO_x$  的 10% 左右) 明显上升,而  $O_2$ 、 $CO_2$ 、 $CO$  基本上保持稳定,分别为 9%~10%、8%~9%、几百 ppm; 而固体颗粒的生成量却随着混合率的上升而下降。

#### 4.2.2 WPD 混合重油

WPD 与重油混合同样存在着粘度、密度、燃点等方面的变化。当两者的混合率由 0% 增加到 30% 时,密度由  $0.973g/cm^3$  下降到  $0.885g/cm^3$ ,燃点值由  $52^\circ C$  下降到  $42.5^\circ C$ ,粘度由  $50^\circ C$  时的  $2.275mm/s$  下降到  $1.739mm/s$ 。另外,由于实验使用的是小型四冲程柴油机,不适合使用重油,这也给实验带来了一定的难度。但经过多次实验,成功地完成了实验。图 5 为混合率分别为 0%、25%、50% 时的示功图。图 6 是在上述三种混合率下着火滞后和排烟温度。从图 5、6 说明随着混合率的升高在着火滞后、爆压上 WPD/F.O 比 WPD/D.O 更为突出。图 7 为  $O_2$ 、 $CO$ 、 $CO_2$  生成量与不同混合率的关系图。图 7 说明  $O_2$ 、 $CO$ 、 $CO_2$  随着混合率的上升有不同程度的下降。这表明 WPD 与重油混合能改善重油的燃烧状况。图 8 为上述条件下  $NO$  及  $PM$ 、 $SOF$ 、 $DS$  等固体颗粒的变化情况。实验说明随着混合率的上升, $NO$  的生成量明显上升,从 800ppm 上升到 1000ppm,而  $PM$ 、 $SOF$ 、 $DS$  等固体颗粒却明显下降。

