DEVELOPMENT OF HYDROGEN BURNER -PhaseⅡ: Asphalt-Mixture Production Test-

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Abstract

The Paris Agreement was established in 2015 as a global measure to combat global warming. In response to this, the Japanese government announced in 2021 its aim to reduce greenhouse gas emissions by 46% by 2030 compared to the levels in 2013. The asphalt plant (AP) industry has also been actively working to reduce greenhouse gas emissions to address current issues. In APs, the greenhouse gas CO_2 is primarily emitted from fossil fuels consumed in drying and heating aggregates. Consequently, burners have been developed to use hydrogen fuel as a next-generation fuel to replace fossil fuels, as hydrogen fuel does not emit CO_2. Our company, in collaboration with Tokyo Gas Engineering Solutions Corporation developed a 500-kW hydrogen burner in March 2023[1]. This paper reports on an asphalt mixture production test using the hydrogen burner to examine whether the developed 500-kW hydrogen burner can be used in APs.

1. Introduction

Since the Industrial Revolution in the late 18th century, humanity has reaped the rewards of harnessing heat and electrical energy, but at the expense of substantial fossil fuel consumption. However, the price has resulted in significant damage to the environment including the atmosphere, oceans, and rivers. In recent years, there has been a noticeable surge in the frequency of extreme weather phenomena like torrential rain, El Niño, and La Niña. Temperatures have particularly been rising since 1850, and according to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the temperature is expected to rise by 3.3 to 5.7°C by the end of this century. This is why United Nations Secretary-General Antonio Guterres has warned, saying that without our actions to address these issues, we will enter an era of global boiling, which will be even more serious than global warming.

With the entire world sharing a sense of crisis regarding these environmental issues, the Paris Agreement was adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in 2015. Its objective was to make "efforts to keep the temperature rise well below 2°C and within 1.5°C compared to pre-industrial revolution levels." In recent years, COP28, held in November 2023, advocated tripling the capacity of renewable energy and doubling the energy-saving rate by 2030 to achieve the 1.5°C target. Each country has expressed its intention to further accelerate the transition away from the dependence on fossil fuels[2].

In line with the Paris Agreement, Japan announced in 2021 its aim to reduce greenhouse gas emissions by 46% in 2030 compared to 2013. To achieve this goal, the Ministry of Economy, Trade and Industry took the lead in formulating the "Green Growth Strategy for Carbon Neutrality in 2050." The Green Growth Strategy formulates implementation plans for 14 key areas in which growth is expected from both industrial and energy policy perspectives, and hydrogen is listed as one area of energy-related industries. As for hydrogen, we aim for a supply of around 20 million tons in 2050 at a supply cost of around 20 yen/Nm^3 or less (around the unit calorific value of city gas in 2024), and we expect its introduction to expand in the energy industry[3].

In addition, one of the challenges of the third period of the Strategic Innovation Creation Program (SIP) is the construction of a smart energy management system, which aims to efficiently utilize electricity, hydrogen, and heat derived from renewable energy to establish next-generation social infrastructure[4].

Currently, 79% of the CO_2 emissions from APs come from the fuel used for drying and heating aggregates, 19% from the electricity consumed in offices and other facilities, and 2% from heavy machinery fuel and other sources. Regarding the CO_2 reduction effect per calorific value based on heavy oil, if gas is used as fuel, this switch is expected to result in a 25% reduction with city gas and a 15% reduction with propane gas. However, achieving further reductions will require some combination of other technologies. Biomass burners developed in the past that utilize fuels such as glycerin, wood tar, rice husks, and carbonized fuel can reduce CO_2 emissions through the introduction of biomass fuel[5]. However, establishing a supply system for transporting and utilizing biomass fuel from areas where it is available is essential. Consequently, expanding the use of biomass fuel to all APs in a short period presents significant challenges.

In response to this situation, we have developed a burner capable of utilizing hydrogen fuel, which is expected to serve as an alternative to the fossil fuels traditionally employed in APs. Hydrogen is a remarkably clean, carbon-neutral fuel, as its combustion process generates solely water vapor, without CO_2 emissions. Considering fuel safety and ease of use in the APs, we prioritized the development of a hydrogen burner and began joint development with Tokyo Gas Engineering Solutions Corporation in 2022 in order to improve the product accuracy as quickly as possible. In March 2023, our joint endeavors brought about the successful development of the 500-kW hydrogen burner.

