

# Meeting the Challenge of Realizing a High Ratio Co-Firing System with Woody Biomass

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Although pulverized coal-fired power plants are important as base load power sources, they emit a large amount of carbon dioxide (CO<sub>2</sub>). Given this, it is necessary to reduce their CO<sub>2</sub> emissions, and co-firing with carbon-neutral woody biomass is an important measure for achieving this. However, while Japan possesses an abundance of forest resources, the actual biomass-to-coal ratio achieved in co-firing remains as low as a few calorific percent. Aiming to achieve 50% co-firing on a thermal basis, IHI has been working to verify and demonstrate the effectiveness of a comprehensive system — including the supply chain for the woody biomass — in cooperation with some universities. Eventually, in 2015, IHI carried out demonstration tests involving processes from logging, wood collection, processing, and transportation through to co-firing power generation at a 150 MW-class commercial thermal power plant. These tests demonstrated that a co-firing biomass-to-coal ratio of 25% (thermal basis) can be achieved using fuel produced from timber grown in Japan, all of whose processes are done in Japan.

## 1. Introduction

Currently, thermal power generation is the most important means of base load power generation fulfilling the crucial role of supplying electric power in Japan. Among the fuels for thermal power generation, coal is advantageous because it can be stably supplied from a wide area at reasonable cost. However, its high CO<sub>2</sub> emission intensity is a major issue with respect to measures against global warming. Hence, changing fuel from coal to carbon-neutral woody biomass (hereinafter referred to as “biomass”) is considered to be an effective means of reducing CO<sub>2</sub> emission intensity in thermal power generation.

Also, with timber volume increasing year by year, wood resources in Japan have reached a maximum since the end of World War II. However, amid reduced timber demand and falling prices, many of these resources have been left unused. Hence, effective utilization of these abundant untapped wood resources as fuel for power generation — which represents a long-term stable large-quantity demand — is expected not only to contribute to measures against global warming, but also, as a sustainable energy source produced in Japan, to increase the energy self-sufficiency ratio and improve trade balance by reducing the import of fossil fuels.

In addition, co-firing of biomass in coal-fired power generation plants has the following technical advantages.

- (1) If solid fuels are directly utilized in world-class performance power generation plants, then high energy efficiency can be achieved, since there is no conversion

loss due to gasification or liquefaction.

- (2) Large-scale coal-fired power generation plants in Japan have exhaust gas treatment facilities that satisfy strict emission standards. Therefore, introduction of biomass with properties similar to coal can minimize additional environmental load and large-scale investment in additional facility development or remodeling.
- (3) Co-firing systems have high operational stability because of their flexibility in fuel procurement. For example, if one fuel is unexpectedly in short supply, this can be compensated for by increasing supply of the other.

In Japan, coal-fired power generation plants mainly use pulverized coal, and many of them have already introduced co-firing because of its above-mentioned advantages. However, the following problems currently exist.

- (1) The biomass-to-coal ratio is low. In pulverized coal firing boilers, which are the main type used in large-scale coal-fired power generation plants, technical constraints limit biomass co-firing to a calorific value ratio of a few percent.
- (2) A stable supply system for large amounts of biomass fuel has not been established.

## 2. Background to the challenge

In order to solve the above problems, IHI Corporation, jointly with Tohoku and Chiba Universities, was entrusted from 2011 to 2012 with implementation of the “Global

Warming Countermeasure Technology Research, Development and Demonstration Program: Design of green supply chain for woody biomass fuels for use in coal power stations in Japan<sup>(1),(2)</sup> by the Ministry of the Environment. Although on a small scale, IHI implemented comprehensive demonstration tests for all processes, from timber collection and fuel production through to long-distance transportation and utilization in combustion. In addition, by performing and integrating additional element tests and analyses, IHI obtained estimation results indicating that the co-firing of domestic biomass fuels with high biomass-to-coal ratios in furnaces using dedicated biomass combustion burners is a feasible option which satisfies the requirements for energy utilization ratios and economic efficiency.

However, since most commercial pulverized coal-fired power generation plants (commercial boilers) have a capacity of 500 MW or more, equipment remodeling requires a huge investment. In addition, since electric power suppliers are responsible for the stable supply of power to consumers, they cannot be expected to introduce large-quantity biomass co-firing without a proven track record. On the other hand, according to an interview survey with people directly related to the forestry industry in Japan, large-quantity biomass co-firing poses the following issues:

- (1) Difficulty guaranteeing high-volume, stable, continuous demand for biomass fuels;
- (2) Difficulty achieving economically feasible biomass fuel production costs; and
- (3) Disturbance of the market by cheaply imported or illegally logged timber.

Issue (1) is inextricably linked to the concerns of power producers. With regard to issue (2), it is clear from the above examination that current timber collection methods (prioritizing shape), which are based on use as building materials, are not efficient or economical, and so the establishment of an efficient method of timber collection and processing is required. Issue (3) cannot be solved under the current distribution system, which is not suited to strict market control (differentiating local timber from timber of other regions and imported timber). Hence, even if issue (1) is solved, there is the danger of forest resources being depleted by excessive, illegal or destructive logging in the areas close to power plants.

Therefore, taking advantage of the valuable experience and knowledge obtained through the above research and development, IHI conducted a series of large-scale verification tests in order to deal with the aforementioned issues, including a commercial scale verification test (using the power generation plants in the Kamaishi Works of the Nippon Steel Corporation, with a capacity of 149 MW). Taking the outcome of these tests as an important milestone, IHI endeavored to promote introduction into coal-fired power generation plants in Japan through the “Low Carbon Technology Research, Development and Demonstration Program”<sup>(3),(4),(5)</sup> promoted by the Ministry of the Environment, and IHI’s application to the program was successfully adopted.

Based on the above background, and aiming for early

commercialization, there now follows a description of a series of efforts centered on full-scale demonstration of a total biomass co-firing system, together with the corresponding results obtained.

### 3. Contents of project

Predicted bottlenecks were identified with respect to establishment of the overall system, and implementation of the project was correspondingly divided into the following three topics.

- (1) Co-firing boiler system (fuel handling, exhaust gas system, and overall configuration of power plant)
- (2) Combustion system (combustion burner and fuel pulverization system)
- (3) Fuel supply system (biomass fuel supply, from timber collection at source to power plant)

The details of these systems are described below.

#### 3.1 Co-firing boiler system

##### 3.1.1 System configuration

In order to perform demonstration tests of high biomass-to-coal ratio co-firing power generation in a 150 MW-class commercial plant, we conducted investigation of a pretreatment system to feed biomass fuel to the boiler. The boiler with which the demonstration tests were conducted had been used for co-firing of coal with biomass at a low biomass-to-coal ratio and, at the time of the tests, was provided with an additional system comprising a coal mill and corresponding burners in order to increase the biomass-to-coal ratio by increasing the pulverizing capacity. Using the additionally provided system, co-firing demonstration tests were conducted with the temporary feeding facility. It was assumed that successful demonstration of one biomass feeding system would prove that higher biomass-to-coal ratios could be achieved by further increasing the number of such systems. **Figure 1** shows the configuration of the system used in the demonstration tests, **Fig. 2** the placement of the pretreatment system used in the tests, and **Table 1** an outline of the tests. The component equipment constituting the biomass feeding system, such as the flow conveyor, was subjected to individual pre-shipment tests at the manufacturing plant in order to confirm stable biomass transfer.

The demonstration tests were conducted for two types of biomass fuels, i.e., wood pellets (hereinafter referred to as “pellets”) and wood chips (hereinafter referred to as “chips”). In order to feed pellets, the interior of the coal mill was modified so as to increase its pulverizing capacity. For the feeding of chips, in the light of past experience, fine-grained chips that had been dried and crushed in advance were used. As described in **Section 3.2**, individual pulverizing tests on pellets and chips were carried out with a coal mill, and biomass-to-coal ratios determined from the results.

##### 3.1.2 Investigation of biomass storage and feeding systems

Using a model device simulating actual equipment, demonstration tests were conducted for the storage and feeding of pellets, chips (50 mm or less) and fine-grained chips (5 mm or less) in a dried and undried condition. It was

