Development of Hydrogen Burner – Phase I –

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Abstract:

Reduction of carbon dioxide (CO_2), which is a greenhouse gas (GHG), is an urgent challenge imposed on international society. According to the Sixth Strategic Energy Plan approved by the Japan' s Cabinet in October 2021, reducing consumption of fossil fuels and substituting carbon neutral renewable energy towards the year 2030 is considered to be an effective means of achieving a 46 % decrease in GHG in comparison with 2013. As part of this social situation, it is also necessary to grapple energetically with reduction of GHG emissions by asphalt plants in a form that keeps pace with national government policies. In this, switching to fuels such as hydrogen which do not generate CO_2 when burned is considered the most effective approach. This paper reports on the development status of a hydrogen burner that can be applied to asphalt plants.

1. Introduction

In 2015, COP21 (21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change) approved the Paris Agreement, which mandated the establishment of reduction targets for greenhouse gas (GHG) emissions as an international framework for global warming countermeasures after 2020. Based on this, at COP26, which was held in Glasgow (United Kingdom) in November 2021, Japan announced the targets of reducing GHG emissions by 46 % from 2013 by 2030 and achieving net-zero GHG emissions by 2050[1]. At COP27, held in Sharm el-Sheikh, Egypt in November 2022, international society as a whole reaffirmed its commitment to strengthening awareness of global warming countermeasures in the content of the resolutions adopted at COP26.

One leading technology which has attracted attention for reducing emissions of GHG in order to achieve these targets is renewable energy, that is, solar, wind power, geothermal, hydro power and biomass, and urgent efforts to ensure widespread adoption of technologies that utilize these forms of renewable energy are being made in international society as a whole. In light of these trends, Nikko Co., Ltd. is also grappling with burner combustion of hydrogen, ammonia and other fuels that have attracted interest as alternative fuels for fossil fuels. The purpose of the development described in this report is to develop a burner which enables combustion of hydrogen in order to reduce use of fossil fuels.

Hydrogen is a carbon neutral fuel which does not generate carbon dioxide (CO_2) when burned. However, because CO_2 is emitted in the production processes of almost all of the hydrogen in general distribution, carbon neutrality cannot be achieved as long as the hydrogen used as fuel is not produced by using solar, wind or other forms of renewable energy that do not emit CO_2.

Asphalt plants (hereinafter, AP) mainly use heavy oil or city gas in dry heating of aggregates. An AP with an annual asphalt mixture shipping volume of 100 000 tons consumes approximately 900 000 L of heavy oil, which emits 2 440 tons of CO_2[2]. If the burner fuel of this AP is switched to hydrogen, for example, assuming that the energy substitution ratio (hereinafter, cofiring ratio) is 30 %, annual reductions of approximately 270 000 L in heavy oil consumption and 729 tons of CO_2 emissions are possible.

On the other hand, when hydrogen is used as a burner fuel, the following are considered to be matters for concern: i) Because hydrogen burns several times faster than heavy oil or city gas, backfire and abnormal combustion are possible. ii) Hydrogen combustion forms a large amount of thermal NOx (nitrogen oxides) due to its high combustion temperature. iii) Because of the extremely high temperature of the hydrogen flame, thermal damage of the burner, combustion chamber and other combustion equipment is feared.

Therefore, in this hydrogen combustion test, we confirmed that the assumed heat output can be obtained by burning hydrogen with the actual burner and verified the above-mentioned matters of concern, and also clarified the correlation between the concentration of NOx formed by combustion and various parameters. This article reports the status of development of a hydrogen burner which is applicable to AP. Here, we wish to note that the development of the hydrogen burner was carried out jointly using test equipment provided by Tokyo Gas Co., Ltd.

2. Hydrogen as Fuel

2.1 Properties of Hydrogen

Hydrogen is a colorless, odorless gas at normal temperature and pressure. Its molecular weight is 2.01588, boiling point is -252.9 °C (at normal pressure), density is 0.0899 g/L and specific gravity is 0.0695[3]. Its heating value is 10.8 MJ/Nm^3. **Table 2-1** shows a comparison of the main fuels[4].