In this test, the developed hydrogen burner was installed in a small test plant and an asphalt mixture was produced. A test construction with the manufactured asphalt mixture was conducted to evaluate the balance during operation in the small test plant and the quality as a paving material. The use of hydrogen fuel increases the amount of water vapor in the combustion exhaust gas, and thus we examined the effects of the water vapor in the exhaust gas on the quality of the asphalt mixture, the aggregate temperature control during the AP operation, and the apparatuses in the AP. This paper reports the results of the test in which an asphalt mixture was produced using the hydrogen burner in a small test plant operated by MAEDA ROAD CONSTRUCTION Co., Ltd.

Table 1 Comparison between Fuels Used in AP and Hydrogen Fuel[6,7,8]

Fuel	Heavy oil A	Propane Gas	City Gas (methane)	Hydrogen
Boiling Point at Atmospheric Pressure(°C)	≧150	−42.1	−161.6	−252.9
Lower Calorific Value per Volume(MJ/Nm³)	−	91.2	41.6	10.8
Lower Calorific Value per Mass(MJ/kg)	41.9	46.6	50.2	120.4
CO_2 Emission per Calorific Value(tCO_2/G J)	0.0693	0.059	0.0499	−

2. Hydrogen Fuel in AP

2.1 Comparison of Fuels Used in AP and Hydrogen Fuel

Most of the fuel used in burners at APs across the country is heavy oil A. In urban and coastal areas, the use of city gas and propane gas as fuel is expanding, and the use of gas fuel for industrial equipment is also rapidly accelerating. **Table 1** shows a comparison of the fuels mainly used in APs and hydrogen fuel[6,7,8].

At a temperature of 20°C under atmospheric pressure, only heavy oil A exists in liquid form, while propane, city gas, and hydrogen exist in gas form. The calorific value per volume is propane > city gas > hydrogen. To obtain the same calorific value using hydrogen gas instead of city gas, a flow rate about four times greater is required.

Hydrogen has a lower boiling point of -252.9°C compared to other gaseous fuels, requiring a large amount of energy to liquefy. However, its calorific value per mass is 120.4 MJ/kg, which is twice that of other fuels. Although energy is required to liquefy hydrogen, the volume is reduced to 1/800 of its original size, making it more efficient to transport. Additionally, hydrogen is attracting attention as a fuel that the government is promoting for carbon neutrality.

2.2 Fuel Conversion to Hydrogen in AP

An advantage of converting the fuel used in AP burners to hydrogen is that CO_2 is no longer emitted during the drying of aggregates. This is an important step toward achieving carbon neutrality in APs. However, there are several issues with the current conversion to hydrogen fuel:

・Higher costs for facility and fuel
・Need for storage in a low-temperature liquefied state
・Necessity to use green energy for vaporization
・Difficulty in supplying the required amount of hydrogen to APs

At present, hydrogen is more expensive than conventional fuels, and unlike city gas, there are few places where it can be supplied via pipelines. As a result, the cost of hydrogen fuel storage equipment is a constraint on capital investment. Therefore, to expand the use of hydrogen in AP, the priority is to increase the supply of hydrogen and develop the hydrogen infrastructure.

3. Mixture Production Test

3.1 Test Conditions

A test using heavy oil was conducted with a burner exclusively compatible with heavy oil. The mixed combustion of compressed natural gas (CNG, i.e., City Gas 13A) and hydrogen was performed with various introduction ratios of hydrogen, based on calorific value.