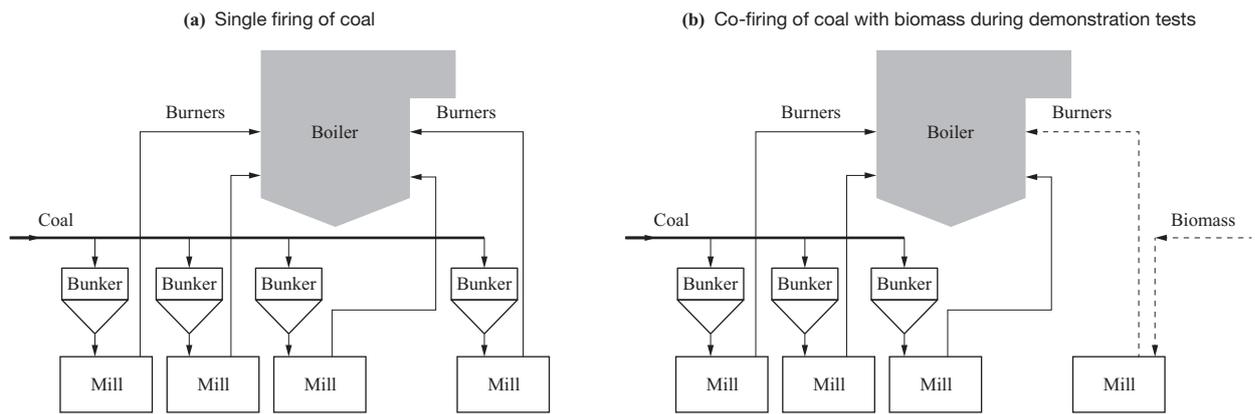


Fig. 1 Configuration of the system

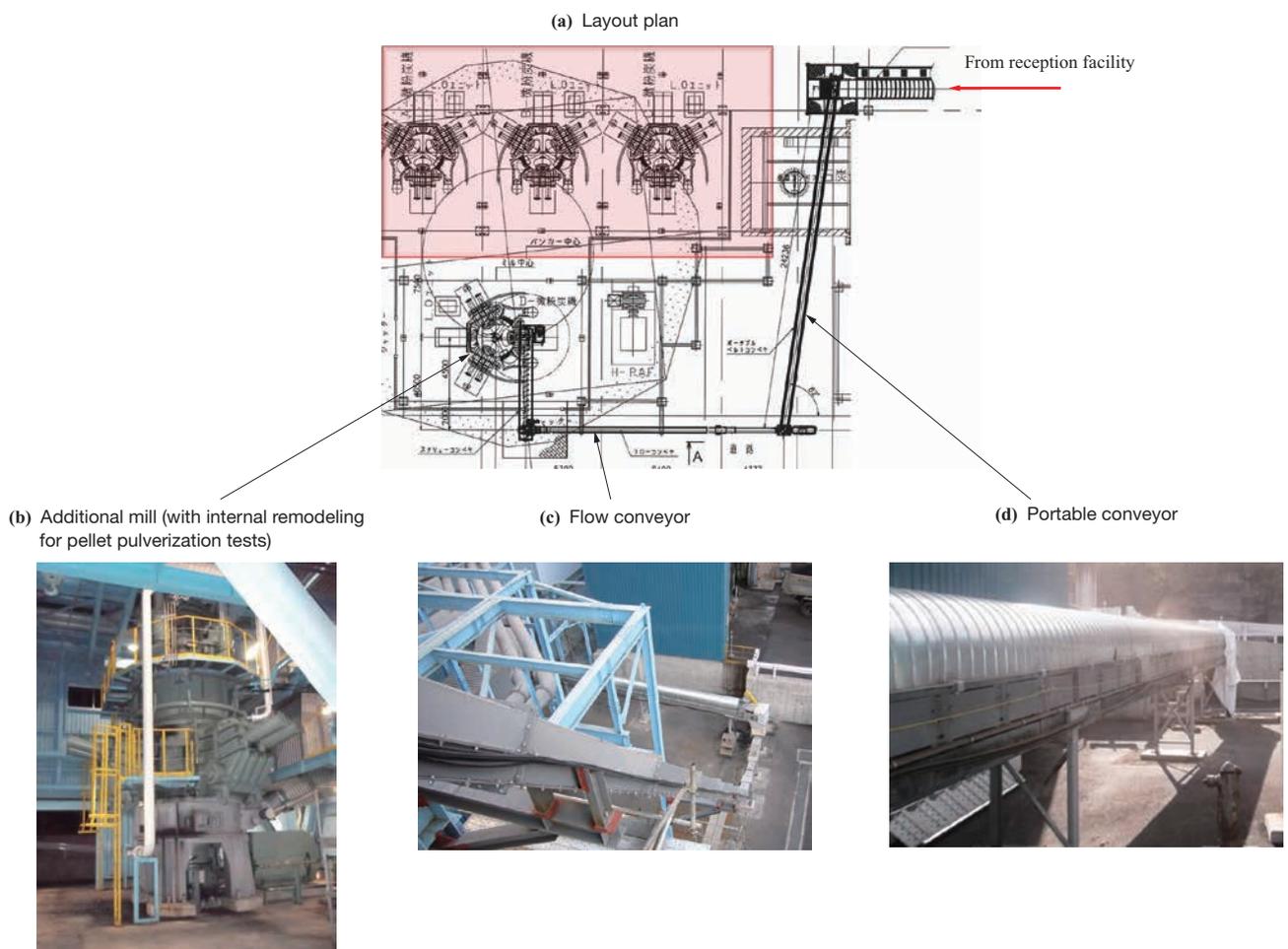


Fig. 2 Placement of pretreatment system in the demonstration tests

Table 1 Overview of the demonstration tests

Test conditions	Description	Biomass-to-coal ratio (calorific value ratio) (%)
Dry fine-grained chips - Single pulverization - Single combustion	Cut and pre-dried chips (of size 5 mm or less and moisture content approx. 10%) are subjected to single pulverization in one of the four coal mills, and single combustion in coal burners connected to the mill.	8
Pellets - Single pulverization - Single combustion	One of the four coal mills is remodeled to be suitable for pulverizing pellets; pellets are subjected to single pulverization in the mill, and single combustion in coal burners connected to the mill.	25

confirmed that pellets could be handled in the same way as coal, but that chips showed lower fluidity than coal, and therefore required a specific storage structure and discharge mechanism suitable for their characteristics. Planning of the biomass storage and feeding system (shown in Fig. 3) was based on these test results. In addition, it was decided to procure the necessary amounts of biomass shown below prior to the tests and store them in the power generation plant.

Dry fine-grained chips :

approx. 500 m<sup>3</sup> (approx. 100 tons based on an assumed bulk specific density of 0.2 t/m<sup>3</sup>)

Pellets :

approx. 1 000 m<sup>3</sup> (approx. 600 tons based on an assumed bulk specific density of 0.6 t/m<sup>3</sup>)

Because pellets undergo deformation when they absorb moisture, they were transported in trucks that enabled them to be covered, and were stored indoors. Figure 4 shows how biomass for the demonstration was carried in and stored. In addition, in order to prevent fire during long-term storage of the biomass, thermometers were inserted into the deposited pellets for regular monitoring of pellet temperature during the storage period. During the test period of approx. two months, there were no increases in pellet temperature due to oxidation or ignition.

### 3.1.3 Demonstration test results in commercial plant

Demonstration tests for the co-firing of coal with dry fine-

grained chips and pellets were conducted with a 150 MW-class commercial plant. Typical data from the demonstration tests and trend data for co-firing of coal with pellets at a pellet-to-coal ratio of 25% are shown in Table 2 and Fig. 5 respectively. In the demonstration tests of co-firing coal with dry fine-grained chips and pellets (conducted through single combustion and pulverization), combustion load was adjusted, with the biomass fuels being incrementally fed into a furnace that was initially in a single-coal-firing state. By setting combustion load to approx. 5% less than the rated load, a control margin was provided so as to suppress overload. Hence, the tests were conducted in a manner that allowed stable commercial operation. In the demonstration tests for co-firing of coal with dry fine-grained chips, the amount of combustion was as low as 8% of burner capacity, so an ignition burner (heavy oil burning) was used throughout the tests. As a result, all the tests exhibited stable combustion, and no problems were caused by biomass co-firing.

In the demonstration tests for co-firing of coal with pellets, the pellet-to-coal ratio was increased to the target of 25% (actual maximum performance was 26%), and the boiler heat absorption was almost the same as for single firing of coal. Because biomass fuels contain almost no ash, nitrogen, or sulfur, the discharged amounts of soot/dust, nitrogen oxide (NO<sub>x</sub>), and sulfur oxide (SO<sub>x</sub>) were reduced in proportion to the increase in co-firing ratio. Compared to the case of single firing of coal with three coal mills, the biomass

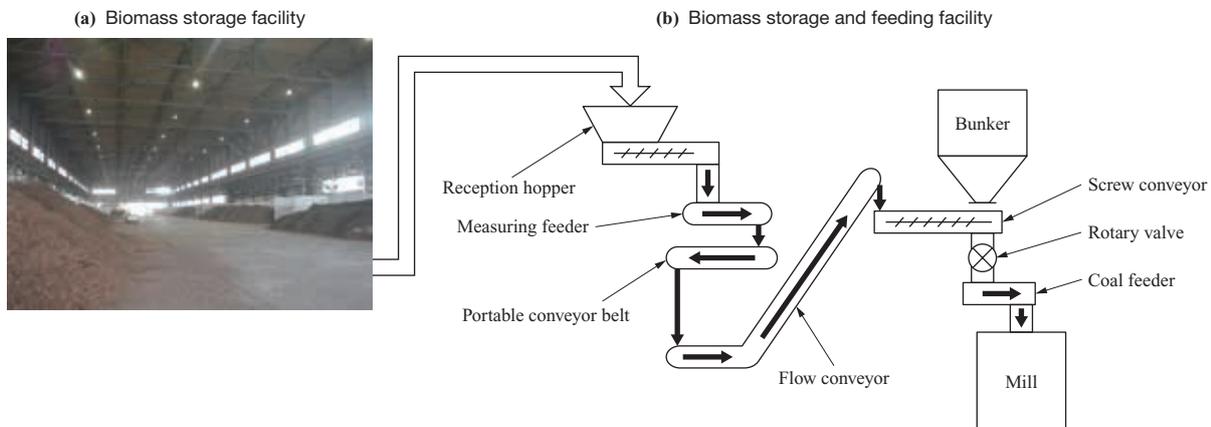


Fig. 3 Storage and feeding system



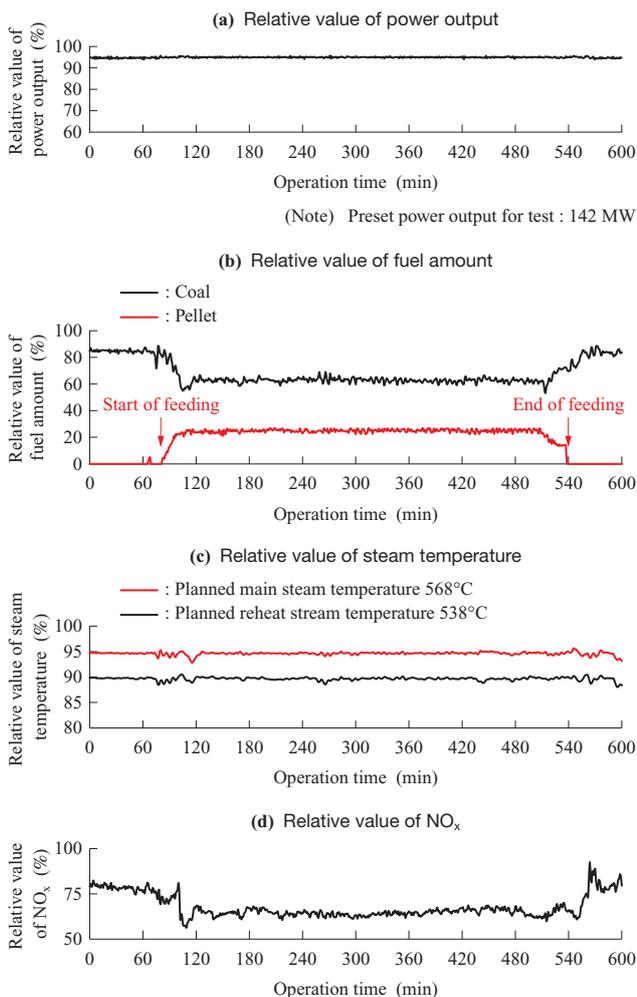
Fig. 4 Biomass carry-in and storage for the demonstration tests

**Table 2** Typical data from the demonstration tests

Item	Test conditions			
	Unit	Co-firing of coal with 8% dry fine-grained chips, 4-mill operation	Co-firing of coal with 25% pellets, 4-mill operation	Single firing of coal, 3-mill operation
Power output	MW	142	142	148
Main steam temperature	°C	568	568	568
Reheated steam temperature	°C	538	538	538
Water supply temperature	°C	275	275	277
Calorific value of coal (lower)	kJ/kg	26 220	26 220	26 220
	kcal/kg	6 260	6 260	6 260
Calorific value of biomass (lower)	kJ/kg	17 190	1 710	—
	kcal/kg	4 110	4 230	—
Calorific value of heavy oil (lower)	kJ/kg	40 690	—	—
	kcal/kg	9 720	—	—
Coal input amount	% <sup>*1</sup>	88	74	100
Pellet input amount	% <sup>*1</sup>	8	26	—
Heavy oil input amount	% <sup>*1</sup>	4	—	—
Boiler efficiency	Relative value <sup>*2</sup>	0.997	0.996	Taken as 1.0
Field measurement	NO <sub>x</sub>	Relative value <sup>*2</sup>	0.84	Taken as 1.0
	Soot (at boiler outlet)	Relative value <sup>*2</sup>	0.72	Taken as 1.0

(Notes) \*1 : Calorific value ratio

\*2 : Relative value with respect to single firing of coal



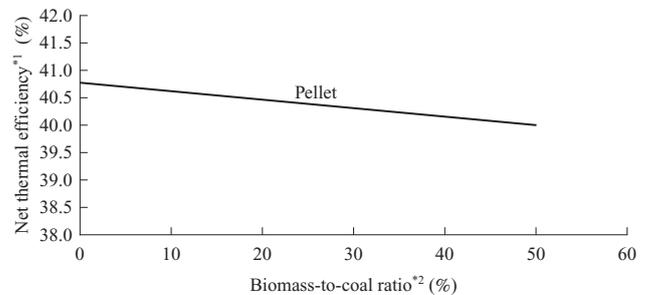
**Fig. 5** Demonstration tests: Trend data for co-firing with 25% pellet fuel

co-firing in the demonstration tests required four mills, and boiler efficiency was reduced by 0.3 to 0.4% (relative value) due to ① the increase in the volume of primary air sent into the mills and ② the necessity of lowering the temperature of the primary air at the biomass mill feed ports for safety reasons.