Table 2-1 Comparison of main fuels[4]

Fuel	Ammonia NH_3	Propane C_3H_8	Methane CH_4	Hydrogen H_2
Boiling point at atmospheric pressure (°C)	-33.3	-42.1	-161.6	-252.9
Liquefaction pressure at 20 °C (atm)	8.5	8.5	Gas at all times	Gas at all times
Lower heating value (MJ/kg)	18.6	46.6	50.2	120.4
Combustibility equivalence ratio range (-)	0.63 -1.40	0.51 -2.51	0.50 -1.69	0.10 -7.17
Maximum combustion velocity (m/s)	0.07	0.43	0.37	2.91
Ignition point (°C)	651	432	537	500
Maximum adiabatic flame temperature (°C)	1750	2020	1970	2120

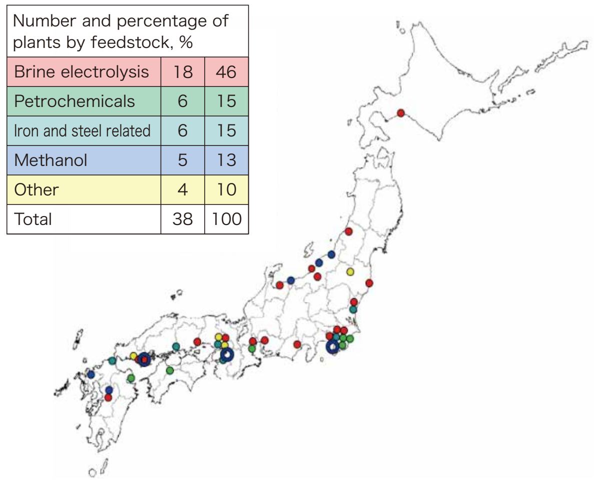
Hydrogen is stable at normal temperature and does not react chemically with elements other than fluorine[5]. When burned, it produces water by bonding with oxygen. Hydrogen has the characteristic feature of a wide explosive concentration range in air of 4.1 % to 74.2 %[3]. For convenience, hydrogen is given different names classified by color depending on differences in the production methods, as described in the following section.

2.2 Classification of Hydrogen by Differences in Production Methods

Gray hydrogen is produced by a steam reforming reaction of fossil fuels, and a large quantity of CO_2 is emitted as a byproduct[6]. Brown hydrogen is produced from coal, and this process also emits a large quantity of CO_2. White hydrogen is produced as a byproduct when manufacturing other products. Therefore, the amount of hydrogen produced is governed by the production volume of the main product.

Green hydrogen is produced by electrolysis of water using electric power generated from renewable energy that does not emit CO_2. Blue hydrogen is produced by steam reforming of fossil fuels in the same manner as gray hydrogen, but the CO_2 generated in this process is captured and treated so that net-zero CO_2 is emitted into the atmosphere[6]. Turquoise hydrogen is produced by pyrolysis (thermal decomposition) of methane using renewable energy. Because methane-derived hydrogen is produced as a solid, no CO_2 is emitted, but the carbon produced by this process must be sequestered permanently. Yellow hydrogen is produced by electrolysis of water using electric power generated by nuclear power. Thus, if hydrogen is to be used as a carbon neutral fuel, it must be produced by a method that does not emit CO_2.

Figure 2-1 shows the hydrogen production bases in Japan[7]. As can be seen from this figure, hydrogen production is concentrated in heavy chemical industry zones. If it is possible to transport hydrogen from these areas by lorries, etc., supply of hydrogen can be promoted relatively easily.



Number and percentage of plants by feedstock, %		
Brine electrolysis	18	46
Petrochemicals	6	15
Iron and steel related	6	15
Methanol	5	13
Other	4	10
Total	38	100

Figure 2-1 Hydrogen production bases in Japan

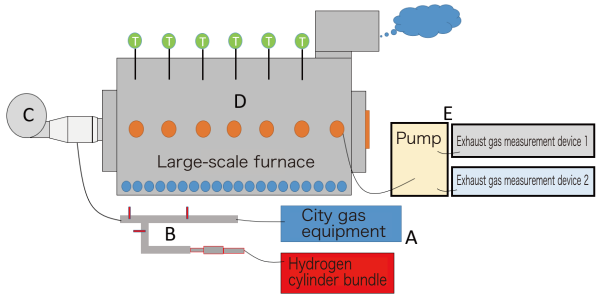


Figure 3-1 Flow of test equipment

3. Hydrogen Combustion Test

3.1 Test Equipment

Figure 3-1 shows the flow of the hydrogen burner test equipment. In this figure, A is the hydrogen cylinder bundle and city gas supply equipment, B is the solenoid valve unit, C is the hydrogen burner, D is the combustion furnace and E is the exhaust gas measurement devices. Thermometers are installed in the combustion furnace so as to understand the temperature distribution in the furnace. The exhaust gas measurement devices measure the concentrations of oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen monoxide (NO), nitrous oxide (N_2O), nitrogen oxides (NOx), etc.

