Experimental investigations on spontaneous combustion of pulverized coal in the oxyfuel combustion system

Takashi KIGA*, Mizuki NISHIMURA*, Akihiro KOMAKI* and Wonyoung CHOI*

* IHI Corporation
3-1-1, Toyosu, Koto-ku, Tokyo 1358710, Japan
E-mail: kiga5249@ihi-g.com

Abstract
CCS (Carbon Dioxide Capture and Storage) is one of the technologies able to adequately displace CO\textsubscript{2} from fossil fuel fired power plants and the only technology capable of reducing large-scale emissions. In particular, coal emits a lot of CO\textsubscript{2}, although it is an important energy resource in terms of energy security. To address this situation, IHI had developed oxyfuel combustion technology to capture CO\textsubscript{2} from coal-fired power plants, and the demonstration using a 30MWe unit in Australia was successfully carried out. In order to commercialize the technology widely, how to configure the primary gas system is one of the important examination items. When adding oxygen into the primary gas system, depending on the type of mill, pulverized coal deposited in the mill may ignite spontaneously. To investigate the spontaneous combustion characteristics of the deposited pulverized coal under oxyfuel conditions, therefore, laboratory-scale experiments were carried out. A pulverized coal was deposited in a 100mm cubic mesh box, and it was installed in a thermostatic chamber. Then the mixed gas of N\textsubscript{2}/O\textsubscript{2} or CO\textsubscript{2}/O\textsubscript{2} was introduced into the chamber, and the temperature in the coal sample was measured. From the results, there was little temperature difference at which spontaneous combustion occurred between N\textsubscript{2}/O\textsubscript{2} and CO\textsubscript{2}/O\textsubscript{2} atmosphere, but there was a tendency that it might be relatively hard to occur under CO\textsubscript{2}/O\textsubscript{2} atmosphere. The results also showed a tendency that the influence of temperature was stronger than the oxygen concentration.

Keywords: Oxyfuel, Coal, Coal fired power plant, Carbon dioxide capture and storage (CCS), CO\textsubscript{2}, Spontaneous combustion

1. Introduction
According to a report released by the IEA (2019), energy demand in 2018 increased by 2.3% over the previous year. This is about twice the average growth rate after 2010. The power sector accounted for more than half of the increase in energy demand. Looking at the supply sector for such increased demand for electricity, renewable energy such as solar and wind power increased by 4% from the same period of the previous year, accounting for almost a quarter of the increase in global energy demand. However, oil and coal increased by 1.3% and 0.7%, respectively, leading to an increase in CO\textsubscript{2} emissions. Natural gas, which is shifting from coal, recorded a high growth rate of 4.6%. The background to the increase in energy demand is that the global economy has expanded 3.7% in 2018, and demand for fossil fuels such as coal has increased, especially in emerging Asian countries. Besides China, Europe and the United States are also increasing their renewable energy ratio, but it is said that the growth rate of renewable energy has not kept pace with the growth of global power demand, and the IEA calls for further spread of renewable energy and improvement of energy efficiency. On the other hand, coal-fired power plants are expected to continue to be used from now on, especially in emerging countries, from the viewpoints of responding to unstable renewable energy, fuel prices and energy security. So, the establishment of the technology to reduce CO\textsubscript{2} emissions is urgently needed.

There is CCS (Carbon Dioxide Capture and Storage) as a method of operating a coal-fired power plant while significantly reducing CO\textsubscript{2} emissions by capturing CO\textsubscript{2} emitted from thermal power plants and storing CO\textsubscript{2} deep underground. IHI has developed oxyfuel combustion method and chemical absorption method as CO\textsubscript{2} capture
technology. Both methods can be applied to a conventional power plant consisting of boiler, steam turbine and generator regardless of whether it is a new one or an existing one. The process is schematically shown in Fig. 1. Oxyfuel combustion was demonstrated for 3 years at No.4 unit of the Callide A power station in Australia, which is a pulverized coal-fired power station. It was successfully completed the consistent demonstration from capturing CO₂ to injecting underground (Callide Oxyfuel Project - Final Results, 2018).