The demonstration test results were used to predict the net thermal efficiency of a pulverized coal-fired power generation plant of capacity 500 MW operated using co-firing with pellets at a pellet-to-coal ratio of 50%. The results are shown in Fig. 6. As can be seen, the net thermal efficiency decreases with increasing pellet-to-coal ratio due to the increase in power that accompanies the increased volume of primary air.

### 3.1.4 Effect of combustion ash

Although the ash generated by combustion of biomass fuel is approx. 1/10 or less of that for coal, ash composition differs, with biomass ash having high levels of alkaline components. Hence, it is necessary to confirm the effect of combustion ash when coal is co-fired with biomass. However,

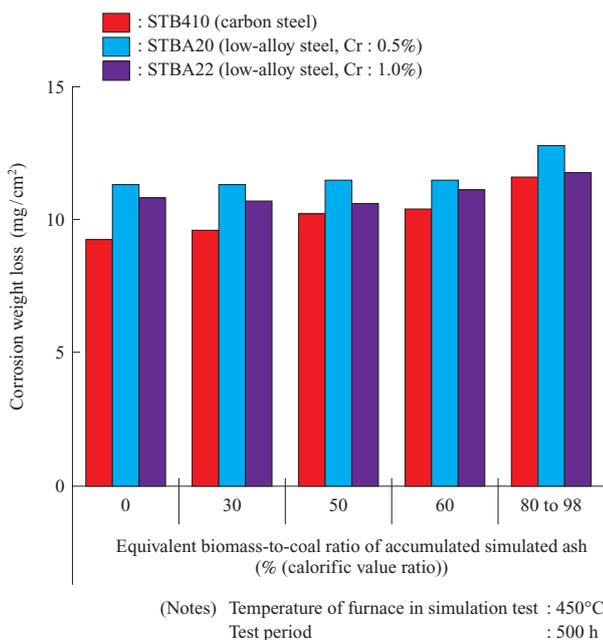


(Notes) \*1 : Higher calorific value base  
\*2 : Calorific value ratio

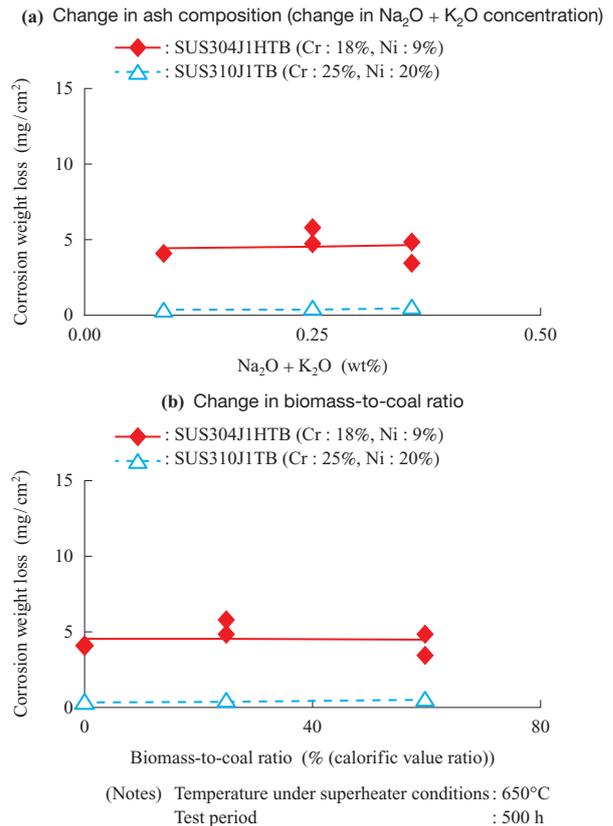
**Fig. 6** 500 MW-class pulverized coal-fired model power plant: Net thermal efficiency in biomass co-firing

demonstration tests are short term, and it is difficult to use them to evaluate long-term effects due to co-firing, such as changes in ash adhesion and corrosion of pipes. For this reason, coal and biomass were co-fired in a small-scale furnace, ash simulating the composition of this combustion ash was applied to heat conduction pipe materials, and corrosion tests were performed in which these materials were exposed to the temperature and gas atmosphere existing inside a boiler. **Figure 7** shows the results of corrosion tests for ash applied to pipe materials used in the heat conduction pipes of furnaces. The ash used had compositions which corresponded to single firing of coal, and to co-firing with biomass at different biomass-to-coal ratios up to 80–98%. As shown in the figure, different ash compositions did not result in any large difference in the amount of corrosion.

In the 150 MW demonstration tests, probes simulating heat conduction pipes were inserted into the furnace in order to get the ash accumulated on them for analysis of its characteristics. Corrosion tests were conducted using artificial ash that had been produced on the basis of the analysis results. The results indicated that co-firing of coal with biomass caused the ash generated in the area close to the superheater to have higher alkali and sulfate concentration than for single firing of coal. However, the increments in  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  concentration were equivalent to approx. 0.15 wt%, and the effect on corrosion of such a small difference in ash composition was considered to be small. **Figure 8** shows the effect of ash composition and biomass-to-coal ratio on the corrosion weight loss of stainless steel under superheater conditions. When co-firing with coal at a biomass-to-coal ratio of 25% (calorific value ratio), the area close to the furnace wall burner was in a highly reducing environment, with a large concentration of unburnt carbon in

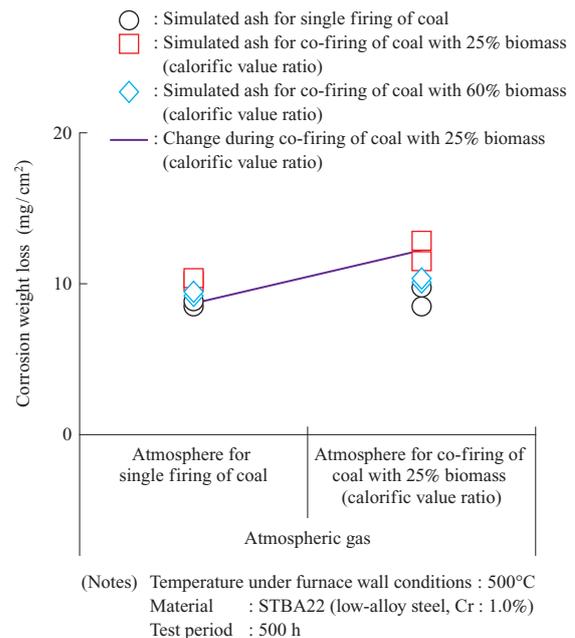


**Fig. 7** Ash deposition and corrosion tests conducted under furnace simulation conditions at 450°C for 500 hours comparison of corrosion weight loss for each alloy



**Fig. 8** Effect of ash composition and biomass co-firing ratio on corrosion of stainless steel under superheater conditions

the attached ash, and the corrosion weight loss tended to be higher than for single firing of coal. However, this increase in weight loss was small, and was not considered to be at a level that would cause problems for practical use. **Figure 9** shows the effect of atmospheric gas and ash type on the



**Fig. 9** Effect of atmospheric gas and ash type on corrosion of Cr-Mo steel under furnace wall conditions

corrosion weight loss of Cr-Mo steel under furnace wall conditions.

### 3.2 Combustion system

#### 3.2.1 Background

In current commercial pulverized coal-fired power generation plants, the upper limit of biomass-to-coal ratio for co-pulverization is approx. 5%, and, in order to co-fire with high biomass-to-coal ratios, single pulverization of biomass is required. However, when used for single pulverization of biomass, whether chips or pellets, vertical roller mills designed exclusively for pulverization of coal achieve only a capacity of 1/7 to 1/10 of that for single pulverization of coal, due to poor discharge of the pulverized biomass out of the mills. As a measure to solve this problem, a contraction flow acceleration ring was installed on a mill, as shown in Fig. 10, and demonstration tests were performed in order to determine its effectiveness. As a result, it was confirmed by 2013 that, for pellets, the pulverization capacity of the mill could be increased to a level equal to (mass ratio 100%) or greater than that for single pulverization of coal. In 2014, based on identification of the pulverization and combustion characteristics of different types of chips and pellets, additional demonstration tests were conducted using an in-house large-scale co-firing test facility with a further improved contraction flow acceleration ring, and successful co-firing of coal with biomass was achieved at a biomass-to-coal ratio of over 50%.

Based on this achievement, in 2015, additional demonstration tests were conducted for the co-firing of coal with chips and pellets in a 150 MW-class commercial plant.