In this test equipment, a device which prevents backflow of the flame in the piping was installed to secure the safety of the combustion device.

3.1.1 Hydrogen Burner

The appearance of the hydrogen burner is shown in **Photo 3-1**. As shown in the photo, in order to enable safe and reliable ignition, the gas flow route of this hydrogen burner is divided into a pilot gas line for use in ignition and a main gas line which maintains stable combustion. For safety, city gas is used in the pilot gas line for ignition. A premixing method is adopted, in which city gas and hydrogen are mixed before entering the main gas line of the burner. Although use of a hydrogen mono-fuel burner is assumed in the future, considering the fact that operation by cofiring (mixed fuel combustion) of hydrogen and city gas is the main pattern at present, the burner itself makes it possible to burn either of these fuels with a single main gas line. Combustion air is supplied from the back end of the burner. The ratio of the actual combustion air to the theoretical amount of air for the fuel (hereinafter, excess air ratio) can be changed arbitrarily. The burner is also equipped with a sensor to detect the flame. The fuel gas is injected by a special nozzle and burns while mixing with the air in the burner throat.

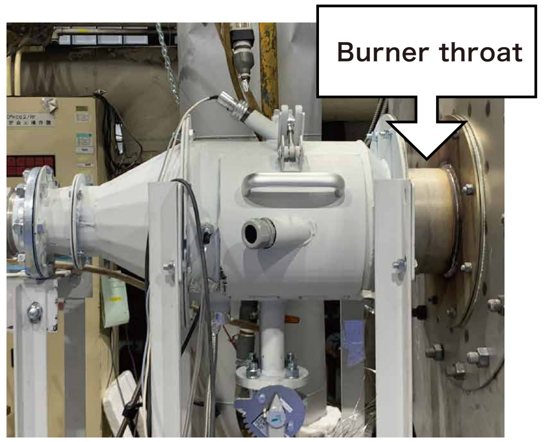


Photo 3-1 Hydrogen burner

3.1.2 Solenoid Valve Unit

The solenoid valve unit used in this test is shown in **Photo 3-2**. The city gas line is equipped with a flowmeter, solenoid valve and ball valve, and adjustments of the flow rate are performed manually. The hydrogen line supplies hydrogen from the cylinder bundle after pressure reduction, and is equipped with a flow control device which can adjust the flow rate to a preset value. The city gas line and hydrogen line converge downstream from the solenoid valve unit, and the city gas and hydrogen are supplied to the main line of the hydrogen burner after mixing. The city gas line also includes a branch line, which makes it possible to supply city gas to the pilot line.

Photo 3-2 Solenoid valve unit

3.1.3 Hydrogen Cylinder Bundle

The hydrogen cylinder bundle used in the test is shown in **Photo 3-3**.

Photo 3-3 Hydrogen cylinder bundle (in rear of the photo)

Table 3-1 Specification of hydrogen cylinder bundle

Specification of hydrogen cylinder bundle	
Content	Compressed hydrogen
Filling pressure	19.6 MPa
Capacity	300 Sm3
Number of cylinders	30

Table 3-1 shows the specification of the hydrogen cylinder bundle used in this test. As seen in the photo, the hydrogen cylinder bundle consists of multiple hydrogen cylinders in a single unit, and is filled with hydrogen at a high pressure to improve transportation efficiency. In this test, the cylinder bundle is connected to a pressure-reducing valve, and the hydrogen is supplied to the solenoid valve unit after pressure reduction.

3.1.4 Test Furnace

The combustion furnaces used in the test are shown in **Photos 3-4** and **3-5**. For comparison, two types of combustion furnaces were used, one being a medium-scale unit and the other a large-scale unit. The capacity of the medium-scale furnace was suitable for a burner test with an output of approximately 500 kW. An inner castable lining was installed in the furnace for heat insulation and heat-retention. Air-cooling tubing was installed in the medium-scale combustion furnace to reduce the exhaust gas temperature. A total of 15 thermocouples (3 rows in the width direction x 5 rows in the total length direction) were provided to measure the temperature distribution in the furnace. The capacity of the large-scale furnace was suitable for a burner test with an output of approximately 800 kW. A castable lining was installed in the unit for heat insulation and heat-retention, and water-cooling tubing was installed in the furnace to reduce the exhaust gas temperature. In the large-scale furnace, 30 thermocouples (5 rows in the width direction x 6 rows in the total length direction) were provided. The capacity ratio of the large-scale furnace to the medium-scale unit is approximately 2.3 times.

