

Storage and Handling of Low-Rank Coal

— Experimental and Numerical Investigations into the Spontaneous Heating Behavior of Low-Rank Coal Stored in a Silo —

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The spontaneous heating behavior of sub-bituminous coal stored in a 120-ton experimental silo was investigated. The temperature distribution in the coal bed and the oxygen concentration in the silo were measured. A heated zone formed in the central part of the coal bed, and its maximum temperature reached over 45°C during storage. After nitrogen entered the silo, the heating of the coal bed was suppressed due to the resultant reduction in oxygen concentration in the silo. The heating behavior was numerically analyzed using a computational fluid dynamics (CFD) model that took into account gas flow through the coal bed and heat generated by oxygen being absorbed into coal particles. The numerical temperature distribution in the coal bed was consistent with the experimental results.

1. Introduction

In Japan, the ratio of energy produced from coal to total energy had been about 22% up to FY2011, but the ratio was 25.5% in FY2014 and has been on the increase in the last several years⁽¹⁾. On the other hand, high-rank coal (bituminous coal), which has been used as fuel for energy and power, is increasing in price. Therefore, low-rank coal (sub-bituminous coal and lignite coal) which is cheap and possessing half of total coal reserves is being utilized or its utilization considered^{(2),(3)}.

Low-rank coal has higher propensity for spontaneous heating. It is therefore expected that the utilization of low-rank coal into an existing power plant which is designed to operate using high-rank coal will require more stringent safety measures for the handling of coal⁽⁴⁾.

Recently, some thermal power plants have been using bituminous coal with properties similar to those of sub-bituminous coal. Even though their coal storage facilities have sensors for monitoring coal temperature and water-spray facilities for cooling, there have been incidents of spontaneous combustion.

Moreover, in case of low-rank coal, spontaneous combustion may occur in a shorter time period compared to high-rank coal. Therefore, the technology for reliable prediction of spontaneous heating behavior is required for the utilization of

low-rank coal. IHI Group has been conducting research on the spontaneous combustion of coal⁽⁵⁾⁻⁽⁷⁾, and the scope recently expanded to include low-rank coal. This paper describes the result of monitoring spontaneous heating behavior in a low-rank coal bed stored in an experimental silo, and the technology to predict the heating behavior using numerical simulation.

2. Characteristics and spontaneous heating behavior of low-rank coal

2.1 Properties of low-rank coal

Coal is classified by its degree of carbonization, but the parameter of degree of carbonization varies from the standard of a country. For example, classification by amount of volatile matter is adopted in the U.S. whereas classification by a combination of calorific value and fuel ratio, as stipulated in the Japanese Industrial Standard (JIS), is adopted in Japan. **Table 1** shows the JIS classifications of coal. Coal with a low calorific value, i.e., sub-bituminous coal and brown coal, is called “low-rank coal,” and coal with a high calorific value, i.e., bituminous coal, is called “high-rank coal.”

Figure 1 shows the classification of coal and biomass by O/C (Oxygen/Carbon) and H/C (Hydrogen/Carbon) atomic ratios based on the Van Krevelen’s coal band (Van Krevelen diagram). The figure illustrates the process of carbonization — biomass (wood) turns into brown coal by dehydration; next, brown coal turns into sub-bituminous coal by

Table 1 Coal classification (JIS M 1002)

Classification		Calorific value ^{*1} (corrected dry, ash-free) kJ/kg {kcal/kg}	Fuel ratio	Coking property
Grade of coal	Subcategory			
Anthracite (A)	A ₁	—	≥ 4.0	Non-coking
	A ₂			
Bituminous coal (B, C)	B ₁	≥ 35 160 {≥ 8 400}	≥ 1.5	Strongly coking
	B ₂		< 1.5	
	C	≥ 33 910 and < 35 160 {≥ 8 100 and < 8 400}	—	Coking
Sub-bituminous coal (D, E)	D	≥ 32 650 and < 33 910 {≥ 7 800 and < 8 100}	—	Weakly coking
	E	≥ 30 560 and < 32 650 {≥ 7 300 and < 7 800}	—	Non-coking
Brown coal (F)	F ₁	≥ 29 470 and < 30 560 {≥ 6 800 and < 7 300}	—	Non-coking
	F ₂	≥ 24 280 and < 29 470 {≥ 5 800 and < 6 800}	—	