#### 3.2.2 Investigation of fuel treatment system

Figure 11 shows a pellet mill with a contraction flow acceleration ring. By 2014, this had been redesigned with improvements (Fig. 11-(b)) and, for pulverization of pellets, demonstrated a pulverization capacity corresponding at maximum to a biomass-to-coal calorific ratio of 75% and mass ratio of 100% or more. Figure 12 shows the relationship between fuel supply amount and mill differential pressure for the pellet and coal mills. Stable mill operation can be evaluated according to the mill differential pressure. When pulverization cannot keep up with the supply rate of the

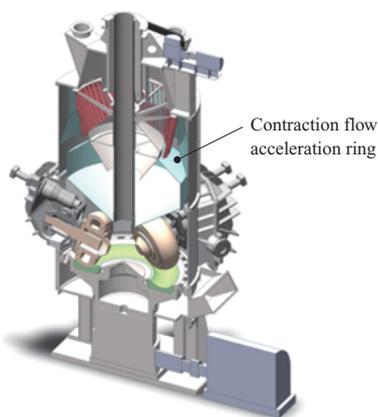


Fig. 10 Schematic drawing of a mill equipped with a contraction flow acceleration ring

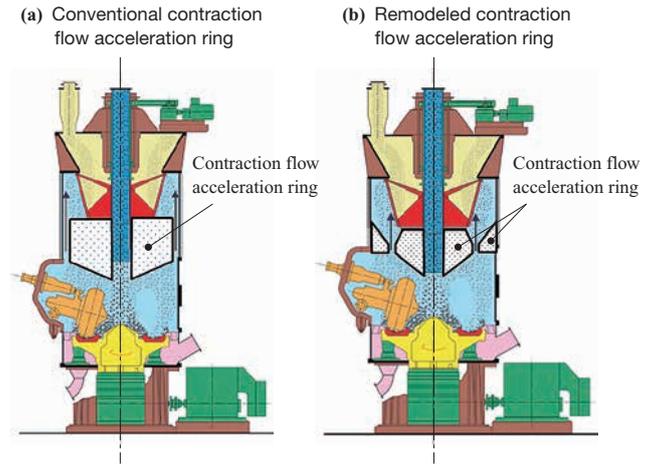


Fig. 11 Wood pellet mill equipped with a contraction flow acceleration ring

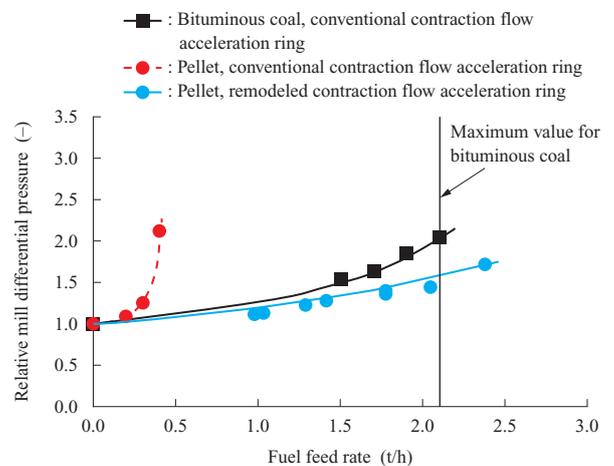


Fig. 12 Relationship between fuel (pellet or coal) supply and mill differential pressure in wood pellet mill or coal mill

biomass, more and more non-pulverized and partially pulverized biomass circulates inside the mill, and the mill differential pressure continually rises.

Demonstration tests were conducted in order to investigate the following six items. In the course of these tests, consideration was given to minimizing the extent of modification of existing pulverized coal-fired boilers, and to the situation in Japan regarding biomass supply (chips account for a large portion). The corresponding results are also described below.

#### (1) Co-pulverization of coal with fine-grained chips

For the method in which coal and biomass are pulverized in the same coal mill (co-pulverization), it was confirmed that stable co-pulverization of coal with fine-grained chips (of diameter less than 5 mm and moisture approx. 30%) could be achieved at a maximum biomass-to-coal mass ratio of 15% and calorific value ratio of 6.5%.

As a result, the same biomass-to-coal ratio of 15% (mass ratio) was achieved as in the in-house tests.

Figure 13 shows the results for co-pulverization of coal with fine-grained chips. It was also confirmed that mill

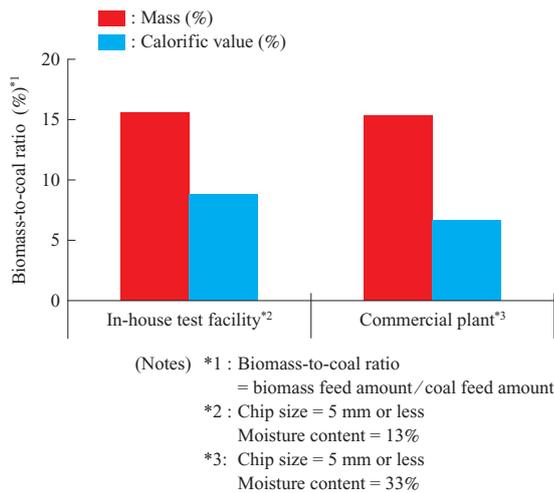


Fig. 13 Results of co-pulverization tests using coal and fine-grained chips

differential pressure tended to increase with increasing biomass-to-coal ratio.

(2) Single pulverization of fine-grained chips

In order to achieve a high biomass-to-coal ratio with fine-grained chips, demonstration tests were conducted to confirm whether fine-grained chips (of size 5 mm or less and moisture 10%) could be singly pulverized in a coal mill.

As a result, it was confirmed that fine-grained chips could be singly pulverized at a rate corresponding to a biomass-to-coal ratio of 8% with respect to the designed heat input of the furnace. Figure 14 shows the relative mill differential pressure when dry fine-grained chips were pulverized. As with the in-house demonstration tests, relative differential pressure, which represents the stability of mill operation, increased as the supply of dry fine-grained chips increased. Figure 15 shows the percentage of pulverized dry fine-grained chips passing through a 1 mm sieve. As can be seen from the figure, this percentage shows a downward trend as the supply of dry fine-grained chips increases. When the supply

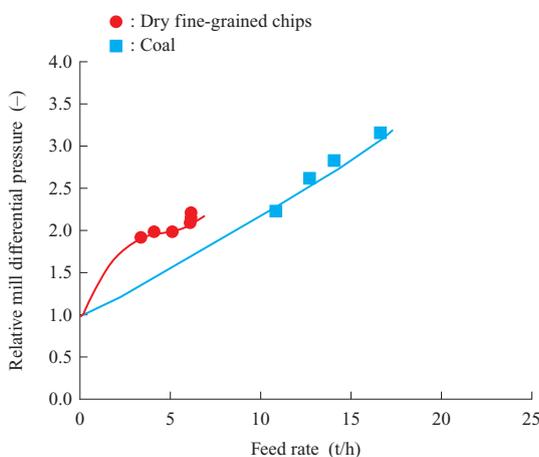


Fig. 14 Relative mill differential pressure in single pulverization of dry fine-grained chips (actual power plant)

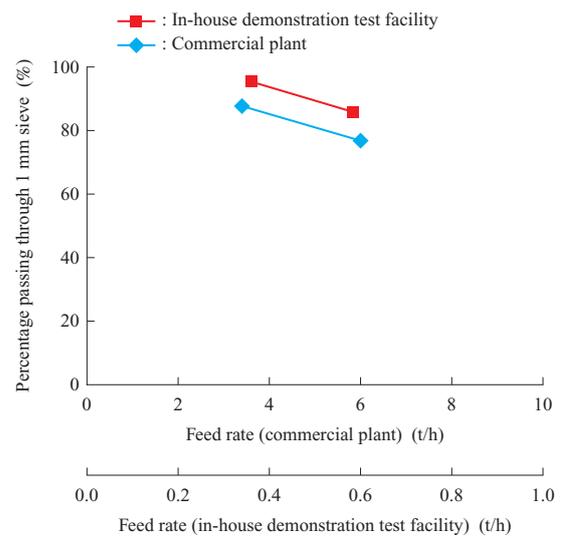


Fig. 15 Passing ratios for pulverized product of dry fine-grained chips passed through a 1-mm sieve

was the same, the relative mill differential pressure when pulverizing dry fine-grained chips was higher than when pulverizing coal, and the processing capacity of the mill was lower for dry fine-grained chips than for coal. Single pulverization enabled higher processing capacity of the mill for fine-grained chips (biomass-to-coal ratio) than co-pulverization with coal, and the diameters of the pulverized chips were suitable for combustion. However, it should be noted that the heat input (load) of the dry fine-grained chips pulverized under these conditions was too small with respect to the capacity of the coal firing burner, and so co-firing could not be maintained without supplemental firing. This is an issue that needs to be considered.

(3) Single pulverization of pellets

In order to achieve a high biomass-to-coal ratio with pellets, in-house demonstration tests were conducted to investigate the single pulverization of pellets using a coal mill into which a remodeled contraction flow acceleration ring, shown in Fig. 11-(b), had been installed.

As a result, it was confirmed that pellets could be singly pulverized at a stable rate corresponding to a biomass-to-coal ratio of 25% with respect to the designed heat quantity of the furnace. Figure 16 shows the relative mill differential pressure when pellets were pulverized. As with the in-house demonstration tests, the relative differential pressure, which represents the stability of mill operation, increased as the supply of pellets increased. Figure 17 shows the percentage of pulverized pellets passing through a 1 mm sieve. As can be seen from the figure, this percentage shows a downward trend as the supply of pellets increases. When the supply was the same, the relative mill differential pressure was slightly lower when pulverizing pellets than when pulverizing coal, and so the contraction flow acceleration ring improved the

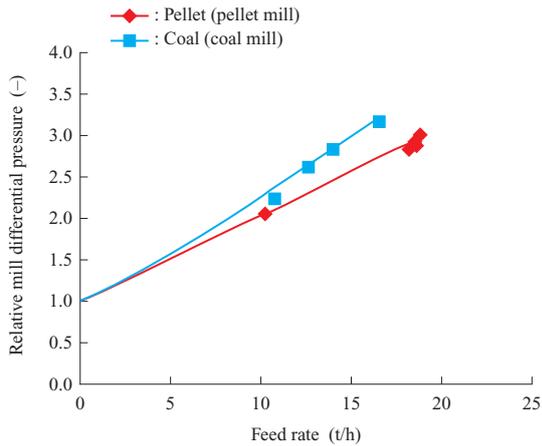


Fig. 16 Relative mill differential pressure in single pulverization of wood pellets (actual power plant)

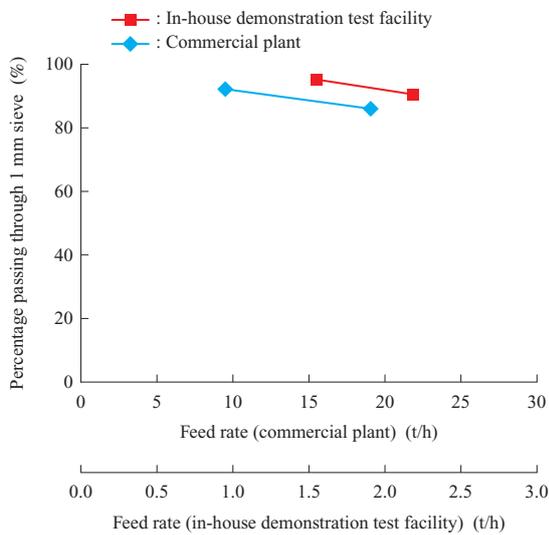


Fig. 17 Passing ratios for pulverized product of wood pellets passed through a 1-mm sieve

processing capacity of the mill.