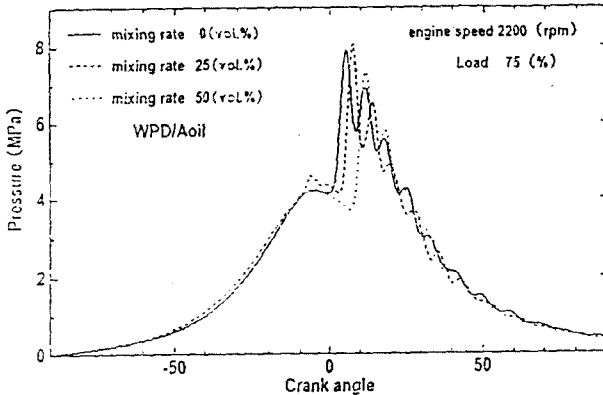


图 5 混合率分别为 0%、25%、50% 时的示功图

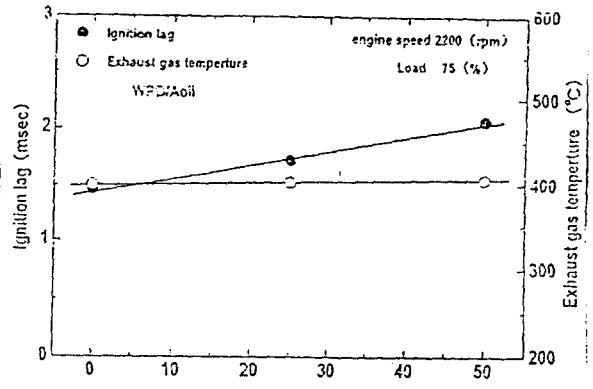


图 6 不同混合率下着火滞后和排烟温度

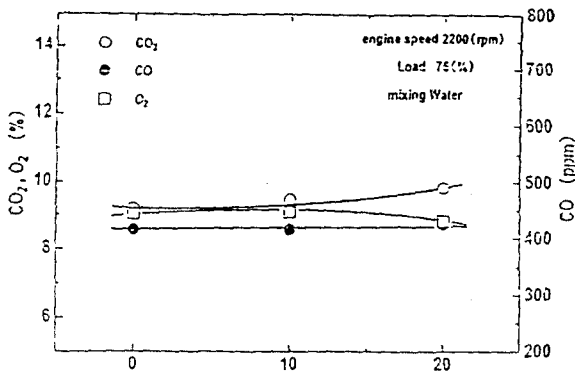


图 7  $O_2$ 、 $CO$ 、 $CO_2$  生成量与不同混合率的关系图

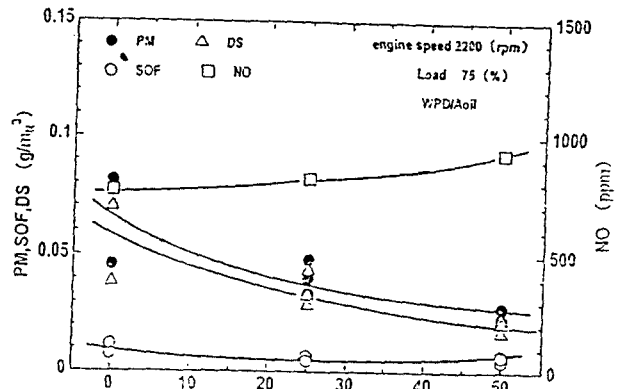


图 8 不同混合率下  $NO$  及  $PM$ 、 $SOF$ 、 $DS$  等固体颗粒的变化情况

#### 4.2.3 $NO_x$ 及固体颗粒的消除

从上述实验说明混合油燃烧后  $NO_x$  及固体颗粒的生成量并没有得到改善与控制。随着人类环境保护意识的不断提高,对环保的要求也会越来越高。因此,必须对混合油燃烧后排放到大气中的  $NO_x$  及固体颗粒减少到最少。为了控制上述有害物质的生成量,在实验过程中采用加入水及喷油延时等方法,取得了

一定的效果。图 9、10 分别为 O<sub>2</sub>、CO、CO<sub>2</sub> 与 NO、PM 随着不同混合水量后的变化情况。

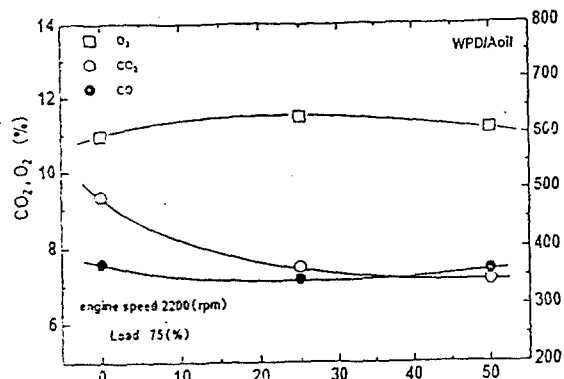


图 9 O<sub>2</sub>、CO、CO<sub>2</sub> 在与水混合后的含量

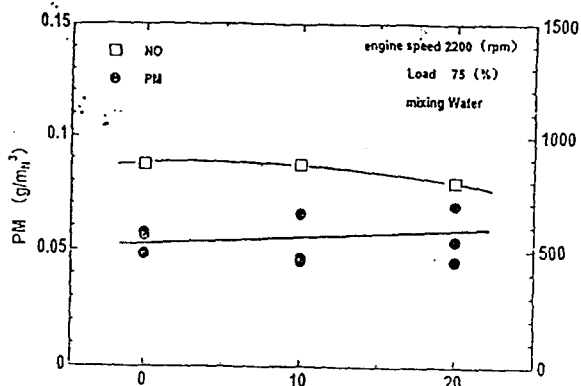


图 10 NO、PM 在与水混合后的含量

## 5 结论

本文的研究目的对混合油在船用柴油机上的适用性研究。此外，对它的经济性、环保性等方面也作了一定的研究。通过上述一系列实验得出主要结论如下：

1. 在开口炉中试验表明能够有效地改善燃烧性能，减少及固体颗粒的生成量。
2. 在柴油机上实验说明随着混合率的上升，出现了着火滞后及生成量的上升。
3. 通过加入水及喷油滞后能有效地控制及固体颗粒的生成量。
4. 由于实验条件自身限制，只能在小型四冲程柴油机上实验，给实验带来了一定的难度，同时影响到实验数据的准确性。因此，如果能在大型船用柴油机上进行实验，实验数据将更加客观、全面。

## References:

1. Okaya Yuzou, "Development of New Technique for Reprocessing of Waste Plastic Materials" paper, vol. December 1997, pp.3.
2. Nishida Osami, Proceeding of 61<sup>th</sup> Symposium of Japan Marine Engineering Society, 25<sup>th</sup> October 1998, pp.13-16.
3. Nishida Osami, Proceeding of 256<sup>th</sup> Symposium of Japan Marine Engineering Society, October 1998, pp.11.13-16.