(Note) *1: Calorific value (corrected dry, ash-free)
= Calorific value/(100 – Ash content correction factor × Ash content – Moisture content) × 100

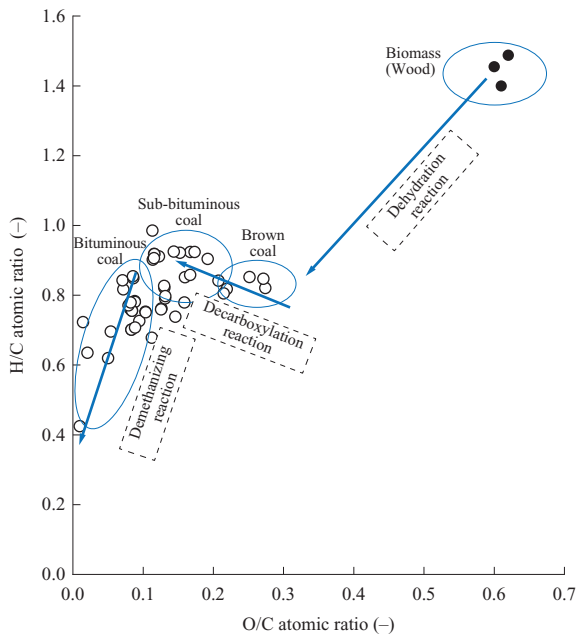


Fig. 1 H/C and O/C ratio for several coal and biomass specimens (Van Krevelen diagram)

decarboxylation; and then, sub-bituminous coal turns into bituminous coal by demethanization. In addition, coal is also classified by the country and the place where the coal mine is located. Then the values on the coal band show considerable variation. This implies that the coal storage and handling technology which is specifically designed for individual coal mine might be required depending on the coal properties.

As shown in **Fig. 1**, the O/C atomic ratio of low-rank coal is higher than that of high-rank coal because low-rank coal contains larger quantities of oxygen-containing functional groups, such as –COOH and =O. These functional groups react with oxygen at low temperature, and heat is also generated. Low-rank coal is therefore prone to occur spontaneous combustion during its storage and handling^{(3), (4)}. Safety measures for coal storage management must be taken before the utilization of low-rank coal.

2.2 Characterization of spontaneous heating

The spontaneous combustion of coal during storage or handling is caused by heat produced by the reaction of oxygen adsorbed from the air by the coal. As coal is gradually oxidized at low temperature, the phenomenon is called a low-temperature oxidation reaction⁽⁵⁾.

The rate of low-temperature oxidation reaction r , representing an Arrhenius-type reaction rate equation as shown in equation (1), is expressed using the activation energy E_a and pre-exponential factor A_c .

$$r = A_c \times \exp(-E_a/RT) \dots\dots\dots(1)$$

R : Gas constant

T : Reaction temperature

Figure 2 shows the relationships between the activation energy produced in the low-temperature oxidation reaction of equation (1) and the volatile matter content of coal with

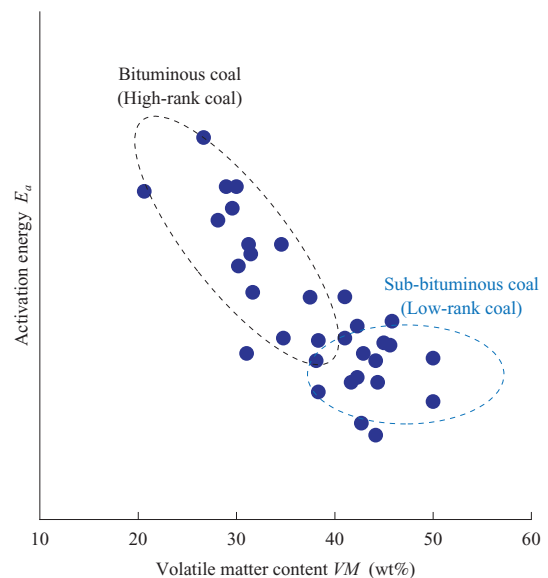


Fig. 2 Relationship between the activation energy produced in low-temperature oxidation and the volatile matter content of various coal specimens

regard to specimens from the coal IHI Group previously studied (coal specimens in **Fig. 1** differ from those in **Fig. 2**). High-rank coal specimens has higher activation energies than low-rank coal specimens, indicating that the high-rank coal specimens exhibit lower rate of low-temperature oxidation reaction expressed by equation (1). The values of activation energy of low-rank coal specimens widely dispersed. Therefore, low-rank coal specimens cannot be characterized only on activation energy unlike high-rank coal specimens, but consideration of the pre-exponential factor needed as well.