(4) Burner system

Figure 18 shows the flames produced during co-firing of coal with pellets in the in-house demonstration tests (performed using a commercial scale plant). In these tests, it was confirmed that stable co-firing could be achieved with existing coal burners. The flame from the pulverized pellets was slightly darker than that from coal.

(5) Co-firing at a biomass-to-coal ratio of over 50%

In order to understand the heat absorption of a furnace during co-firing of coal with pellets at a biomass-to-coal ratio of over 50%, demonstration tests were conducted using a multi-burner type combustion test furnace. Figure 19 shows a simplified block diagram of a large-scale multi-burner type combustion test furnace. In this furnace, coal was pulverized beforehand in the coal mill and stored in a pulverized coal bin. The mill was then remodeled so as to be suitable for pulverizing pellets. The pellets were

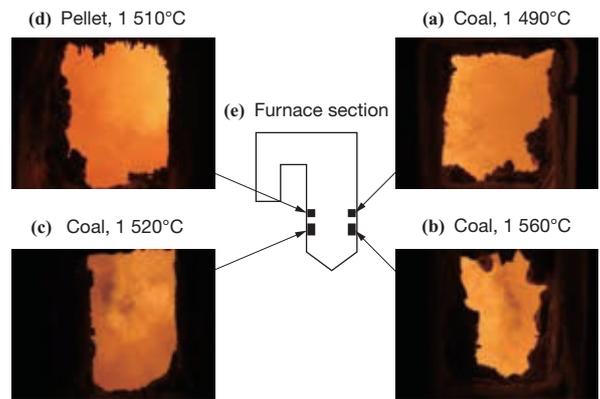


Fig. 18 Condition of flame in co-firing tests with wood pellets (actual power plant)

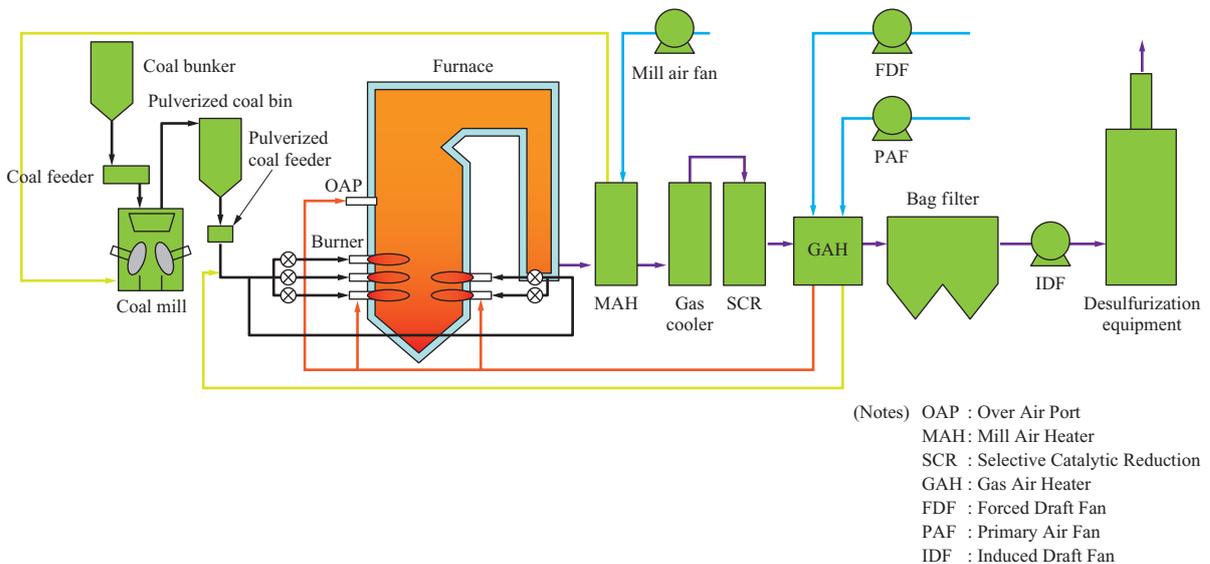


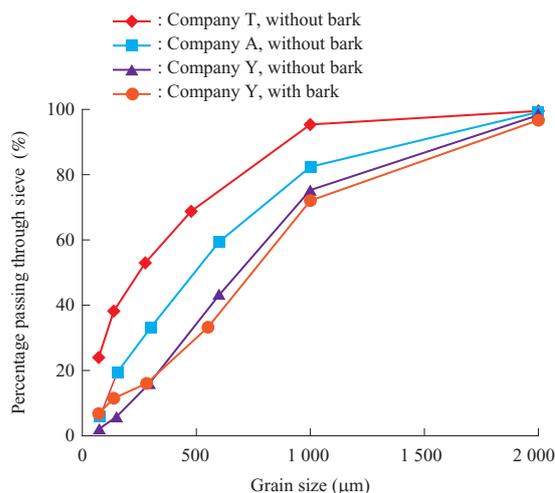
Fig. 19 Simplified block diagram of a large-scale multi-burner combustion test furnace

pulverized and fed into three-stage burners, and the pulverized coal was fed from the pulverized coal bin into two-stage burners. With respect to an equivalent coal combustion capacity of 2.0 t/h, the pellets were co-fired in the furnace at a biomass-to-coal calorific ratio of over 50%.

**Figure 20** shows the emission gas properties and unburnt content in the ash that were obtained in the co-firing tests using a large-scale combustion test furnace. Because the pellets have low S, N and ash content, the  $\text{NO}_x$ ,  $\text{SO}_2$ , CO, and soot concentrations in emissions during co-firing were reduced. The unburnt content in the ash for co-firing of coal with pellets was almost the same as that for single firing of coal, with co-firing at high biomass-to-coal ratios having no effect on ash content. The heat absorption of the furnace was higher for co-firing of coal with pellets than for single firing of coal. This is because the large amounts of volatile content produced from the pellets facilitated the spreading of flames and thereby equalized heat absorption inside the furnace, and because the heat absorption of the furnace as a whole was greater for co-firing of coal with pellets than for single firing of coal.

(6) Confirmation of the effect of biomass fuels

From investigation of the pulverization properties of different types of pellets, it was determined that the grain size distribution of pulverized biomass varies depending on pellet manufacturer and whether pellets contained bark or not. Out of concern regarding the effect this might have on combustion properties, element tests for the single pulverization and combustion of different types of pellets produced in Japan were conducted. The results demonstrated afresh that the grain size distribution of pulverized pellets varied depending on pellet type. **Figure 21** shows the grain size distribution of pulverized pellets (supplied at

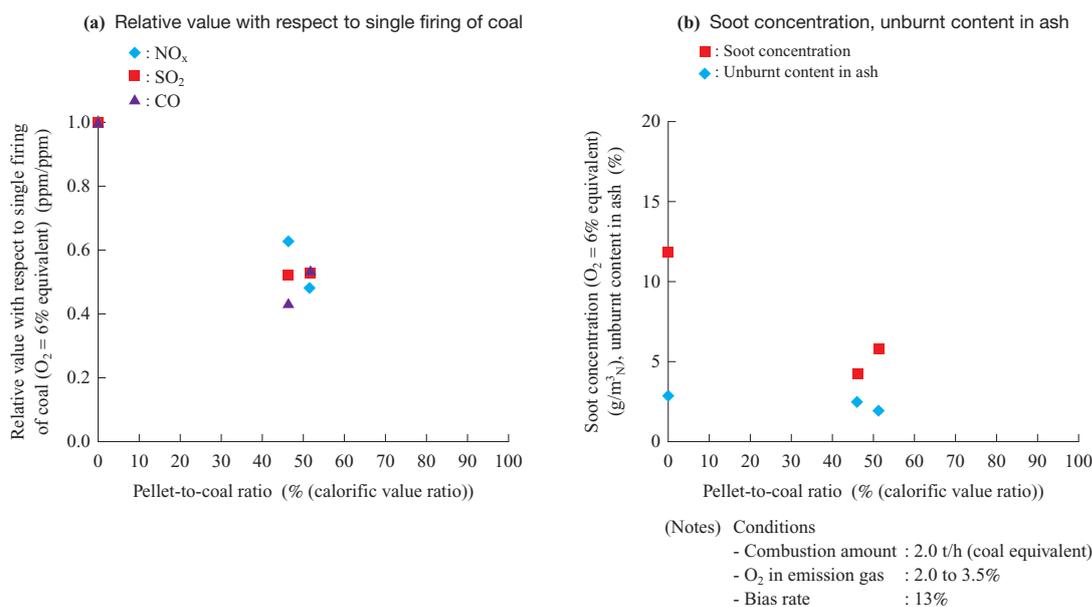


**Fig. 21** Particle size distribution of pulverized wood pellets (Supply amount : 1.5 t/h)

a rate of 1.5 t/h). In the combustion tests, it was confirmed that single firing of pulverized pellets could be performed using coal firing burners regardless of pellet type. **Figure 22** shows the state of the burner flame (in the combustion test furnace) during pellet combustion. From these findings, it is considered that single firing of pulverized pellets can be performed if the grain size distribution is within the range examined in these tests.

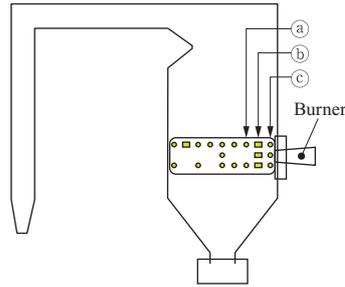
**3.3 Fuel supply system**

A series of tests and investigations emphasizing actual demonstration were conducted in order to deal with the issues previously identified in **Chapter 2**: (1) difficulty guaranteeing high-volume, stable, continuous demand for biomass fuels; (2) difficulty achieving economically feasible biomass fuel production costs; and (3) disturbance of the market by cheaply imported or illegally logged timber.