# Application of Waste Plastic Disposals to Marine Diesel Engines

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**Abstract:** This paper illustrates a new idea methods and result of WPD oil applied to marine diesel engines. In recent years, we must make an effort to develop an advanced technique for recycling of waste plastics in order to utilize scrapped plastics as fuel source for diesel engine. It is very important and necessary for us to cope with the increasing calorific value and the growing need of environment protection. The experiment fuel oil was obtained by mixing of diesel oil, WPD and water.

**Key words:** WPD; diesel engine; particulate matter; NO<sub>x</sub> ; CO<sub>x</sub>

## 1. Introduction

In the word today, 129 million tons of plastics are annually generated, 60% of which, equals 69 million tons, are recycled to fuel oil. If the total amount were recycled it would fill up 350 tankers of 200000 tons. As the result, polystyrene-made receptacles from supermarket and so forth have been collected and reprocessed in processing tower at temperature of 400 ~ 500°C back to fuel oil. The purpose of this paper is to study the applicability of thermal processed fuel oil ( hereafter called waste plastic disposal or WPD ) to marine diesel engines using low quality fuel oil. In the experiment, stability of engine operation and components of exhaust gas, such as NO<sub>x</sub> and CO<sub>x</sub>, have been inspected from basic and applicable points of view.

## 2. Properties of WPD

Table 1 shows the results of components analysis and the formation of WPD. The mains of WPD are styrene-based components, which count for 60% of the fuel in volume.

Diesel oil or A heavy fuel oil and WPD are mixed at rates for the experimental use. Although the ignition temperature of diesel oil is 80~100 °C but it decreases as WPD mixing rate increase. At the rate of 50% the ignition temperature of the mixture is 40%. The relation between surface tension and density, which affect the formation of particulate matters and the mixing rate, is illustrated in figure 2. The figure shows the increase in both of these values along with the increase in the mixing rate.

## 3. Experiment method and apparatus

With the aim to run diesel engines on WPD, experiments on an intermittent combustion chamber under atmospheric pressure were first conducted before that on diesel engines. The engine ( YANMAR NF19E ) for experiment is of single horizontal cylinder four-stroke diesel engine with continuous rated power of 11.8kW at 2200rpm. The mixing rate between WPD with diesel oil, as well as A heavy fuel oil is defined by the ratio of WPD/diesel oil and WPD/ A heavy fuel oil respectively. The experiment apparatus is illustrated in figure 1.

The oils used for the experiment are made by mixing WPD with diesel oil or A heavy oil at different ratios. In

order to evaluate the engine operation and the characteristics of exhaust gas components, such as NO<sub>x</sub> and CO<sub>x</sub>, particulate matters etc, the change in combustion pressure, ignition lag and components of exhaust gas have been measure. Table 2 shows the oil for the experiment.

#### **4. Experiment results and considerations**

##### **4-1. Experiment on open combustion chamber**

In order to gasp the properties of mixed oil characteristics of exhaust gas and combustion experiments were conducted on an open combustion chamber. The combustion chamber is provided with a built-in heater, a fuel nozzle with the opening pressure of 11.27 MPa and a Bosch type fuel injection pump driven by an electric motor. As the ratio of WPD/diesel oil varies from 0–100vol.% ignition lag and combustion time decrease from 6 to 3 (ms) and 130 to 80 (ms) respectively and NO concentration from 20 to 7 (ppm) due to the addition of WPD.

##### **4-2. Experiment on diesel engine**

###### **a. WPD mixed diesel oil**

The experiments were carried out at constant load of 75% while WPD mixing rate is varied. As shown in figure 2, ignition lag and combustion pressure increase along with the increase in the mixing rate. However, the finish points of combustion are alike. As the mixing rate increases, while the ignition lag increases the exhaust gas temperature goes down slightly at the mixing rate of 10% but no considerable change could be seen.

Figure 3,4 illustrate the distribution of NO<sub>x</sub>, O<sub>2</sub>, CO and particulate matters concentration in relation with WPD mixing rate. Accompanied with the increase in WPD mixing rate, because of the increase of the maximum combustion pressure, NO<sub>x</sub> concentration dependently increases, especially NO<sub>2</sub>, accounts for 10 vol.% of NO<sub>x</sub>, remarkably goes up. Concentrations of O<sub>2</sub>, CO<sub>2</sub> and CO are almost constant at the value of about 9–10%, 8–9%, and hundreds ppm respectively. The figure also shows the reduction in particulate matters' concentration in relation with increasing WPD mixing rate, by half at the mixing rate of 40 vol.%.