Table 2 Test Parameters

Fuel	・Heavy oil A ・CNG ・Hydrogen ・Mixed Combustion of CNG and Hydrogen (30%, 50%, 80%)
Flow Rate of Aggregate	・5t/h ・3t/h(Only Single-Combustion of Hydrogen)

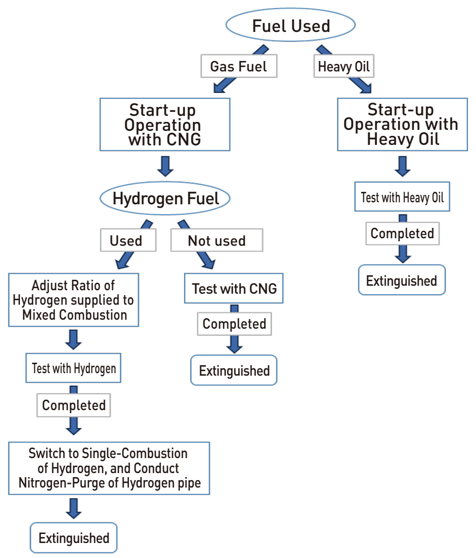

Figure 1: Operation Flowchart

When extinguishing the fire after using hydrogen, the state of single-fuel combustion of hydrogen was set to ensure that the remaining hydrogen and air did not form a flammable mixture in a pipe. The fire was then extinguished with a nitrogen purge, and subsequently, the gas inside the pipe was replaced. The temperature of the aggregate was adjusted during operation by drying the aggregate while controlling the fuel flow rate to maintain a stable aggregate temperature of 210°C. The parameters used in this test are shown in **Table 2**, and the flowchart of the operating method is shown in **Figure 1**.

3.2 Facility for Test

A 500-kW hydrogen burner was installed in a small test plant owned by MAEDA ROAD CONSTRUCTION Co., Ltd. The burner used is the one we jointly developed with Tokyo Gas Engineering Solutions Corporation in March 2023. **Photo 1** shows the external appearance of the installed hydrogen burner.

3.2.1 Hydrogen Burner

In this test, the hydrogen burner was ignited in the same way as our conventional gas burners, using pilot ignition with city gas. The system uses a premixing method in which city gas and hydrogen are mixed in the burner's gas line, which allows for single-fuel burning of city gas, co-combustion of hydrogen, and single-fuel burning of hydrogen using a single burner nozzle. The air for combustion was supplied from a fan behind the burner, and the ratio of the required air amount to the flow rate of hydrogen fuel was adjusted as needed[1].

3.2.2 Fuel Supply Line

Photo 2 shows an apparatus for CNG combustion used in the test. In the CNG supply line, equipment was used such as a flow meter, a solenoid valve, and a ball valve. In this test, the flow rate was set to be adjustable so that the mixed-fuel-burning ratio was changeable as needed to investigate the effect on the plant.

In the hydrogen supply line, hydrogen at 14.7 MPa was supplied from a curdle (i.e., a bundle of cylinders where the gas outlets are collected), and the pressure was reduced to 0.2 MPa by a pressure reduction unit for supply. The hydrogen flow rate was adjusted using a mass flow controller.

The higher the pressure of the gas fuel, the smaller its volume. Accordingly, the reduced volume has an increased calorific value per unit capacity, resulting in a decrease in the size of the cylinders and the diameter of the pipe. To reduce the volume while increasing the energy density, both CNG and hydrogen are filled in the cylinders at a high pressure of 14.7 MPa. However, if used at high pressure, they may damage the apparatus and cause misfires due to sudden pressure fluctuations. Therefore, the pressure was reduced before being supplied to the combustion apparatus.

The CNG and hydrogen supply lines are combined at a junction pipe to supply the fuels to the hydrogen burner. A switching valve was installed for single-fuel combustion, and a check valve was installed on the hydrogen supply line as a safety measure against backflow.

3.2.3 Test Plant

Photo 3 shows the small test plant used in the test, and **Table 3** displays the specifications of the unit equipment in the plant. The drying kiln had a size of Φ 1100 mm × 3500 mm, and the plant had a capacity of 5 t/h for drying aggregate. The hydrogen burner was configured to be retrofitted in the same way as our conventional gas burners. This hydrogen burner was replaced with the heavy oil burner in the small test plant, and a mixture production test was conducted.