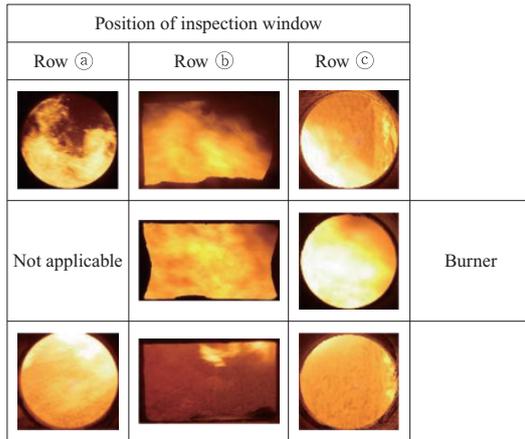


**Fig. 20** Emission gas properties and unburnt content of ash obtained in co-firing in large-scale combustion test furnace

(a) Positions of inspection windows on furnace wall of test plant (left wall)



(b) Company T : burner flame  
(cedar grown and processed in Japan without bark)



(c) Company Y : burner flame  
(cedar grown and processed in Japan without bark)

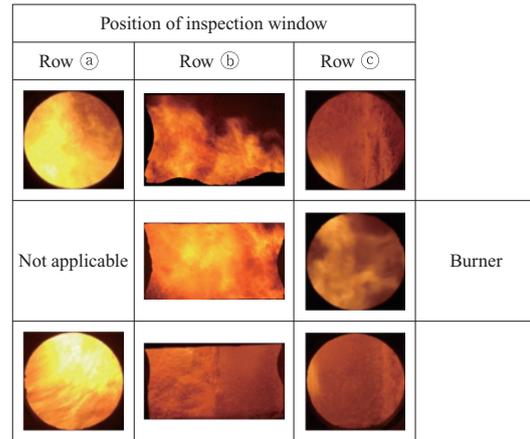


Fig. 22 Photos of burner flame in co-firing of wood pellets (Coal combustion test facility)

### 3.3.1 Biomass processing and transportation systems

Focusing on pellet fuels, possible requirement specifications for biomass fuels were examined, taking into consideration conditions on the usage and manufacturing sides, energy efficiency, etc. As part of this process, actual biomass fuels were experimentally manufactured using different manufacturing processes, and the energy consumption (MJ/t) for each was measured and compared. **Figure 23** shows a comparison of the energy consumption during pellet manufacture. The pellets in Case 1 were manufactured from

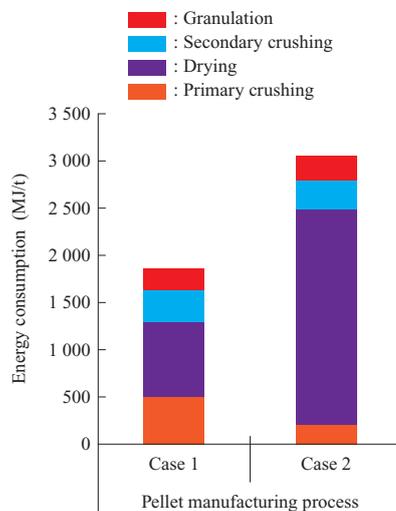


Fig. 23 Comparison of energy consumption in pellet manufacture

pre-dried raw materials, and those in Case 2 from fresh timber. As can be seen from the figure, the selection of manufacturing process can make a large difference to the energy consumption during pellet manufacture.

Based on these results, measures were examined to effectively reduce energy consumption associated with the processing and transportation of biomass fuels. Focusing on the moisture content of the raw timber material as the most important factor affecting energy consumption, the energy required for each relevant process was measured and compared, from collection of fresh timber materials (with high moisture content) through to manufacturing of the pellets. **Figure 24** shows a comparison of the energy consumed during pellet manufacture. Based on the above, the effect of moisture content reduction on the energy efficiency of co-firing was expressed as a fuel material flow (shown in **Fig. 25**). Together with the energy consumed when transporting biomass (described below), this was used for evaluation of the biomass processing and transportation system.

### 3.3.2 Biomass collection and transportation system

Procurement, processing and transportation methods (including collection from a wide area) were examined that are compatible with the forms of biomass fuels investigated in the previous section. Here too, focus was placed on the drying process (natural and artificial drying, etc.), and, based on energy consumption actually measured in the past, investigation was performed of collection and transportation

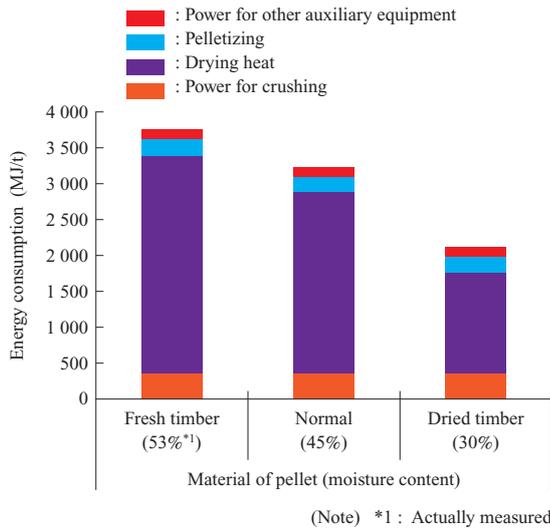


Fig. 24 Comparison of energy consumption in wood pellet manufacture

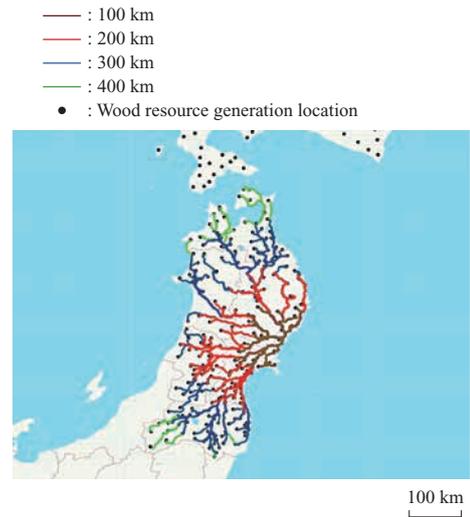


Fig. 26 Analysis of fuel collection range

systems that are capable of reducing energy consumption. Together with the results from the previous section, numerical simulation predicts that drying the raw timber naturally to a certain extent enables timber resources within a few hundred kilometers of a power generation plant to be utilized while limiting biomass fuel energy loss to not more than 20%. Figure 26 illustrates the analysis results for the biomass fuel collection range.

In order to confirm these analysis results and acquire verification data, long-distance biomass transportation tests were conducted that assumed extensive biomass resource collection. This utilized actual transportation of approx. 800 km from the manufacturer of the biomass fuel for the element tests (in Fukushima Prefecture) to the test plant (in Hyogo Prefecture). Direct transportation by truck and transportation by truck and rail freight (container freight) were both carried

out between the same shipping location and destination, and a comparison of energy consumption confirmed that the method using rail freight was more energy efficient. Figure 27 shows a comparison of energy consumption during pellet transportation.

However, by actually performing mass transportation of biomass, the practical constraints and problems for each means of transportation became clear. In particular, although energy efficient, rail freight is subject to constraints which do not apply to truck transportation, such as the following: ① the number of rail freight terminals is limited; ② the number of rail freight container connections is limited; and ③ the loading capacity of rail freight containers is small due to their physical constraints. In addition, tests were performed in which biomass fuel was loaded into specially shaped containers, in an attempt to enhance biomass fuel transportation efficiency.

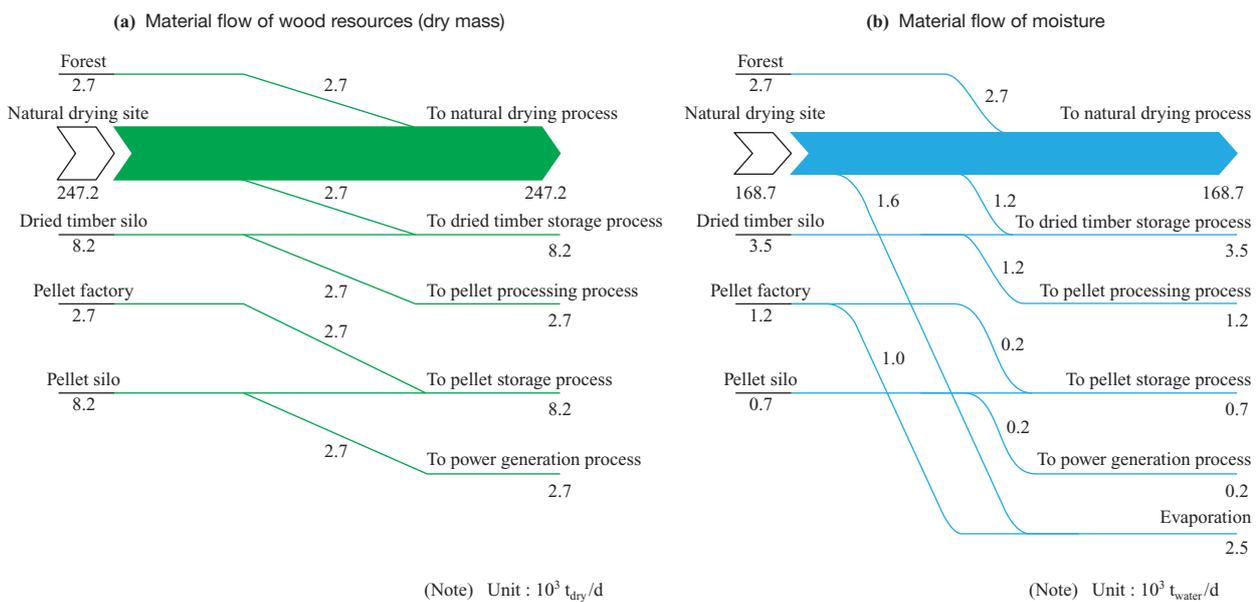
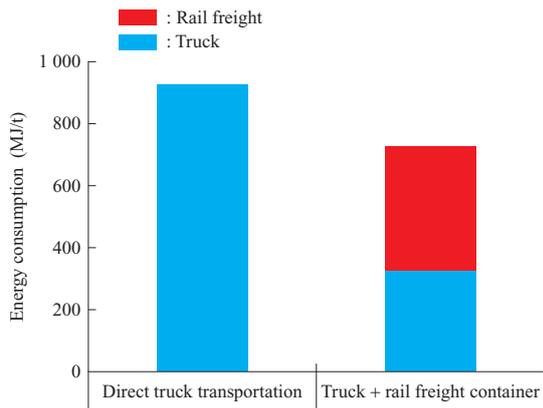


Fig. 25 Fuel material flow



**Fig. 27** Comparison of energy consumption in wood pellet transportation

Based on the above elemental test results, a logistics network was investigated as a supply chain comprising of multiple processes, from raw material collection in forests through to use of the biomass fuel in power generation. **Figure 28** shows the biomass fuel supply chain. It was estimated that, if the moisture content was reduced to approx. 30% (wet weight standard), then mass transportation of biomass fuel to a power plant could be achieved with an energy consumption of 20% or less of the energy that the fuel generates. In order to verify this conclusion, transportation tests were conducted involving transportation of a total of approx. 800 tons of biomass fuel.