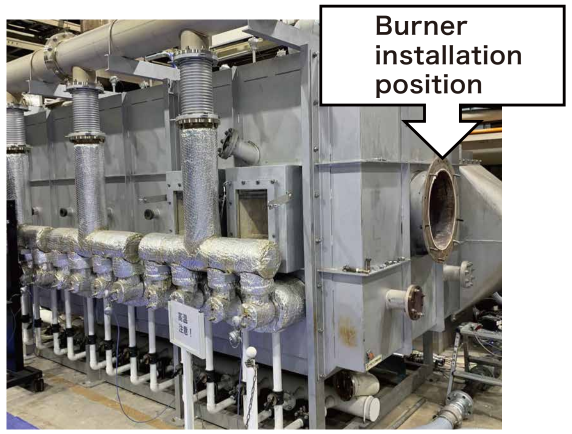


Photo 3-4 Medium-scale furnace

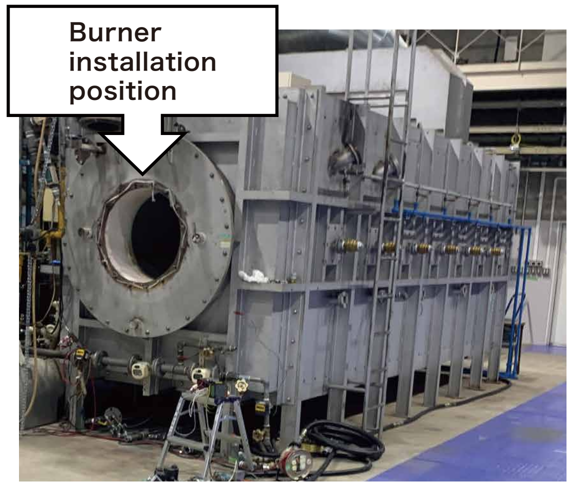


Photo 3-5 Large-scale furnace

3.1.5 Exhaust Gas Measurement Devices

The types of exhaust gas measurement devices used here are shown in **Table 3-2** and **Table 3-3**. As shown in these tables, the exhaust gas measurement device manufactured by Hodaka Co., Ltd. in **Table 3-2** was used for all measurements except N_2O, and the exhaust gas measurement device manufactured by Fuji Electric Co., Ltd. in **Table 3-3** was used in the measurements of N_2O.

Table 3-2 Specification of Hodaka exhaust gas meter

Exhaust gas measurement device 1	
Manufacturer	Hodaka Co., Ltd.
Type	HT-3500
Measurement method①	Galvanic cell method
Measured gas①	O_2
Measurement method②	Nondispersive infrared (NDIR) absorption method
Measured gases②	CO, CO_2, CH_4
Measurement method③	Low potential electrolysis method
Measured gases②	CO, NO, NO_2

Table 3-3 Specification of Fuji Electric exhaust gas meter

Exhaust gas measurement device 2	
Manufacturer	Fuji Electric Co., Ltd.
Type	ZKJFSC16
Measurement method①	Nondispersive infrared (NDIR) absorption method
Measured gases①	NO, N_2O
Measurement method②	Magnetic method
Measured gases②	O_2

3.2 Test Method

The test conditions were set with the following parameters.

- Size of furnace
- Type of fuel (city gas, hydrogen)

To match the thermal outputs of the two fuels, the test was conducted with 44.4 Nm^3/h of city gas in mono-fuel combustion of city gas and with 167.0 Nm^3/h of hydrogen in mono-fuel combustion of hydrogen.

- Excess air ratio assuming AP
- Combination of burner parts

3.3 Experimental Results and Discussion

3.3.1 Parts Comparison Test

In this test item, among the patterns of part combinations tested up to now, the optimum condition at the present time (Pattern 30) and one close to this company' s standard product (Pattern 19) are compared. In Pattern 30, the burner was designed to reduce local hot spots so as to reduce NOx when burning hydrogen.