In addition, the heating of a coal bed during storage is also affected by the thermal balance between the heat produced by low-temperature oxidation reaction and the heat released from the coal bed. If the amount of heat from the reaction is larger, the coal bed temperature increases, which results in spontaneous combustion⁽⁵⁾. In other words, heating behavior of coal bed is significantly affected not only by the coal properties, but also by many other factors, including the ① shape of the coal bed, ② storage method, ③ diffusion (supply) of air into the coal bed, and ④ ambient temperature.

For this reason, to predict spontaneous combustion in a specific storage situation, a comprehensive consideration of actual storage type, coal type, coal storage quantity, type of storage facility, and more is required.

It has been reported that numerical analysis is suitable for studies of spontaneous combustion for coal storage^{(4), (5)}, and IHI previously conducted the numerical simulation of spontaneous combustion high-rank coal (bituminous coal) bed in two cases which are a pile in open field and a bed stored in a silo^{(5), (6)}.

In the present study, a demonstration test using an experimental silo was conducted, and an improved numerical analysis of spontaneous combustion was developed.

3. Storage experiment of low-rank coal

3.1 Experimental silo

Figure 3 shows the external view of the experimental silo used for the present study. The appearance is similar to an ordinary silo in shape — the top and bottom parts are conical and the central part is cylindrical. It is 5.0 m in diameter and 18.5 m in height, and its coal storage capacity is approximately 120 tons.



(Note) Test site in Numazu Works, IHI Transport Machinery Co., Ltd.

Fig. 3 Experimental coal storage silo

An actual coal silo has two openings — a ventilation hole on the top and an opening at the bottom through which coal is discharged. Due to this configuration, natural convection plays a main role in air entering into the silo. In order to reproduce the air flow, the experimental silo was also designed to be open at the top and bottom.

In addition, thermal insulation material was attached to the wall of the experimental silo in order to reduce the effects of heat loss to the atmosphere and thermal radiation by direct sunlight.

3.2 Monitoring of the coal bed and safety equipment

The experimental silo was provided with 67 temperature sensors, a humidity sensor, and an oxygen concentration sensor. By installing the temperature sensors in the coal bed and on the silo wall, the measurement of the temperature distribution in the coal bed was taken. The humidity and oxygen concentration of the gas in the space above the coal bed were also measured. At the same time, measurement of the ambient temperature was taken during the test. All measured values were recorded in real time to investigate their temporal changes. **Figure 4** shows the location of temperature sensors

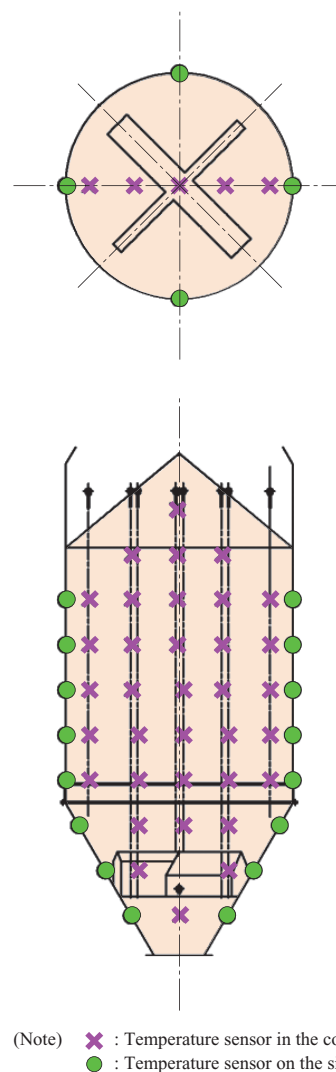


Fig. 4 Location of temperature measurement points in the experimental silo

in the coal bed and on the silo wall. **Figure 5** shows the measurement points of humidity and oxygen concentration in the space above the coal bed.

In addition, a nitrogen charging facility was installed for use in an accident. It was designed to cut off oxygen diffusion to the coal bed. Moreover, water spray equipment was also installed to spray a large volume of water into the coal bed if a rapid temperature rise occurred during the experiment.