3.3 Test Measurement Items

The items measured in this test are shown below:

・Temperatures of aggregate (i.e., input aggregate, discharged aggregate)
・Water content in the aggregate (i.e., ratios of water content in the aggregate before and after the test)
・Components of exhaust gas (i.e., measurements of NO_x, O_2, CO, CO_2, SOX, H_2O, and dust)
・Volume of exhaust gas

The temperatures of the aggregate and the water content in the aggregate were measured by sampling the aggregate on a belt conveyor (before passing through the dryer) and in a hot elevator (after passing through the dryer). The components and volume of exhaust gas were measured at a measurement port in the chimney of the small test plant. **Table 4** shows the method for measuring the exhaust gas components.

Photo 1 Hydrogen Burner

Photo 2 Apparatus for Combustion

3.4 Test Results of Mixture Production

3.4.1 Results of Drying and Heating of Aggregate

Table 5 shows the results of drying and heating aggregate in the single combustion of each fuel at an aggregate supply rate of 5 t/h. Comparing the aggregate temperatures after heating under each test condition, the temperatures ranged from 194 to 203°C, indicating that hydrogen had the same ability to heat aggregates as city gas, and that hydrogen could be operated with the same controllability, such as temperature rise rate.

As shown in **Table 5**, the water content ratio in the aggregate before heating was 4.1% for hydrogen-only combustion, which was lower than 5.3% for heavy oil combustion. However, the water content ratio in the aggregate after heating from hydrogen-only combustion was 0.08%, higher than those from combustion with other fuels. MAEDA ROAD CONSTRUCTION Co., Ltd. confirmed that the quality of the asphalt remains unchanged with hydrogen-only combustion regarding the water content in the aggregate.

The flow rate of the fuel was measured when the aggregate temperature after drying was stable. The calorific value required to dry and heat the aggregate was estimated from the test conditions, and the thermal efficiency was calculated. Hydrogen showed a lower thermal efficiency than heavy oil at 55.8%, but since hydrogen had a thermal efficiency comparable to CNG's 54.6%, it can be operated in the same way as city gas. In general, the radiant heat from a hydrogen flame is adequately smaller than that of a normal luminous flame containing carbon. Accordingly, we believe that the thermal efficiency of hydrogen was lower than that of heavy oil[9]. All fuels have 40% ineffective heat, and additionally, much air entered through the material input port and other portions due to the unique properties of the small test plant. These factors might lead to the exhaust gas temperature, causing ineffective heat.

Photo 3 Small Test Plant

Table 3 Specification of Small Test Plant

Unit Name	Specification*
Dryer	Dimension:Φ1100×3500L Capacity:5t/h
Bag Filter	Filter Cloth: 72 pieces(50㎡)
Exhaust Fan	Air Volume:90㎥/min Static Pressure:310mmAq(3.1kPa)
First Flue	Diameter:Φ380

*Unless otherwise specified, the unit is mm

Table 4 Methods of Measuring Exhaust Gas

Measurement Items	Method of Measuring	Apparatus
Water Content	Moisture absorption tube method	-
Gas Composition Analysis	Orsat Method	-
Dust Amount	Circular Filter Method	-
Sulfur Sulfide	Ion Chromatography	-
Nitrogen Oxides	Ion Chromatography	-
CO	Single-light-source, dual-wavelength type Non-Dispersive Infrared Absorption	CGT-7000

Table 5 Results of Drying and Heating Aggregate

Fuel	[-]	Heavy Oil 100%	CNG 100%	Hydrogen 100%
Volume of Supplied Aggregate	[t/h]	5	5	5
Aggregate Temperature before Heating	[℃]	17	16	17
Aggregate Temperature after Heating	[℃]	194	203	196
Water Content Ratio in Aggregate before Heating	[%]	5.3	3.6	4.1
Water Content Ratio in Aggregate after Heating	[%]	0.02	0.01	0.08
Temperature at Bag Entrance	[℃]	82	70	78
Flow Rate of Heavy Oil	[L/h]	42.0	0.0	0.0
Flow Rate of CNG	[Nm³/h]	0.0	33.0	0.0
Flow Rate of Hydrogen	[Nm³/h]	0.0	0.0	130.2
Calorific Value of Fuel	[kW]	429	372	390
Heat Quantity to Heat Aggregate	[kW]	74	78	75
Calorific Value of Water in Aggregate	[kW]	184	125	143
Amount of Effective Heat	[kW]	257	203	218
Thermal Efficiency	[%]	60.0	54.6	55.8