![Fig. 1 Schematic process of IHI’s CO₂ capture technologies](image)

After the completion of the demonstration operation, in order to further improve the technology and expand the scope of application, we have carried out some additional combustion tests and lab-scale tests at facilities in IHI’s Aioi works (Nishimura, et al., 2018). One of very important difference is the type of mill installed to grind coal into small particles which will be pneumatically conveyed to burners. Beater mills were installed for pulverizing coal in the demonstration plant, while a typical pulverized coal-fired power plant is equipped with vertical roller mills. A beater mill is used generally for high moisture but flammable brown coal and is characterized by impact grinding and drying with high temperature gas. The residence time in the mill is short and there is principally no place where pulverized coal is prominently deposited. The particle size of the pulverized coal produced is relatively coarse. On the other hand, in a vertical roller mill, coal is drawn in between the rollers and grinding table, and a classifier is usually installed inside the mill. Although fine pulverized coal can be obtained with lower power, its internal structure is more complicated and there is a stagnant part, where some pulverized coal deposits may occur, in the mill.

The presence of pulverized coal in the mill is usually the largest contributor to mill fires. That is a spontaneous combustion which occurs over a period of time, begins to auto-oxidize and leads to a runaway exothermic reaction accompanied by the evolution of heat and/or flame. Many studies have been conducted on its detailed mechanism. For example, Furuichi et al. attempted kinetic analysis of oxygen adsorption in a relatively low temperature range of 25 to 55℃, and the oxygen adsorption phenomenon was explained by physical adsorption and chemisorption (Furuichi et al., 1974). Practically, coal rank, particle size, air permeability, geometric size of the deposits, and moisture content of the coal and the air are the most important factors (Alameddin and Luzik, 1986). Among these factors, we experimentally evaluated the effect of coal rank and deposits size in laboratory-scale (Nakamura, et al., 1996).

The oxygen concentration in the gas that conveys pulverized coal from the mills to the burners does not change at 21% in air combustion, but changes from about 3% to around 30% depending on the system in oxygen combustion. Also, air is a nitrogen-based gas, while the recycled flue gas in oxyfuel combustion is a CO₂-based gas. Therefore, in order to build a safe and feasible system, we decided to confirm the effect of the properties of the atmospheric gas on the spontaneous combustion characteristics that cause the mill fire. For the purpose, Nishimura et al. performed a spontaneous combustion test of pulverized coal both in N₂/O₂ atmosphere and in CO₂/O₂ atmosphere changing O₂ concentration and atmosphere temperature (Nishimura, et al., 2018). However, they only reported on the outline and the progress, and have not sufficiently evaluated the results.

Therefore, in order to make clear the spontaneous combustion characteristics of the deposited pulverized coal, we conducted additional laboratory-scale tests, and performed a numerical analysis of spontaneous combustion that simulated the test in a simple manner. In this paper, we report on the test equipment, test contents, test results and evaluation of a series of spontaneous ignition tests in detail, and also report the discussion of the validity of the test results in comparison with the numerical analysis results.
2. Experiment

2.1 Experimental equipment

The schematic flow diagram of the equipment used for this test is shown in Fig. 2. The test equipment consists of \( \text{O}_2 \) and \( \text{N}_2 \) or \( \text{CO}_2 \) gas cylinders, flowmeters, flow control valves, a gas mixing header, a thermostatic chamber, a closed container, a gas pretreatment device, and gas analyzers. The interior of the thermostatic chamber has a double structure to prevent air leakage and maintain the test condition environment. Figure 3 shows the inside of the thermostatic chamber. Sample box is a 100 mm square box made of metal mesh (0.05 mm mesh). Clips were attached to the closed container lid, and the sample box was suspended from the lid. This allowed gas to enter and exit the box from all directions. Three (3) thermocouples were installed as shown in Fig. 4, and the temperatures at the point of 10 mm from the side wall of the sample box, the center of the sample box, and in the thermostatic chamber were monitored. In addition, gas analyzers were installed at the inlet and outlet of the thermostatic chamber, and \( \text{O}_2 \) concentration at the inlet and \( \text{O}_2, \text{CO}_2 \) and CO concentrations at the outlet were measured and used for observation of the ignition situation.
2.2 Test procedure

In the oxyfuel power plant, start-up is performed by air combustion and switched to oxyfuel combustion halfway. Therefore, a test was first conducted to determine whether pulverized coal deposited in an air atmosphere would ignite in an oxygen combustion atmosphere, packing pulverized coal in a mesh box in the air with a following procedure;

1. Put pulverized coal of the fineness of 80% or more through 200 mesh (74 μm) sieve into a sample box.
2. Measure the weight of pulverized coal in the box and calculate the porosity.
3. Quickly install the box filled with the sample pulverized coal inside the container installed in the thermostatic chamber, and install thermometers at two locations (center and side) inside the sample.
4. Turn on the power of the thermostatic chamber and set the temperature in the closed container to the test condition. The temperature is automatically controlled.
5. Start the measurement while flowing the test condition gas at 1.0 L / min.
6. If the temperature of the box center reaches 300 °C, or if 48 hours have elapsed from the start of measurement even if it does not reach 300 °C, the test is ended. This was used as the criteria for ignition and non-ignition.