Figure 3-2 and **Figure 3-3** show graphs of the NOx values for the co-firing ratios of Pattern 19 and Pattern 30, respectively. To consider the effect of error of the exhaust gas measurement devices, the NOx values were converted to an oxygen concentration of 16 %. City gas mono-fuel firing and hydrogen mono-fuel firing with the respective parts are compared. The excess air ratio condition is lower in **Figure 3-2** than in **Figure 3-3**.

It was found that NOx is higher with hydrogen than with city gas regardless of the parts. This is estimated to be an effect of an increase in thermal NOx as a result of the formation of local hot spots because the combustion velocity of hydrogen is faster than that of city gas. Moreover, it was also possible to reduce NOx under conditions with different fuel types and excess air ratios with Pattern 30, which has a parts composition designed for hydrogen use, in comparison with Pattern 19, which is close to this company' s standard product. Because greater priority was given to reducing local hot spots in Pattern 30 than in Pattern 19, it is estimated that thermal NOx decreased due to the effects of that design.

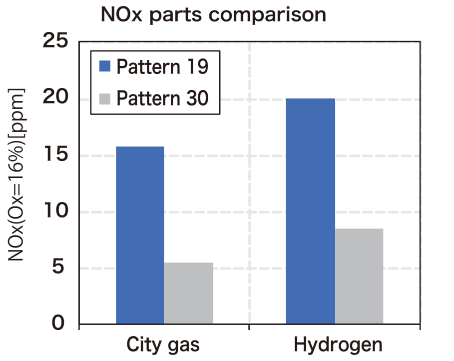


Figure 3-2 Parts comparison of NOx, excess air ratio A

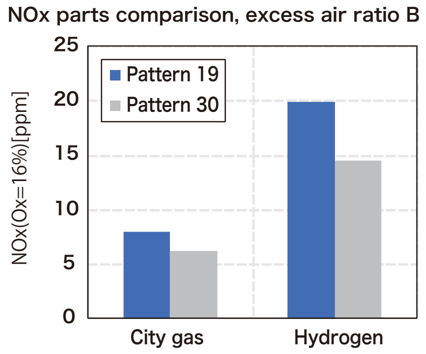


Figure 3-3 Parts comparison of NOx, excess air ratio B

3.3.2 Combustion Furnace Comparison Test

A comparison test of furnaces of different sizes was carried out with the heat output, excess air ratio, component parts and other combustion conditions fixed. The degree of effect of the difference in the furnace heat capacity on various types of measured data was confirmed by this test.

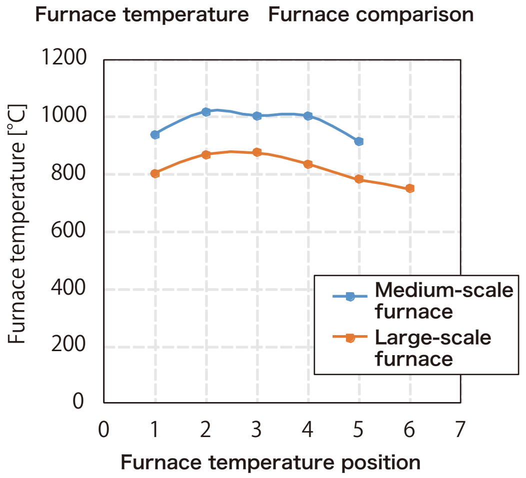


Figure 3-4 Furnace comparison test: Furnace temperature

Figure 3-4 shows the distribution of the furnace temperature when burning city gas at a rate of 44.4 Nm^3/h in the large-scale and medium-scale furnaces. "Furnace temperature position" on the x-axis indicates the approximate distance (m) from the burner.

According to this figure, the temperature of the large-scale furnace is lower than that of the medium-scale furnace through the entire length of the furnace. This is considered to be due to the difference in heat capacity, since the capacity of the large-scale furnace is approximately 2.3 times larger. Moreover, it is thought it seems that the furnace temperature would be even lower in the driers used to dry aggregate in AP, since the drier body is not insulated and constantly exchanges heat with the aggregate.

Figure 3-5 shows the temperature distribution of the burner throat shown in **Photo 3-1**. The throat position on the x-axis shows the temperature measurement positions from the upper surface to the lower surface. In particular, because part of the fuel burns in the burner throat, forming a fireball, thermal damage of the throat is a possibility if the condition of combustion deteriorates. As in the case of the furnace temperature, this figure also shows that the throat temperature is lower in the large-scale furnace than in the medium-scale furnace. Based on this, it can be surmised that the burner throat is strongly affected by radiation from the furnace interior. However, because it is known that radiant heat transfer is proportional to the 4th power of the temperature difference, and the temperature range decreases even further in the driers of actual AP, it is thought that the effect of radiation is extremely weak. Accordingly, if the hydrogen burner is used in an AP, the possibility of heat damage would appear to be even lower than in the large-scale furnace.