###### **b. WPD mixed A heavy fuel oil**

Although the specific gravity of the mixed oil increases as the mixing rate goes up, the ignition point and kinetic viscosity decreases. For instance, when the mixing ratio between WPD and A heavy fuel oil changes from 0/100 to 30/70 the specific gravity changes from 0.873 to 0.885, ignition point from 52 to 42.5°C, kinetic viscosity at 50 °C from 2.275 to 1.739mm<sup>2</sup>/s. Figure 5,6 show the change in combustion pressure, ignition lag and exhaust gas temperature at the mixing ratios of 0vol.%, 25vol.% and 50vol.%. As the mixing ratio increases while the ignition lag increases the combustion time decreases. Figure 7 illustrates the change in concentration of O<sub>2</sub>, CO and CO<sub>2</sub>.

As seen in figure 8, when the mixing rate increases, NO concentration increases within 800 ~1000ppm, but particulate matter and dry soot concentration go down.

###### **c. Reduction of NO<sub>x</sub> and particulate matter emission by water addition**

With the purpose to restrain the emission of NO<sub>x</sub>, emulsive mixtures, shown in table 4, were made by adding water to 20%WPD mixed oil with the aid of emulsification additives nockless 300. During the experiment, the

mixture was fed to the engine while being stirred by an electric belder so as to maintain its uniformity. Along with the increase in the water adding rate, the ignition lag increases and the maximum pressure decreases. As compared to the waterless mixture, at the 30% water mixing rate, the exhaust gas temperature and No and NOx emission decreases by 50°C and 20~30% respectively. As shown in figure 9, CO concentration increases by 2 times at the rate of 30% but CO<sub>2</sub> remains stable. In figure 10, the concentration of soot consisting of dry soot and soluble organic fraction remains unchanged regardless of the water addition.

□

## 5. Conclusion

The purpose of this study is to reuse waste materials and develop a new fuel oil for marine engines. Beside, economic, environmental aspects as well as the efficiency of the engine are also considered.

From the basic and applicable viewpoints, the conclusion on the applicability of the WPD mixed-diesel oil and WPD mixed- A heavy fuel oil derived from this study are as follows:

1. The experiment on the open combustion chamber shows the trend in improving fuel oil ignition and reducing NOx emission.
2. In case of diesel engines. ignition lag and NOx emission increases as WPD mixing rate goes up but continuous operation of engine is attained without failures.
3. For reduction of NOx emission by addition of water, a remarkable is gained as well as the reduction of particulate matters' reduction.

## References:

1. Okaya Yuzou, "Development of New Technique for Reprocessing of Waste Plastic Materials" paper, vol. December 1997,pp.3.
2. Nishida Osami, Proceeding of 61<sup>th</sup> Symposium of Japan Marine Engineering Society, 25<sup>th</sup> October 1998,pp.13-16.
3. Nishida Osami, Proceeding of 256<sup>th</sup> Symposium of Japan Marine Engineering Society, October 1998,pp.11.13-16.

Table.1 WPD Properties

Item	Unit	Value	
Density (15°C)	g/cm <sup>3</sup>	0.939	
Kinetic viscosity (30°C)	mm <sup>2</sup> /s (cSt)	1.189	
Flash point	°C	30.5	
Constituents	Styrene monomer	vol.%	63.9
	Styrene dimer	Vol.%	11.5
	Styrene trimer	vol.%	5.7
	Toluene	vol.%	2.2
	Ethyl benzen	vol.%	1.4
	$\alpha$ -methyl styrene	vol.%	2.2
Others	vol.%	13.1	

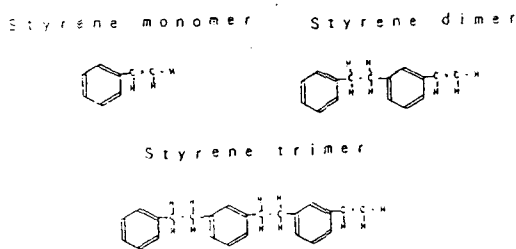


Table.2 Mixing Rate of Experimental Oils (vol.96)