Next, the possibility of spontaneous combustion of pulverized coal deposited during oxyfuel combustion was investigated. In this case, pulverized coal was packed in the box in the atmosphere of the test conditions and the procedure for preparing the sample was as follows;

1. Pulverized coal of the fineness of 80% or more through 200 mesh (74 μm) sieve, and a sample box is put in a glove box.
2. Flow O₂ and N₂ or CO₂ from the gas cylinder so that the inside of the glove box is adjusted to the test atmosphere.
3. Confirm that the inside of the glove box is adjusted to the test condition with gas analyzers, and fill the sample box with pulverized coal using a spatula and a sieve, so that the air surrounding pulverized coal particles can be replaced with gas of test condition as shown in Fig. 5.

2.3 Test coal properties

The properties of coal used in the test are shown in Table 1. The coal is Australian bituminous coal, and was pulverized with a vertical roller mill of which standard volume was 2 t/h, and a part of it was used as test sample.

| Parameters | Units | Values | Base |
|------------|-------|--------|------|
| Gross Calorific Value | J/g | 29210 | dry base |
| Proximate Analysis Moisture | wt% | 5.2 | air dry base |
| Ash | wt% | 13.6 | dry base |
| Volatile Matter | wt% | 33.5 | dry base |
| Fixed Carbon | wt% | 52.9 | dry base |
| Fuel Ratio | - | 1.58 | dry base |
| Total Moisture | wt% | 7.1 | as received |
| Ultimate Analysis Sulfur | wt% | 0.67 | dry base |
| Carbon | wt% | 71.0 | dry base |
| Hydrogen | wt% | 4.32 | dry base |
| Nitrogen | wt% | 1.63 | dry base |
| Oxygen | wt% | 8.82 | dry base |
| HGI | - | 49.0 | air dry base |

Fig. 5 Preparation of test sample in a globe box
3. Experimental results

3.1 Temperature and gas concentration

Figures 6 and 7 show the changes of temperature at positions as shown in Fig. 4 and the concentration of each gas properties at the inlet and outlet of the thermostatic chamber over time with and without ignition according to the

Fig. 6 Change of temperature and gas properties over time when combustion occurred

Fig. 7 Change of temperature and gas properties over time when combustion did not occur
criteria of (5) in section 2.2. Figure 6 is for the case when the ignition occurred at temperature of 100°C with gas of 27% O₂ and 73% CO₂, while Fig. 7 is for the case when the ignition did not occur at temperature of 90°C with gas of 27% O₂ and 73% CO₂. These are the results when the sample was packed in the atmosphere of the test conditions, while almost the same results were obtained when the sample was packed in the air.

As seen in Figs. 6(a) and 7(a), the temperature of the sample exceeds the chamber temperature about 6 hours after the start of test in both cases with and without ignition. From Fig. 6(a), it can be seen that ignition occurs from the center of the sample box. In addition, although the chamber temperature and the temperature at the side of the sample box converge in about 1 - 2 hours after ignition, the temperature at the center of the sample box continues to rise for 6 hours or more. When not ignited, as found in Fig. 7(a), both the sample center and the side temperature converge after exceeding the chamber temperature, keeping a temperature slightly higher than the chamber temperature.

The concentrations of each gas properties are shown in Figs. 6(b) and 6(c) when ignited. CO concentration continues to rise before ignition, and it rises rapidly just before and after ignition. Oxygen is consumed in the thermostatic chamber, so the outlet O₂ drops rapidly and the CO₂ concentration rises. Even after the chamber temperature and the side of the sample box temperature converge, the outlet O₂ is low and the outlet CO₂ keeps high. When not ignited as shown in Figs. 7(b) and 7(c), CO concentration only slightly rises to about 25 ppm according to the temperature change of the sample and then decreases, while the gas composition is constant from the beginning to the end without combustion.