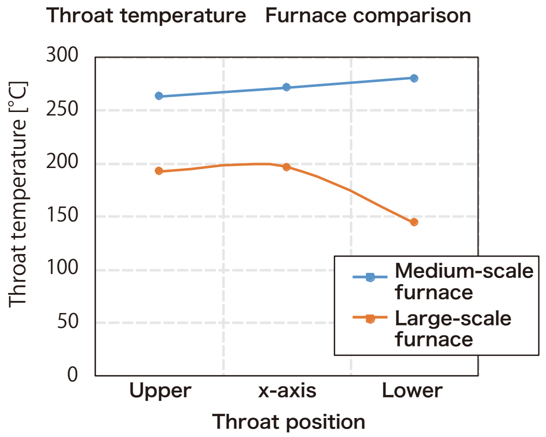


Figure 3-5 Furnace comparison test: Throat temperature

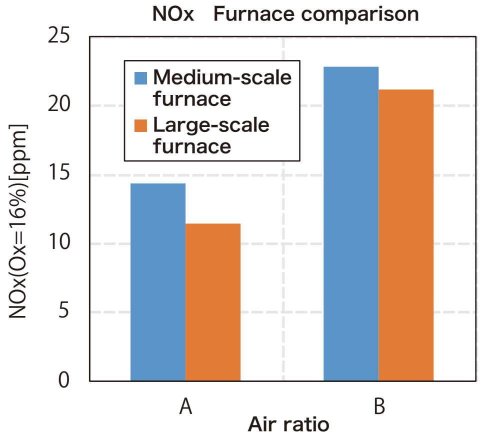


Figure 3-6 Furnace comparison test: NOx

Figure 3-6 shows the NOx values when burning city gas at a rate of 44.4 Nm^3/h in the two furnaces. The excess air ratio is more than 1 under both conditions A and B, but is lower under A than B.

As shown in this figure, NOx is higher in the medium-scale furnace than in the large-scale furnace at both excess air ratios. Because the furnace temperature is higher in the medium-scale furnace than in the large-scale furnace, the higher NOx values are thought to be due to thermal NOx. Furthermore, a larger amount of NOx is generated under condition B, with the high excess air ratio, than under A, with the low excess air ratio. In this case, the high NOx value presumably is an effect of the larger volume of nitrogen entering the furnace due to the higher excess air ratio. In addition, the amount of available oxygen is also larger in B due to the high excess air ratio, and it is thought that this causes rapid combustion and an increase in local hot spots. Under Japan' s Air Pollution Control Act, the emission standard for NOx is 230 ppm 8), and in the 23 wards of the Tokyo metropolitan area, an even stricter standard of 25 ppm is applied 9). The results obtained here can be considered favorable, as the NOx values were less than 25 ppm under both conditions.

From these results, it is assumed that a further reduction of NOx can be achieved if this burner is used by AP driers burning city gas fuel because these facilities operate at a lower atmospheric temperature than the furnace temperature in this test. Although the previous section confirmed that hydrogen combustion generates a larger amount of NOx than city gas combustion, since the NOx value by hydrogen combustion in the large-scale furnace was approximately 20 ppm, and a further decrease in NOx can be expected in AP, it is assumed that this burner can be used even in regions with strict regulatory values for NOx.

4. Future Plans

- Asphalt mixture production tests will be conducted with the hydrogen burner, and the burner and the mix will be evaluated.
- Hydrogen burners with outputs of 5 MW to 10 MW or more, which are used in general AP, will be developed.

5. Conclusion

- A burner which uses both city gas and hydrogen as heat sources was developed for the purpose of reducing CO_2 emissions.
- Combustion tests of city gas and hydrogen were conducted using a burner with a 500 kW class heating capacity.
- It was found that no heat damage occurs in the burner when burning city gas or hydrogen and that both fuels are combustible.
- A combination of burner parts with a low NOx emission, not only with hydrogen but also with city gas, was discovered.
- A comparative study of furnaces of two different sizes confirmed the possibility that NOx will not be a problem even with AP driers with larger heat capacities.

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