3.3 Properties of stored coal and experiment method

Storage experiment using the experimental silo were conducted twice, and two different kinds of coal (coal A and coal B) were stored. **Table 2** shows the proximate analysis of the stored coal. Both coal A and coal B show typical characteristics of sub-bituminous coal — a fuel ratio of approximately 1.0-1.1 and a moisture content upon arrival of

Table 2 Proximate analysis of coal specimens

Item	Standard	Unit	Coal A	Coal B
Moisture content	On arrival ^{*1}	wt%	25.0	29.1
Moisture content	Air-dried ^{*2}	wt%	9.3	21.2
Ash content	Air-dried ^{*2}	wt%	3.1	2.4
Volatile matter content	Air-dried ^{*2}	wt%	42.3	38.3
Fixed carbon	Air-dried ^{*2}	wt%	45.3	38.1
Fuel ratio (Fixed carbon/ Volatile matter content)	—	—	1.1	1.0
Calorific value	Dry/Ash-free	kcal/kg	6 000	5 830

(Note) *1: State upon arrival of coal specimens

*2: State after coal specimens are left in the atmosphere (naturally dried)

approximately 25-29%. In terms of calorific value, they exhibited properties similar to those of brown coal.

Coal was put into the experimental silo in a raw state (The percentage of the particles whose diameter is smaller than 50 mm is over 90%) without being dried, pulverized, or classified. The measurement was started after all prepared coal is loaded in the silo. During the experiment, the silo was left to stand until a predetermined target temperature was reached while the coal bed temperature was monitored.

After the target temperature had been reached, nitrogen was fed into the silo to suppress the low-temperature oxidation of coal, and changes in oxygen concentration and temperature in the silo were monitored.

4. Numerical analysis of heating behavior of stored coal

4.1 Computational domains

Figure 6-(a) shows the brief structure of the experimental silo and **Fig. 6-(b)** shows the computational domains for numerical analysis. The computational domains were two-dimensional and axisymmetric and included a coal bed and a

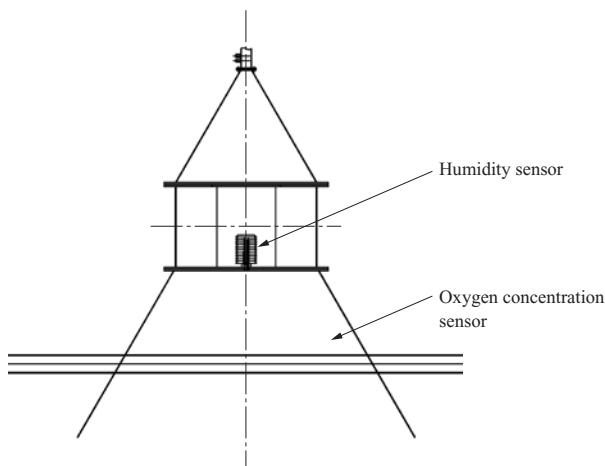
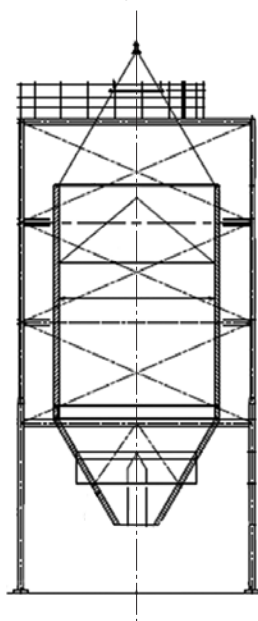


Fig. 5 Location of measuring equipment in the upper part of the silo

(a) Structure of experimental silo
(for storage of coal A)