### 3.2 Effect of circumstance conditions on spontaneous combustion

With respect to the test results using the samples packed in air, the boundary between the ignited condition and the non-ignited condition is drawn in Fig. 8 for the N₂/O₂ atmosphere and the CO₂/O₂ atmosphere, respectively. Although the two boundaries almost overlap and the test data are also scattered, pulverized coal seems to ignite at a lower temperature in the N₂/O₂ atmosphere under conditions of around 20% O₂. Also, it can be seen that even if the oxygen concentration of the atmosphere is increased from 30% to 100%, the temperature of the atmosphere for ignition is reduced only by about 10°C. This means that the influence of the oxygen concentration in the atmosphere on the occurrence of spontaneous combustion is small.

As the reason for this, we wondered if the initial surrounding condition of pulverized coal (namely it was air in the above all conditions) affected the possibility of ignition even if the oxygen concentration around the sample box was changed because all samples were packed in air (oxygen concentration: 21%). Therefore, in order to determine the effects of initial surrounding condition of pulverized coal, the following spontaneous combustion tests were conducted using samples packed in the gas of each test condition. They are corresponding to tests to investigate the spontaneous combustion of pulverized coal deposited during oxyfuel combustion.

![Fig. 8 Effect of circumstance conditions on spontaneous combustion when pulverized coal was packed in the air](image1)

![Fig. 9 Effect of circumstance conditions on spontaneous combustion when pulverized coal was packed in the gas of test condition](image2)
The test results are shown in Fig. 9. It can be seen that the variation in test results is smaller than in Fig. 8 and the boundary can be drawn relatively easily. It is considered that this was because the pulverized coal could be put in the mesh box with being dispersed without aggregation by charging it through a sieve. That is, it can be said that the lower end of the boundary band in Fig. 8 is close to the result in the case when the dispersion was good as shown in Fig. 9. Therefore, judging from the fact that the lower end of the boundary zone in Fig. 8 and the boundary line in Fig. 9 almost overlap, it is evaluated that the gas initially contained in the deposited pulverized coal layer has little effect on the possibility of spontaneous combustion. This is considered to be because most of the gas initially contained in the pulverized coal bed was replaced with the surrounding gas from the upper end of the sample box and through its mesh structure where gas flow was free before the spontaneous combustion phenomenon became active.

4. Discussions

From Figs. 8 and 9, although pulverized coal tends to be less likely to ignite in the CO$_2$/O$_2$ atmosphere than in the N$_2$/O$_2$ atmosphere, the difference is not so clear due to the limited number of data. Therefore, we evaluated the test results based on the time required for ignition and also carried out numerical evaluation using a CFD model.

4.1 Study from the viewpoint of time to confirm combustion

Figure 10 shows the time required for temperature reaches to 300 °C, which is judged to be ignition, among the conditions that sample caught ignition. From Fig. 10, it can be seen that the ignition occurs more slowly in the CO$_2$/O$_2$ atmosphere regardless of the oxygen concentration and temperature, whichever sample was used. On the other hand, when comparing Fig. 10(a) and Fig. 10(b), the ignition time in the CO$_2$/O$_2$ atmosphere was much longer when the sample was packed in air. Furthermore, in Fig. 10(a), the oxygen partial pressure was 2.3 times higher under the condition of 23% oxygen concentration than that under the condition of 10%, and the adsorption rate of oxygen increased significantly, so the time until ignition was clearly reduced. On the other hand, in Fig. 10(b), the conditions under which the effects of oxygen concentration can be compared are conditions where the oxygen concentration is 24%, 27%, and 34%. Under these conditions, the change in oxygen partial pressure is small, so the difference in the time to ignition is small, and it is only possible to confirm the decrease in the time to ignition when the oxygen concentration is 34%.

From the test results in Section 3.2, it was found that in the series of tests this time, the gas contained in the sample was replaced by the surrounding gas before ignition. In other words, the time until ignition includes the time required for gas replacement and that required for reaction including heat transfer. Considering physical properties such as density and kinematic viscosity that affect gas replacement, they are exactly the same in the tests (Fig. 10(b)) in which the samples were packed in the test condition gas. In the tests where the samples were packed in air (Fig. 10(a)), they...
are similar when the surroundings are N₂/O₂ atmosphere. Therefore, the low temperature gas contained in the samples flows out downward. On the other hand, when a sample packed in air is placed in a CO₂/O₂ atmosphere and the included gas is lighter than the surrounding gas, the direction of gas flow during the gas replacement is considered to change. This will be the reason for the considerably longer ignition time as shown in Fig. 10(a).