Table 6 Measurement Results of Exhaust Gas

Fuel Used	[-]	Heavy Oil 100%	CNG 100%	Hydrogen 30%	Hydrogen 50%	Hydrogen 80%	Hydrogen 100%	Hydrogen 100%
Flow Rate of Aggregate	[t/h]	5	5	5	5	5	5	3
CO_2 Concentration	[%]	4.1	2.7	1.8	1.3	0.7	0	0
O_2 Concentration	[%]	15.5	15.6	16.5	16.9	16.7	17.7	17.6
CO Concentration	[ppm]	1472	275	71	15	8	3	3
Amount of Dust	[g/m³]	0.007	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
SOx Concentration	[ppm]	< 3	< 3	< 3	< 3	< 3	< 3	< 3
NOx Concentration	[ppm]	16	5	13	13	13	15	14
NOx concentration (converted to an O_2 concentration of 16%)	[ppm]	15	5	14	16	15	23	20
Volume of Exhaust Gas (wet)	[Nm³/h]	2250	1970	1960	1950	1930	2240	1980
Volume of Exhaust Gas (dry)	[Nm³/h]	1950	1770	1810	1790	1670	2010	1780
Water Content in Exhaust Gas	[Vol%]	13.2	10.4	7.9	8.2	13.5	10.3	10.1
Water Content Ratio in Aggregate	[%]	5.61	3.56	4.09	4.09	3.56	4.09	4.09

Table 7 Results of Estimated Amount of Water Vapor

Fuel Used	[-]	Heavy Oil 100%	CNG 100%	Hydrogen 30%	Hydrogen 50%	Hydrogen 80%	Hydrogen 100%	Hydrogen 100%
Flow Rate of Aggregate	[t/h]	5	5	5	5	5	5	3
Amount of Water Vapor from Aggregate	[Nm³/h]	369.8	229.7	265.3	265.3	229.7	265.3	159.2
Amount of Water Vapor from Fuel	[Nm³/h]	55.6	66.0	92.2	87.1	102.0	130.2	110.0
Amount of Water Vapor from Atmosphere	[Nm³/h]	27.9	25.6	26.4	26.1	24.4	29.5	26.1
Theorical Amount of Water Vapor	[Nm³/h]	453.4	321.3	383.9	378.5	356.1	425.0	295.3
Actual Amount of Water Vapor	[Nm³/h]	297.0	204.9	154.8	159.9	260.6	230.7	200.0
Amount of Condensed Water Vapor	[Nm³/h]	156.4	116.4	229.1	218.6	95.6	194.3	95.3
Amount of Condensed Water	[L/h]	125.7	93.6	184.1	175.7	76.8	156.1	76.6

3.4.2 Measurement Results of Exhaust Gas

Table 6 shows the measurement results of exhaust gas under each condition.

As shown in **Table 6**, the CO_2 concentration was confirmed to be 4.1% from the single-fuel combustion with heavy oil, which decreased to 2.7% from combustion with CNG only. This reduction is due to CNG having a lower CO_2 emission coefficient per calorific value than heavy oil. As the mixed-fuel burning ratio with hydrogen increases, the CO_2 concentration decreases, and no CO_2 was detected under hydrogen-only combustion conditions. This was consistent with the phenomenon, as hydrogen combines with oxygen during combustion to produce only water and no CO_2. Additionally, similar to the CO_2 concentration, the CO concentration tends to decrease as the mixed-fuel burning ratio of hydrogen increases. Specifically, since the test plant was small and the kiln length was short, it is believed that the heavy oil was cooled by aggregate of lower temperature before combustion, resulting in a large amount of unburned heavy oil, which led to the value of 1472 ppm. CO was detected during the hydrogen-only combustion, which is considered to be within the measurement error range of the apparatus (CO measurement range 2500 ppm, with an error of ± 2%).