(b) Computational domains

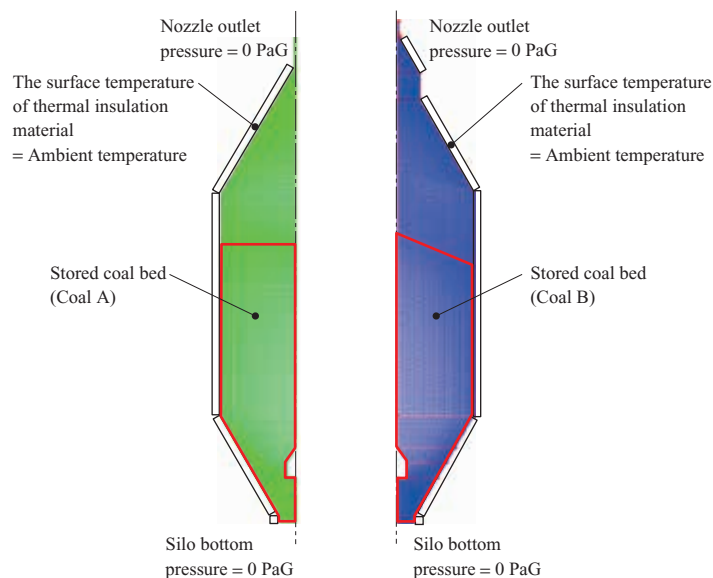


Fig. 6 Cross-sectional view of the experimental silo and the computational domains

space above the coal bed. The shape of the top of each coal bed was configured to the same shape as the coal bed subjected to the storage experiment. Due to the difference in loading method between the two experiments, the shape of upper parts of coal beds differed from each other.

At the top and bottom openings of the silo, no specific flow velocity was given initially in order to simulate natural convection causing air to flow into the coal bed. Changes in the temperature of incoming air were defined using values from a curve fitted to the measured ambient temperature values during each experiment.

4.2 Governing equations

A Computational Fluid Dynamics (CFD) model was applied into the numerical analysis in this paper. The model is an upgraded version of the conventional model⁽⁷⁾, which is taking into account air entering the coal bed, heat generated by low-temperature oxidation, and the change in moisture content of coal. Governing equations are shown below.

- Continuity equation

$$\nabla \cdot \vec{v} = 0 \quad \dots\dots\dots(2)$$

- Equation of momentum conservation

$$\begin{aligned} &\rho_f \frac{\partial \vec{v}}{\partial t} + \rho_f (\vec{v} \cdot \nabla) \vec{v} \\ &= -\nabla p + \mu \cdot \nabla^2 \vec{v} - \frac{\mu}{\alpha} \cdot \epsilon \vec{v} + S_b \quad \dots\dots\dots(3) \end{aligned}$$

- Equation of conservation of a chemical species

$$\begin{aligned} &\frac{\partial \rho_f Y_{O_2}}{\partial t} + \nabla \cdot (\rho_f \vec{v} Y_{O_2}) \\ &= \rho_f D_{O_2, m} \cdot \nabla^2 Y_{O_2} + S_{O_2} \quad \dots\dots\dots(4) \end{aligned}$$

$$\begin{aligned} &\frac{\partial \rho_f Y_{H_2O}}{\partial t} + \nabla \cdot (\rho_f \vec{v} Y_{H_2O}) \\ &= \rho_f D_{H_2O, m} \cdot \nabla^2 Y_{H_2O} + S_{H_2O} \quad \dots\dots\dots(5) \end{aligned}$$

- Equation of energy conservation

$$\begin{aligned} &\frac{\partial}{\partial t} ((1-\epsilon)\rho_s C_{p,s} + \epsilon\rho_f C_{p,f}) + \epsilon\rho_f C_{p,f} (\vec{v} \cdot \nabla T) \\ &= k_{eff} (\nabla \cdot \nabla T) + H_r S_{O_2} - H_{evap} S_{H_2O} \quad \dots\dots\dots(6) \end{aligned}$$

- Oxygen absorption term

$$S_{O_2} = c A_c \exp\left(-\frac{E_a}{RT}\right) \quad \dots\dots\dots(7)$$

- \vec{v} : Flow velocity vector
- ∇ : Laplace operator
- p : Pressure
- μ : Coefficient of viscosity
- $1/\alpha$: Drag coefficient of the coal bed
- ϵ : Porosity of the coal bed
- S_b : Buoyancy term
- Y_{O_2} : Mass fraction of oxygen
- Y_{H_2O} : Mass fraction of moisture
- $D_{O_2, m}$: Diffusion coefficient of oxygen
- $D_{H_2O, m}$: Diffusion coefficient of moisture
- S_{O_2} : Oxygen source term
- S_{H_2O} : Moisture source term
- H_r : Heat of low-temperature reaction