From the discussion so far, the ignition delay in the CO₂/O₂ atmosphere when the sample is packed in the gas under the test conditions shown in Fig. 10(b) is due to the reaction or heat conduction. Firstly, we investigated the possibility of the endothermic reaction between coal and CO₂ although it is hard to think to be occurred because the temperature tested was low around 100 °C. Fig. 11 shows the changes in CO concentration in the gas at the outlet of the thermostatic chamber in the tests conducted in N₂/O₂ atmosphere and CO₂/O₂ atmosphere, respectively. Figure 11(a) shows the results when O₂ concentration is 27% and test temperature is 100°C, while Fig. 11(b) shows those when O₂ concentration is 80% and test temperature is 90°C. Although there is a time lag between the results of N₂/O₂ atmosphere and CO₂/O₂ atmosphere, it is unlikely that CO₂ participated in the reaction because there is no clear difference in CO concentration level. Accordingly the test results are explained as follows. The included gas in the sample is the source of oxygen supply to the pulverized coal, and the pulverized coal absorbs oxygen to raise the temperature, while the included gas suppresses the rapid temperature rise of the pulverized coal. Therefore, it is considered that the atmosphere mainly with CO₂ which has a larger specific heat than N₂ has a larger effect of suppressing the temperature rise of the pulverized coal, and the time until ignition is prolonged.

From the above, in the CO₂/O₂ atmosphere, if the operation is the same as the air combustion, there is little possibility of the occurrence of a special danger in terms of safety, and a slight increase in oxygen concentration is also acceptable. Even when the oxygen concentration is high in a short time, there is a high possibility that ignition can be prevented by lowering the temperature to 80 °C or less.

### 4.2 Investigation by CFD model

In order to confirm the validity of the results of the laboratory test, it was evaluated by unsteady calculation considering gas flow, heat generation by absorption of oxygen, and heat transfer. In the laboratory test, a 100 mm square box made of metal mesh was filled with pulverized coal, while in the analysis, a cylindrical basket with a diameter of 100 mm and a height of 100 mm was assumed to simplify the analysis, and a two-dimensional axisymmetric CFD model (Zhang, et al., 2016) was used as shown in Fig. 12.

The mesh box has no thickness and mass, and allows gas and heat to enter and exit freely without resistance on all sides. The pulverized coal bed was set as a porous bed. The thermal properties and reaction parameters of pulverized coal used in the numerical evaluation are shown in Table 2. Since the inflow of gas is due to natural convection, gravity was considered. As the moisture content in the pulverized coal at the time of the test was relatively small at about 5%, the evaporation of the moisture was ignored. In addition, the analysis aims to evaluate the influence by the difference of

![CO concentration changes in the gas at the outlet of the thermostatic chamber using sample packed in the gas of test condition](image-url)
the atmosphere filled with pulverized coal and the difference by the difference of the test atmosphere of \( \text{N}_2/\text{O}_2 \) and \( \text{CO}_2/\text{O}_2 \), so the detailed adjustment of parameters has not been made.

The analysis conditions and results are shown in Table 3. In the table, “air” denotes the condition in which the pulverized coal is filled in the air, and “noair” denotes the condition in which the pulverized coal is filled in the gas of the test condition. From Table 3, it can be seen that there is an ignition / non-ignition boundary at a temperature about 10°C higher than the test, but it can be said that the test is generally reproduced. Furthermore, as in the simulation results, in the \( \text{CO}_2/\text{O}_2 \) atmosphere the ignition did not occur up to a few degrees higher atmosphere temperature compared to in the \( \text{N}_2/\text{O}_2 \) atmosphere, so it was confirmed that the ignition did not occur easily in the \( \text{CO}_2/\text{O}_2 \) atmosphere.

Moreover, the temperature change in each condition is shown in Fig. 13, where notations of “air” and “noair” are used as same as in Table 3. It can be seen that in the \( \text{N}_2/\text{O}_2 \) atmosphere, the rate of temperature rise is slower when the pulverized coal is packed in the air. This is considered to be due to the fact that the concentration of \( \text{O}_2 \) in the gas of test

---

**Table 2 Thermal properties and reaction parameters**

| Parameters          | Units | Values |
|---------------------|-------|--------|
| Specific heat       | J/kg/K| 1350   |
| Thermal conductivity| W/m/K | 0.48   |
| Activation Energy   | kJ/mol| 47.681 |
| Pre-exponential factor | ml(S)-O2/min/g-coal | 168,700 |