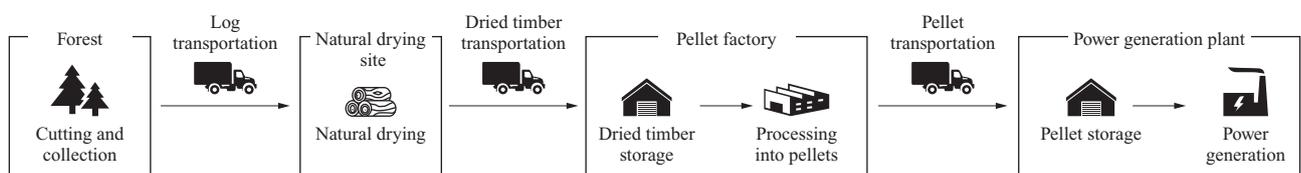
### 3.3.3 Sustainable biomass supply system

Forest soil plays an important role in the growth of trees, i.e., the sustainable supply of biomass, and, from the viewpoint of preventing global warming, it is important to know whether deforestation affects not only the trees themselves but also the behavior of the organic matter that exists in forest soil in large quantities. In this project, focus was placed on forest soil — which has barely been mentioned in the past despite being extremely important to maintaining a sustainable supply of biomass — and an unprecedented

wide-area evaluation was attempted of the effect of deforestation activities, such as clear cutting, thinning, and carry-out, on forests and their soil. This evaluation focused on measurement of the trace amounts of greenhouse gases ( $\text{CO}_2$  and  $\text{CH}_4$ ) emitted from soil. In addition to the generally-used chamber method, a wide area  $\text{CO}_2$  monitoring method utilizing an infrared laser was also evaluated in order to assess its applicability to the extensive measurement of gases in forest areas. In 2013, tests were conducted on the campus of the Faculty of Horticulture, Chiba University (**Fig. 29**) to evaluate the performance of multiple measuring methods, and, in the last year of the project (2015), measurement was actually performed in forests based on the results of these element tests. **Figure 30** shows  $\text{CO}_2$  laser monitoring tests being conducted in the forest. Although the accuracy of the wide area  $\text{CO}_2$  laser monitoring was still low, it was confirmed that measurement in the field could be performed using trees in the forest as reflectors, and demonstrated that two-dimensional density maps could be created using the data obtained.

In addition, in order to evaluate the effects of thinning on forest soil, a continuous soil survey was conducted for approx. one year in an area in which two row line thinning had been performed. **Figure 31** shows the site of the line thinning, and the stand-alone meteorological observation equipment used for measurement. Since there are still few cases of such measurement, the long-term effects of logging on forest soil are still not altogether clear. However, according to the results so far, the effects of logging are believed to be relatively minor, since the increase in sunlight promotes the development of undergrowth. **Figure 32** shows the analysis results for absorption and desorption of greenhouse gases by forest soil after logging.

Solar-powered stand-alone meteorological observation equipment (POTEKA Sta. 2), developed by MEISEI ELECTRIC CO., LTD., was also installed at the measurement site, and used to collect meteorological data in the forest.



**Fig. 28** Supply chain for wood fuel

(a)  $\text{CO}_2$  laser monitoring tests



(b) Measuring gas emission from soil



**Fig. 29**  $\text{CO}_2$  monitoring field tests (at Faculty of Horticulture campus, Chiba University)



Fig. 30 CO<sub>2</sub> laser monitoring tests in forest

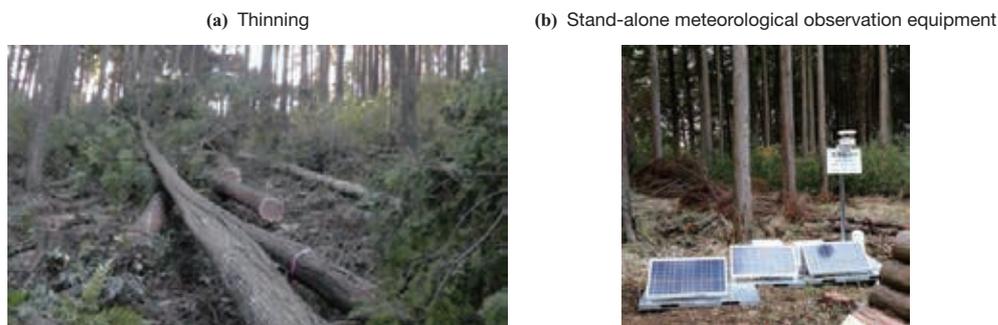


Fig. 31 Line thinning at forest site and installation of stand-alone meteorological observation equipment in Kimitsu, Chiba

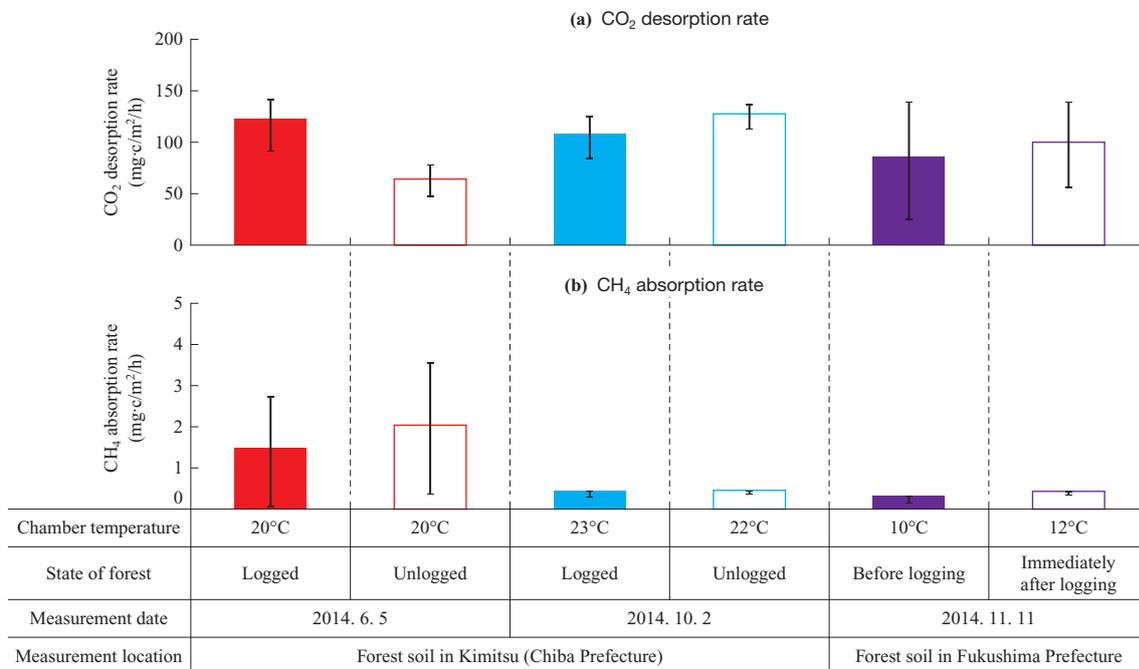


Fig. 32 Results of soil analysis in the logging field

### 3.3.4 Verification of biomass fuel traceability methods

For the purpose of clearly indicating the origins of the raw materials used for manufacturing biomass fuels, methods were investigated that allow easy and reliable identification

of biomass raw material production areas, names of loggers and other information during the downstream distribution and consumption processes. First, the application of IC tags (passive tags) — which allow electromagnetic reading of

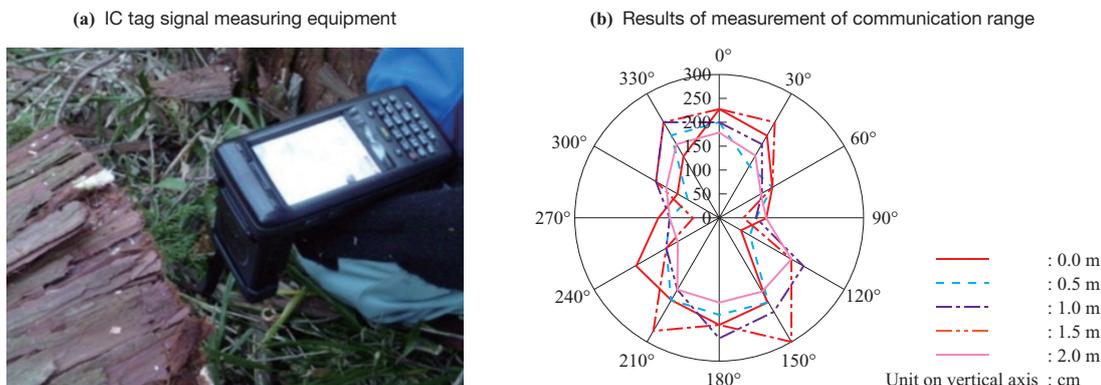
information without contact — was investigated. Several commercially available IC tags were selected as candidates, these were used in element and field tests simulating the conditions during carry-out, collection, and processing. Through the tests, the performance, durability and effectiveness of the tags were determined. **Figure 33** shows IC tag signal measurement tests, and the results of measurement of the communication range. From the series of test results obtained, it was determined that the operability and characteristics of commercially available IC tags were not suitable for use in moist environments, such as in forests or with timber.

For this reason, data reading tests assuming usage under the same carry-out, collection, and processing conditions were conducted using bar codes (one dimensional) and two-dimensional codes, which are very convenient and low in cost. The results confirmed that their operability and characteristics were suitable for use in the relevant environments. **Figure 34** shows an evaluation of the usability of two-dimensional codes.

Based on the above results, investigation was also conducted of a system configuration for data communication over a wider area. In particular, timber traceability tests using two-dimensional codes were conducted through the construction of a system comprising only of commercially available equipment. Persons engaging in the forestry industry participated in the tests. By reading information in the field using smartphones, it was confirmed that the system functioned effectively. **Figure 35** shows implementation of the traceability tests using two-dimensional codes. Some of these methods were also applied to biomass supply demonstration tests, and it was confirmed that they operated without problems.