- H_{evap} : Heat of evaporation of water
- k_{eff} : Effective thermal conductivity of the porous layer
- $C_{p,f}$: Specific heat of air flowing in the coal bed
- $C_{p,s}$: Specific heat of coal particle at constant pressure
- ρ_f : Density of air flowing in the coal bed
- ρ_s : Density of coal particle
- A_c : Pre-exponential factor of low-temperature oxidation reaction
- E_a : Activation energy of low-temperature oxidation reaction
- c : Constant taking into account coal particle size distribution
- R : Gas constant
- T : Temperature
- t : Time

A reaction rate equation derived from low-temperature oxidation experiment⁽⁵⁾⁻⁽⁷⁾ conducted separately was used for the oxygen absorption term. The values of thermal conductivity and specific heat of coal particle were obtained using the transient hot wire method and the using continuous heating adiabatic calorimetry accordingly.

5. Results and discussion

5.1 Temporal changes in the maximum temperature of the coal bed

Figure 7 shows the maximum coal bed temperatures and daily average of ambient temperature measured during the experiment. The storage period for each experiment was as follows: coal A: 125 days; coal B: 46 days. The maximum temperatures showed a tendency to rise exponentially with an increase in the elapsed time from the start of the experiment. For the same elapsed time, it can be seen that coal B exhibited higher temperature and larger increment in temperature than coal A did. In a separately conducted low-temperature oxidation reaction test, both coal types exhibited the same level of reaction rate. Hence, the difference in the

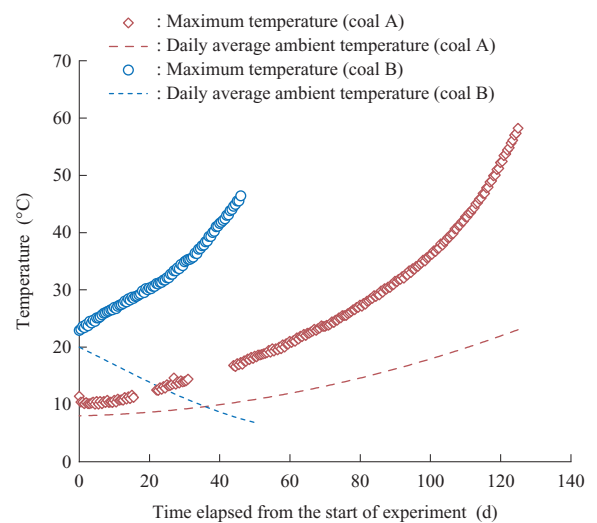


Fig. 7 Maximum coal temperature and average ambient temperature versus elapsed time

increment in temperature seems to be attributable to the fact that these tests were conducted in different season, in other words, at different ambient temperatures (whereas the experiment of coal A was conducted from January to June, the experiment of coal B was conducted from November to December).

Figure 8 shows a comparison of temporal changes in maximum coal bed temperature between the experiment and the numerical simulation. The incoming air temperatures and silo wall temperatures in the numerical simulation were set same as the daily average ambient temperatures as shown in **Fig. 7**. The graph shows that the numerically simulated value of maximum coal bed temperature is in good agreement with the measured value from the storage experiment.

5.2 Temperature distribution in the coal bed

Figure 9 shows the comparison of temperature distribution in the coal bed between the measured results and numerical results with respect to the elapsed days from the start of storage. It can be seen that a heated zone formed in the central part of the coal bed and that the peak temperature region is located near the central axis at approximately 1/3 to

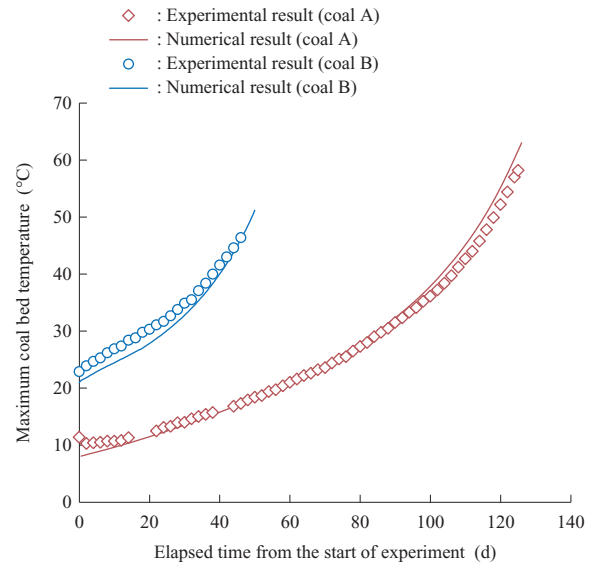


Fig. 8 Comparison of calculation with experimental results (maximum coal temperature)