#	No.1	No.2	No.3	No.4	No.5	No.6	No.7
Vol.%							
WPD	0	10	20	—	30	40	—
D.O							
WPD	0	—	—	25	—	—	50
Oil							

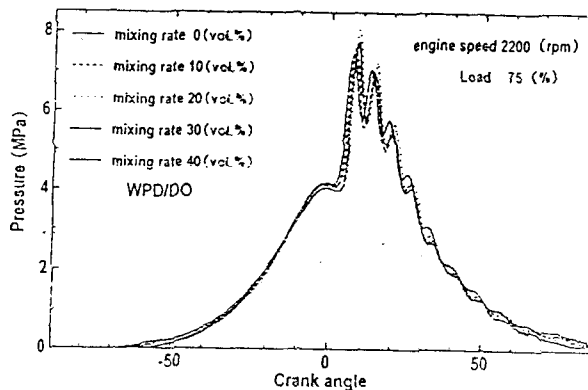
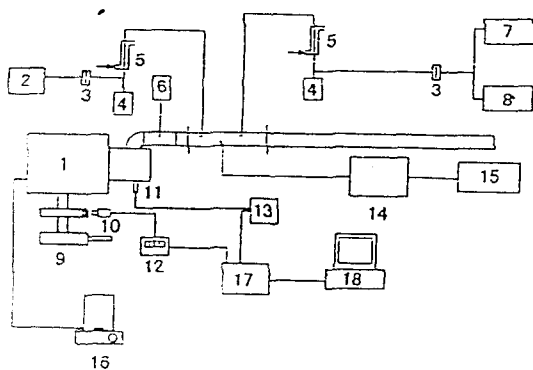


Fig.2 Pressure diagram



- 1.Engine 2.Gas sampler 3.Filter (Particulate Matter) 4.Drain 5.Cooler 6.Thermometer  
 7.Oxygen meter 8.NO<sub>x</sub> analyzer (CLD) 9.Hydraulic dynamometer 10.Sensor  
 11.Pressure sensor 12.Tachometer 13.Pressure meter 14.Pretreatment  
 15.Gas analyzer (NO<sub>x</sub>CPE), CO<sub>2</sub>, O<sub>2</sub>) 16.F.O mixer 17.A/D Converter 18.Computer