### 3.3.5 Biomass supply demonstration tests

**Figure 36** shows leaf drying tests (drying of felled trees whose branches and leaves have not been removed) performed in the forest, and field log drying tests. These were conducted in order to collect basic data in preparation for large-quantity biomass supply tests (involving logging, transfer, drying and intermediary processing of timber). The



**Fig. 33** Measurement results of IC tag measurement tests and communication range

(a) Evaluation of usability

Dirt tests	Scanned image (two-dimensional code)			
	Cause of damage	Abrasion	Dirt	Smear
	Evaluation result	OK	OK	OK
Damage tests (bending)	Scanned image (two-dimensional code)			
	Cause of damage	Bending	Folding	Irregularities
	Evaluation result	OK	NG	NG
Damage tests (tearing)	Scanned image (two-dimensional code)			
	Cause of damage	Tear 1	Tear 2	Tear 3
	Evaluation result	OK	OK	OK

(Note) Size of two-dimensional code : 5 × 5 cm

- (b) Selected code reader
- Compatible code types : one-dimensional and two-dimensional codes
  - Readable distance : up to 15 m



(c) Attached code labels



**Fig. 34** Applicability assessment for two-dimensional codes

(a) Reading of code label with commercial smartphone



(b) Data management system configuration

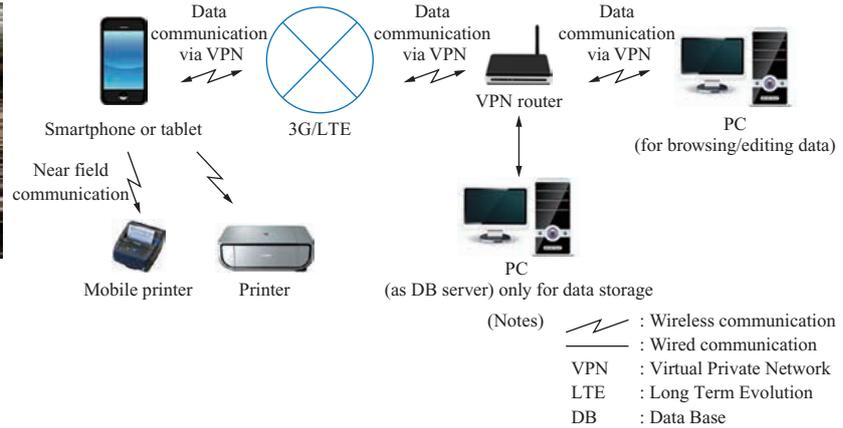


Fig. 35 Traceability system tests using two-dimensional codes

(a) Leaf drying tests (drying of felled trees with branches and leaves not removed)



(b) Field log drying tests



Fig. 36 Logging tests and drying tests

leaf drying (naturally drying) tests (Fig. 36-(a)) were conducted in the forest in Kimitsu City, Chiba Prefecture (refer to Fig. 31) and the field log drying tests on the campus of Chiba University (Fig. 36-(b)). These tests were conducted concurrently with measurement by the above-mentioned stand-alone meteorological observation equipment, which was used to acquire data on long-term changes in moisture content, and to identify factors influencing timber drying and evaluate their effects.

The results confirmed that, even for raw material in the form of logs, moisture content decreased to 40% or less, which is the standard value set in the plan, after a drying period of around several months to half a year. Figure 37 shows the results of the field drying tests on felled timber.

In addition, logging and collection work using forestry machines — including the laying of logging roads — was performed in the national forest in Fukushima Prefecture (Fig. 38), and the energy consumed by this work was measured. Furthermore, problems that were expected to occur during large-quantity timber collection were identified and evaluated. Logging tests involving a combined total of approx. 3 000 m<sup>3</sup> of timber were conducted in Chiba and Fukushima Prefectures, with the timber being naturally dried, collected, transported, processed into biomass fuel, and transported again. Figure 39 shows the test logging site and biomass fuel delivery. The fuel was manufactured at three factories, with data at the time of manufacture being

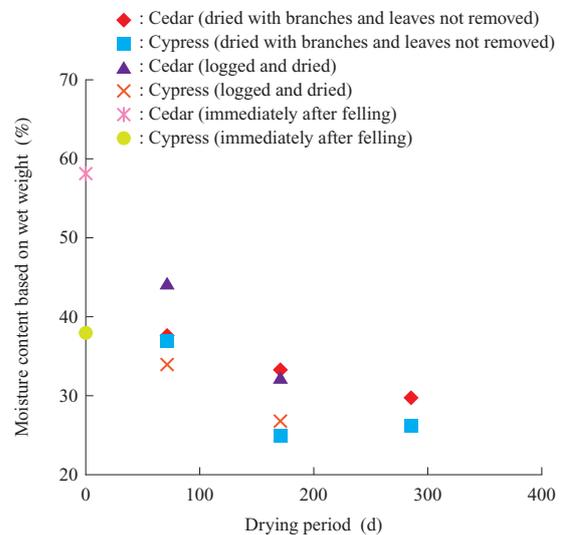


Fig. 37 Results of field drying tests for logged wood

measured, and part of it was transported to a power plant.

This series of tests was conducted over a period of around half a year, encompassed a wide range of activities, from logging through to drying and processing, involved the cooperation of many organizations and concerned persons, and resulted in the successful demonstration of large-quantity supply of biomass fuel produced in Japan. However, it also became clear that there are currently many issues



Fig. 38 Logging tests

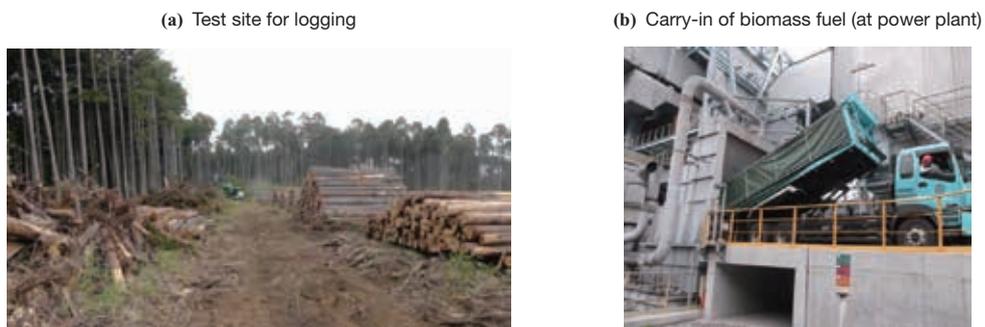


Fig. 39 Logging test site and fuel carry-in

relating to collection, distribution, and various other processes.

## 4. Summary of results

### 4.1 Biomass co-firing boiler system

Examination was first performed of each system in a pulverized coal-fired power generation plant, such as pretreatment, storage, feeding, and auxiliary equipment. In the demonstration tests that were conducted on the basis of that evaluation, safe, stable co-firing was successfully performed using dry fine-grained chips and pellets through problem-free operation of indoor storage, truck transportation and conveyor feeding (including temporary equipment).

As previously expected, boiler performance and environmental data showed an improvement in  $\text{NO}_x$  and  $\text{SO}_x$  concentrations, which are relevant to environmental standards, with a slight reduction in boiler efficiency (within 0.5%) due to the presence of biomass.

With regard to heat transfer inhibition and corrosion due to the accumulation of ash on the boiler heat conduction pipes, ash composition was determined by taking samples of accumulated ash from the furnace and from the area near the superheater. Corrosion tests were then conducted using

simulated ash that had been artificially produced on the basis of the above compositional analysis. The results indicated that, although not problematic in the short term, co-firing of coal with biomass fuel should be expected to slightly increase the amount of corrosion compared to single firing of coal, due to the increased biomass-to-coal ratio in the reducing atmosphere of the burner zone.

### 4.2 Biomass co-firing combustion system

A pellet mill mounted with a contraction flow acceleration ring was developed with the aim of achieving pulverization of pellets corresponding to a ratio of 75% with respect to coal (calorific value ratio). It was then confirmed in demonstration and commercial scale plants that pulverized pellets of equal quantity to that of pulverized coal could be supplied. These plants were also used to demonstrate that existing pulverized coal burners could be used as biomass burners. In addition, successful co-firing of coal with biomass fuel in a furnace at a biomass-to-coal ratio of 50% (calorific value ratio) was confirmed in a test plant with a heat input of 20 MW·t/h.

Through the above tests, it was confirmed that co-firing did not have a significant effect on emission gases or heat absorption, and that no problems occurred in the boiler.

### 4.3 Biomass fuel supply system

Several demonstration tests were conducted regarding the issues of utilization, processing, collection, transportation, sustainable supply, and traceability of biomass. The results of these tests demonstrated that biomass resources in Japan have the potential to meet the demand created by co-firing of coal with biomass at a biomass-to-coal ratio of 50% in pulverized coal-fired power generation plants of capacity 500 MW.

Satisfying conditions such as keeping the moisture content of the raw material to 30% or less based on wet weight makes it possible to keep the consumption of the entire system to 20% or less of the energy of the biomass.

In terms of both abundance and growth increment per unit area, available biomass resources in Japan are at a higher level than in Europe and the United States, and the available transportation networks for biomass distribution are not necessarily of a low standard. Therefore, through planned operation of efficient forestry machinery, it is believed that sustainable logging can be achieved while minimizing damage to forests.

## 5. Future issues regarding widespread adoption

The demonstration tests not only yielded a large amount of information but also identified the following future issues.

### 5.1 Biomass co-firing boiler system

- (1) There are still many points that are unclear regarding the long-term effect of biomass ash on boilers during co-firing at high biomass-to-coal ratios. Therefore, it is necessary to establish a system that will allow pulverized coal-fired power generation plants around the country to collect and share information on this issue.
- (2) When large quantities of biomass are used, there are concerns regarding dust and heat generation during storage and transportation, and wear during long-term use. It is therefore necessary to investigate and develop peripheral equipment and safety systems to deal with these issues.

### 5.2 Combustion system

- (1) In the future, it is anticipated that various processing methods other than pellet production will be used, and that biomass fuels made from different raw materials will be supplied. It will therefore be necessary to systematically and empirically study these new types of biomass fuels from the perspective of combustion and pulverization properties.
- (2) In order to deal with the above, it will be necessary to develop pulverization mechanisms that are more efficient and have larger capacity than current mills.

### 5.3 Fuel supply system

- (1) In order to use biomass resources in Japan effectively and efficiently, it is necessary to link the following as an integrated market: ① logging and transportation of timber; ② storage and drying of biomass; ③ manufacture and storage of pellets;

④ distribution of biomass; and ⑤ demand for biomass fuel at power generation plants.

- (2) Establishment of such a fuel supply system requires the introduction of advanced technologies such as ICT.
- (3) In many respects, the currently available information on forest resources in Japan is not sufficient for operation of the above system. Even from the perspective of ensuring a sustainable balance between utilization and preservation of natural land, it is necessary to perform comprehensive and accurate surveys utilizing ICT, such as remote sensing, in order to acquire a thorough understanding of the current situation.

## 6. Conclusion

With the cooperation of all concerned, co-firing of coal with biomass at high biomass-to-coal ratio in a commercial power generation plant — which had previously been an unexplored area of endeavor in Japan — was successfully verified through establishment of a total system that utilizes biomass resources in Japan, from logging of timber through to delivery of biomass fuels to the plant. It is anticipated that this outcome will contribute to the widespread adoption of biomass co-firing, which represents a promising measure against global warming in the field of coal-fired power generation.

This research resulted in winning the METI Minister's Award in the New Energy Award 2016 from the New Energy Foundation jointly with Nippon Steel as an advanced initiative expected to significantly reduce CO<sub>2</sub> emissions and expand the adoption of forest biomass through biomass utilization in existing pulverized coal-fired power generation plants.

### — Acknowledgments —

This research could not have been implemented without the cooperation and advice of the many persons concerned. We would like to express special appreciation to the personnel at the Kamaishi Works of Nippon Steel and the National Federation of Forest Owners' Co-operative Association for their extensive and generous cooperation.

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