**Table 3 Numerical simulation results of spontaneous combustion**

| Atmosphere | Temp. [°C] | Environment where sample was packed | Results, ignition was occurred or not |
|------------|------------|-------------------------------------|--------------------------------------|
| \( \text{N}_2 \) (30%) | 100 | air | occurred |
| \( \text{O}_2 \) (70%) | 100 | noair | occurred |
| \( \text{CO}_2 \) (30%) | 97 | noair | not occurred |
| \( \text{O}_2 \) (70%) | 95 | noair | not occurred |
| \( \text{N}_2 \) (30%) | 110 | noair | occurred |
| \( \text{O}_2 \) (70%) | 105 | noair | occurred |
| \( \text{CO}_2 \) (30%) | 102 | noair | occurred |
| \( \text{O}_2 \) (70%) | 100 | noair | not occurred |
| \( \text{N}_2 \) (30%) | 100 | air | not occurred |

(a) Long time span (~24 hour)  
(b) Short time span (~9 hour), (only “noair” conditions)

Fig. 13 Numerical simulation results of spontaneous combustion
condition is 70% and higher than the air. On the other hand, in the CO$_2$/O$_2$ atmosphere, the temperature rise speed is extremely slow when the pulverized coal is packed in the air. This is thought to be due to the low concentration of O$_2$ in the pulverized coal bed and the fact that the low temperature air contained in the pulverized coal bed is difficult to move (go down) because N$_2$ is lighter and more viscous than CO$_2$ as discussed in section 4.1.

5. Conclusions

The effect of pulverized coal deposited in the mill under oxyfuel atmosphere on safety was investigated from the viewpoint of spontaneous combustion. Pulverized coal was packed in a mesh box and placed in a thermostatic chamber, and it was confirmed whether it ignited at some conditions of oxygen concentration and atmospheric temperature. Next, the numerical simulation utilizing 2D CFD model confirmed the validity of the laboratory test results. As a result, the following became clear.

(1) In spontaneous combustion tests in which pulverized coal is packed in a mesh box, the method of pulverized coal input affects the results. Stable data can be obtained by a method of feeding without aggregation using a sieve.

(2) The ignition occurs at a slightly higher temperature and it takes longer time to ignite even under the same O$_2$ concentration in CO$_2$/O$_2$ atmosphere than in N$_2$/O$_2$ atmosphere.

(3) The numerical simulation also showed that the ignition is more likely occurred in the N$_2$/O$_2$ atmosphere. This is considered to be due to higher specific heat of CO$_2$ than that of N$_2$.

(4) The occurrence of spontaneous combustion is affected by the O$_2$ concentration in the atmosphere gas, but in an atmosphere with O$_2$ concentration of 20 to 30% or more, the influence of the atmosphere temperature is more strongly exerted.

From the above, the possibility of mixing O$_2$ into primary gas in oxyfuel combustion was clarified from the viewpoint of spontaneous combustion, and a guideline could be obtained.

References

Alameddin, A. N. and Luzik A. J., Coal dust explosion in the cement industry, in Kenneth L Cashdollar and Martin Hertberg, editors, Industrial dust explosions, ASTM STP 958 (1986) Philadelphia, American Society for Test and Materials, pp.217-233.

Callide Oxyfuel Project - Final Results (4 May 2018) http://hub.globalccsinstitute.com/sites/default/files/publications/202090/cop-finalresults-publicreport-march2018.pdf

Furuichi, R. Kobayashi, H. and Okamoto, G., Oxygen Adsorption on Coals in the Temperature Range of 25-55°C, Hokkaido University Collection of Scholarly and Academic Papers, Vol.70 (1974), pp.87–89 (in Japanese).

IEA, Global Energy & CO$_2$ Status Report 2018, https://www.iea.org/geco/ (2019).

Nakamura, M. Kiga, T. Takahashi, K. and Suzuki, K., Low-Temperature Oxidation of Pulverized Coal, Ishikawajima-Harima engineering review, Vol.36, No.3 (1996), pp.208–212 (in Japanese).

Nishimura, M. Komaki, A. and Yamada, T., Current activities for commercialization of oxyfuel power plant, Transactions of the JSME (in Japanese), Vol.84, No.859 (2018), DOI: 10.1299/transjsme.17-00399.

Zhang, J. Choi, W. Ito, T. Takahashi, K. and Fujita. M., Modelling and parametric investigations on spontaneous heating in coal pile, Fuel 176(2016), pp.181-189.