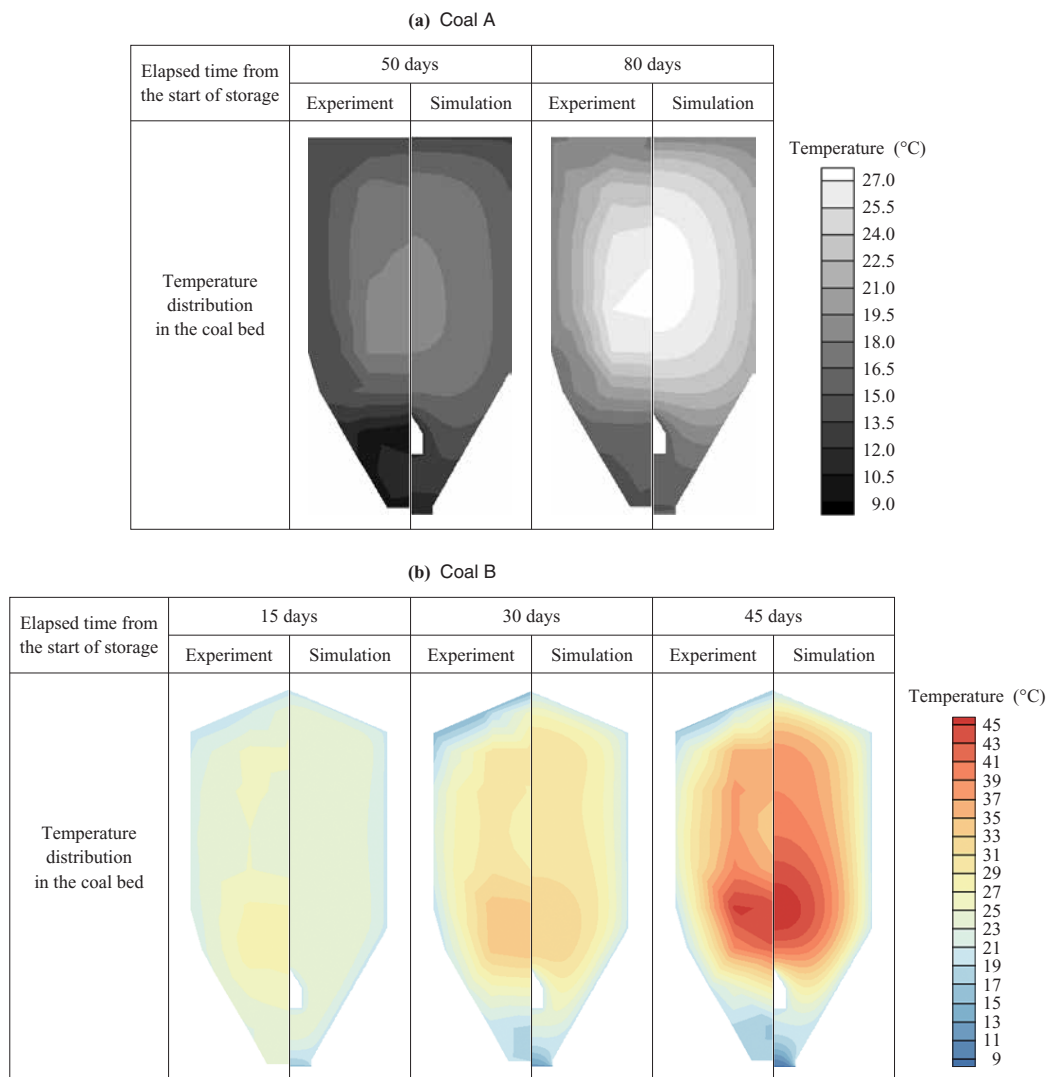


Fig. 9 Comparison of calculation with experimental results (temperature distribution in coal bed)

1/2 the height of the silo from its bottom. This temperature distribution seems to be attributable to the fact that the central part of the coal bed is less susceptible to heat loss through the wall surface. Both the experimental results and numerical results exhibit the same trends in temperature distribution and its temporal changes.