NOx concentration (converted to O_2 concentration of 16%)

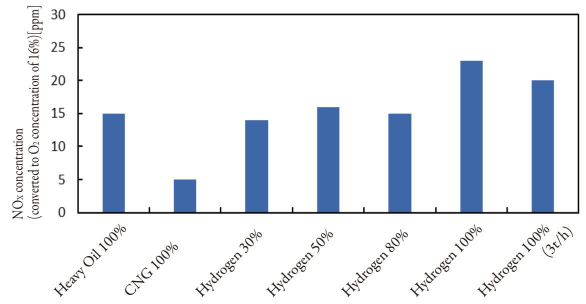

Figure 2: Results of NOx concentration (converted to O_2 concentration of 16%)

As shown in **Table 6**, the amount of dust from the gas fuel was below the measurement limit, and was lower than the regulation value from the heavy oil, and also no problems were observed from hydrogen combustion.

Figure 2 shows a graph of the NOx concentration converted to an O_2 concentration of 16%. Thermal NOx is a concern when the burner is used in AP. The Air Pollution Control Act sets standards for NOx emissions, and the emissions standard for aggregate-drying ovens is 230 ppm. Hence, NOx concentration needs to meet these standards[10]. Under all the measurement conditions this time, the NOx values were lower than the standard values. The NOx value from the hydrogen-only combustion was 23 ppm, which is higher than the 5 ppm from the CNG-only combustion and showed similar results to the tests conducted at the development stage of the burner. This is consistent with the trend that hydrogen causes thermal NOx to increase more than CNG, as it is known to burn at a faster rate and create localized high-temperature areas.

Table 7 shows the estimated amount of condensed water vapor based on the measurement results of the water content in the exhaust gas.

The test results showed that the actual water vapor was 297.0 Nm^3/h from the heavy oil-only combustion, 204.9 Nm^3/h from CNG-only combustion, and 230.7 Nm^3/h from hydrogen combustion.

Theoretically, 0.8 kg of water is produced when 1 Nm^3 of hydrogen is burned. As shown in Table 7, hydrogen has a higher ratio of fuel-derived water vapor than heavy oil or CNG, and thereby using hydrogen fuel will increase the total amount of water vapor from aggregate drying. However, the influence of the amount of water vapor derived from the fuel on the actual amount of water vapor was within an acceptable range, as the ratio of water vapor in the exhaust gas was mostly derived from aggregates under all the measurement conditions this time, although the water content of aggregate varied depending on the test conditions, ranging from 3.56% to 5.61%. Furthermore, it was confirmed that the calculated amount of condensed water vapor was not proportional to the mixed-fuel burning ratio of hydrogen fuel.

The amount of saturated water vapor changes depending on the exhaust gas temperature, which we believe resulted in the amount of condensed water vapor varying from 76.6 to 184.1 L/h, as shown in Table 7. From the appearance of the chimney and smoke when the exhaust gas temperature was raised at the small test plant where a preliminary test was conducted, we confirmed that switching to hydrogen fuel does not necessarily increase the amount of condensed water vapor, but that the amount of condensed water discharged can be reduced by controlling the temperature of the exhaust gas.

4. Conclusion

We developed a 500-kW hydrogen burner and conducted an asphalt-mixture production test. We had been concerned about the effects of water vapor generation during hydrogen combustion and the quality of the resulting asphalt mixture. However, the test results confirmed that we can operate the hydrogen burner in the same way as a gas burner, and it does not cause any quality issues.

Unfortunately, to install hydrogen burners in actual AP equipment, social issues remain, such as the aforementioned "high cost for facility, fuel, and storage" and "securing sufficient hydrogen fuel." The unit price difference per calorific value between city gas and gray hydrogen is approximately double, and the unit price difference between green hydrogen and gray hydrogen is approximately six times. To address these issues, support and subsidies are being discussed to make hydrogen easier to use by 2030, and thereby we need to prepare to install hydrogen burner equipment in APs at any time. We plan to scale up the burner to a burner with an output of 5MW or more for use in general APs. The test results in Phase 1 showed that the 500-kW hydrogen burner can maintain low NOx combustion when burning city gas in addition to hydrogen, allowing it to be used for city-gas-only combustion.

Furthermore, as hydrogen is expected to help achieve carbon neutrality in fields other than AP, we are also focusing on developing new products by utilizing hydrogen-burner combustion technology and low-NOx combustion technology.

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