Fig.1 Experimental schematic diagram

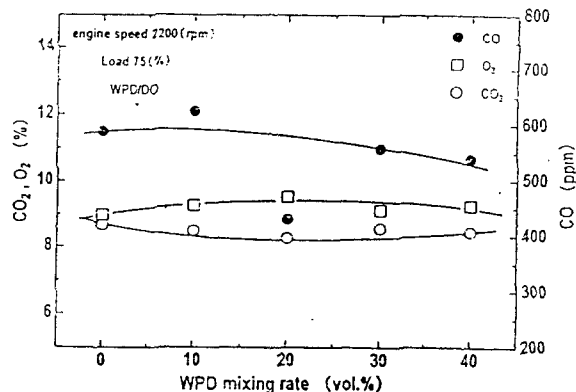


Fig.3 Change in CO<sub>2</sub>, CO, O<sub>2</sub> concentration

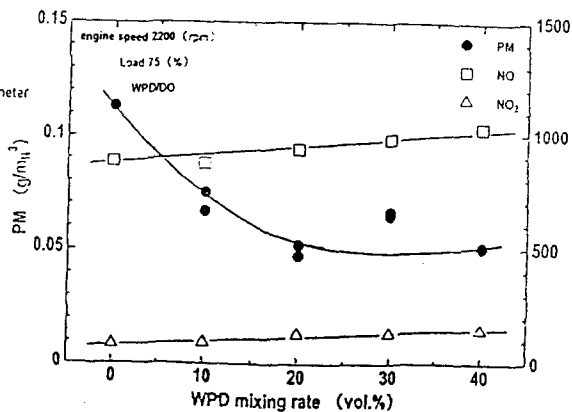


Fig.4 Change in PM, NO, NO<sub>2</sub> concentration



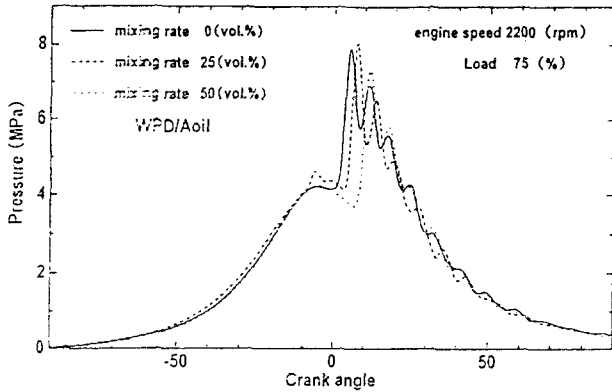


Fig.5 Pressure diagram

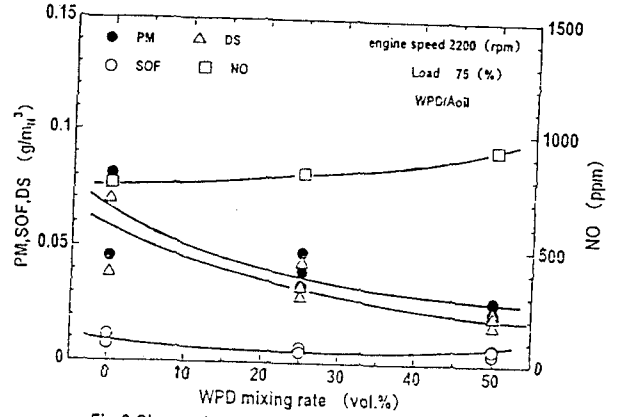


Fig.8 Change in PM,DS,SOF, NO concentration

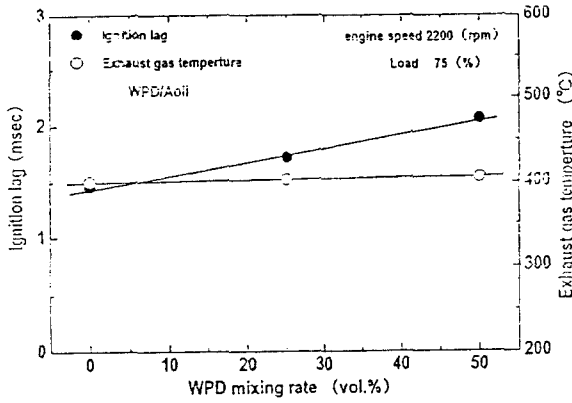


Fig.6 Change in ignition lag and exhaust gas temperature

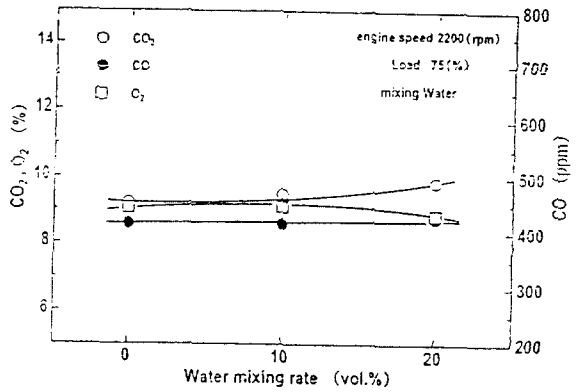


Fig.9 Change in CO<sub>2</sub>,CO,O<sub>2</sub> concentration

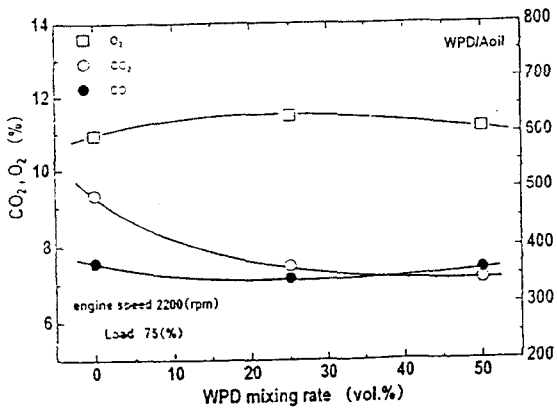


Fig.7 Change in CO<sub>2</sub>,CO,O<sub>2</sub> concentration

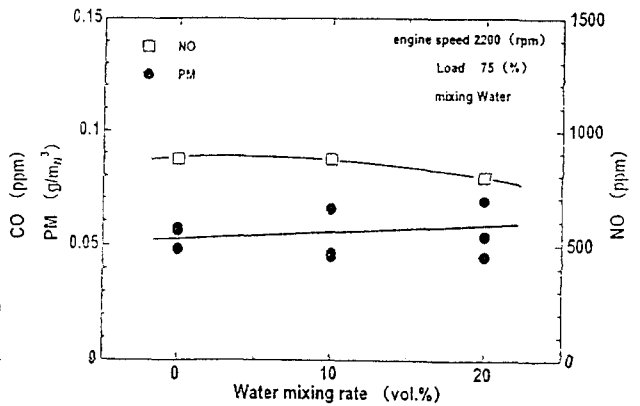


Fig.10 Change in PM,NO concentration