5.3 Humidity of gas in the silo

The measured values of relative humidity of the gas in the space above the coal bed were approximately 100% for both experiments. In addition, a lot of water droplets were observed condensing on the inner wall surface of silo above the coal bed. This phenomenon seems to have occurred through the following process, i) as the coal heated, the moisture in the coal vaporized, ii) the water vapor then condensed in the space above the coal bed, where temperatures were relatively lower than those in the coal bed.

5.4 Nitrogen charging into the coal bed

During the storage test of coal A, the maximum temperature of the coal bed exceeded the target temperature (on the 125th day from the start of the experiment). At this moment, gaseous nitrogen was put into coal bed from the bottom of the silo.

Its volume flow rate was 384 l/min for the first four hours. Subsequently, the flow rate was gradually reduced to 100 l/min. **Figure 10** shows the change in oxygen concentration in the space above the coal bed after nitrogen was fed into the silo. (Due to a temporary trouble of the measuring equipment, no measurements were taken for a certain period of time. For this period, calculation results are shown instead.) When about 24 hours elapsed after nitrogen had been flowed into the silo, the oxygen concentration reached below 5%, and its level was maintained.

With nitrogen filled in the silo, the temperature of the coal in storage stopped to increase, and it gradually decreased at a rate of approximately 0.7°C per day. A study of the dependency of

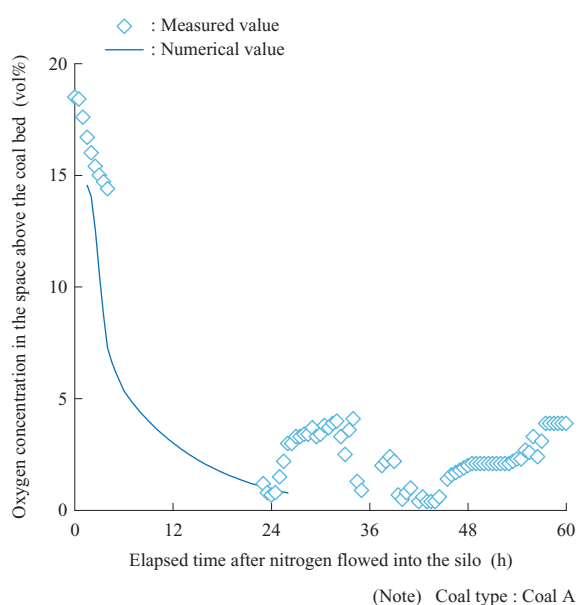


Fig. 10 Oxygen concentration in gas above the coal bed after nitrogen enters the silo

low-temperature oxidation reaction on oxygen concentration⁽⁵⁾ has revealed that by reducing the oxygen concentration in the coal bed below 5%, the rate of low-temperature oxidation decreases to less than half. It is thought that the oxygen concentration in the coal bed decreased below 5% in a short time by the nitrogen filled in the silo, and it reduced the rate of low-temperature oxidation reaction and then suppressed the heat generation.

6. Conclusion

The experiments with a duration of several weeks were conducted on low-rank coal (sub-bituminous coal) being stored in an experimental silo. It was confirmed that a heated zone was formed in the central part of the coal bed and that the rate of coal bed temperature increase was affected by the ambient temperature. Numerical analysis was conducted taking into account changes in ambient temperature, as well as air entering the coal bed, heat generated by low-temperature oxidation occurred in coal particles, and the transfer of the moisture, correctly reproducing the maximum temperature of stored coal. In case of the temperature distribution in the coal bed, the numerically simulated results showed good agreement with measured results in the storage experiments.

As a control method for overheating of coal bed, nitrogen charging into the silo was conducted. Gaseous nitrogen flowed into the coal bed from the bottom of the silo after the maximum coal bed temperature reached the predetermined target temperature. Within 24 hours, the coal bed was filled with nitrogen and the oxygen concentration decreased below 5%. As a result, the coal bed temperature gradually decreased. It was found that nitrogen had little effect in cooling the coal bed, however it could reduce the oxygen concentration, which was highly effective for suppressing low-temperature oxidation.

IHI Group will carry out public relations activities to inform customers operating coal storage and handling facilities of the outcomes of the present study. It is our hope to make proposals for the improvement of existing facilities to make them suitable for low-rank coal or newly constructing coal storage facilities suitable for low-rank coal, based on predictions of its heating behavior.

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