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Development of Highly Efficient Combustion in Coke Oven Bleeder Pipe

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Abstract:

Coke oven dissipation bleeder is an emergency equipment to prevent leakage of surplus coke oven gas and to combust it safely. One of serious problems at flaring is generation of large black smoke. Black smoke contains a large amount of soot which is caused by thermal decomposition of coke oven gas. Various studies have been conducted on the mechanism of soot formation, but it has not been fully elucidated in commercial flaring equipment. In this study, we elucidated the mechanism of suppressing soot generation using combustion experiments and numerical simulation and developed a technology for a smokeless dissipation bleeder by promoting combustion. This technology has been introduced to all coke ovens in JFE Steel and contributed to suppressing the generation of black smoke.

1. Introduction

Coke ovens are facilities that produce coke by carbonization of coal, and also recover the coke oven gas (COG) generated in the coke carbonization process. The COG generated by coke ovens is conveyed to a gas refining plant through a dry main and suction main by blowers. However, the COG cannot be recovered if the suction blower or gas refining plant stops due to a power outage or other trouble. Since the temperature of the furnace body of the coke oven cannot be reduced quickly, even if it becomes impossible to recover the COG due to an equipment stop, carbonization of coal and generation of COG will continue. If generation of COG continues, the pressure in the coke oven and piping will increase, and leakage of COG from the brick joints and abnormal combustion may occur.

Therefore, coke ovens are equipped with dissipation bleeders as safety equipment to prevent this kind of trouble. A dissipation bleeder is installed in the dry main, and reduces the pressure in the dry main and furnace by opening when equipment trouble occurs and allowing the COG to dissipate. During dissipation, the COG is detoxified by burning.

Figure 1 shows the combustion structure of a dissipation bleeder. In the general dissipation bleeder combustion method, COG is supplied from the bleeder pipe, and combustion air is supplied by natural suction of outside (atmospheric) air through the space between the bleeder pipe and a hood installed at the end of the bleeder pipe. However, in this combustion method, black smoke (soot) is generated during combustion discharge. Therefore, in this research, we elucidated the mechanism of reduction of black smoke by combustion experiments and a numerical simulation, and developed a technology for a smokeless dissipation bleeder combustion.

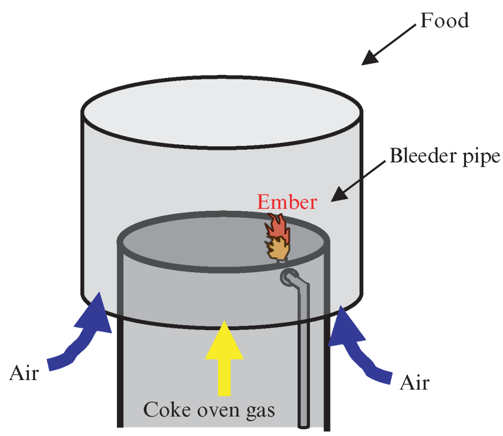

Fig. 1 Combustion structure of bleeder pipe

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2. Study of Smokeless Combustion

2.1 Cause of Black Smoke

Black smoke is visible smoke that occurs as a result of flocculation of soot particles. Various studies have investigated the mechanism of soot generation, but it still has not been fully elucidated. Nevertheless, soot particles are formed by the combustion reaction of hydrocarbons, and hydrocarbons form soot particles when a lack of high temperature air causes thermal decomposition of the fuel molecule.

Diffusion combustion is a type of combustion in which the fuel and oxidizers are supplied separately to the combustion field, and its flame form is called a diffusion flame. Because thermal decomposition occurs in areas with a comparatively low temperature and lack of oxygen, the diffusion flame is directly influenced by the structure of the fuel. **Table 1** shows the types of fuels and the difficulty of soot generation in diffusion flames. Larger rank numbers mean soot forms more easily. Refined COG has comparatively high difficulty of soot formation (Rank 4), but tar forms soot extremely easily (Rank 12). Therefore, it can be thought that COG containing tar before refining forms soot easily.

The dissipation bleeder is thought to form a diffusion flame with a flame structure like that shown in **Fig. 2**. Because a diffusion flame forms at the contact surfaces between the fuel and air, an unburned state occurs inside the flame, where only fuel exists. Accordingly, soot particles form inside the flame during combustion of hydrocarbon gases. The formed soot particles grow as they rise, and then reach the reaction zone (i.e., flame). Although the soot that reaches the reaction zone is oxidized by the oxidation reaction, aggregations of unreacted soot particles are discharged outside the bleeder, where they are cooled and form black smoke, which has a black appearance. To summarize this process, the interior of the diffusion flame is in an unburned state, soot particles form under this condition, and then become black smoke due to incomplete oxidization in the reaction zone.

Table 1 Fuel type and difficulty of soot generation

Rank	Fuel	Rank	Fuel
1	Natural gas	7	Coke
2	LPG	8	Lignite
3	Production gas	9	Low volatility bituminous coal
4	Coke oven gas	10	Crude oil
5	Kerosene	11	High volatility bituminous coal
6	Diesel	12	Tar

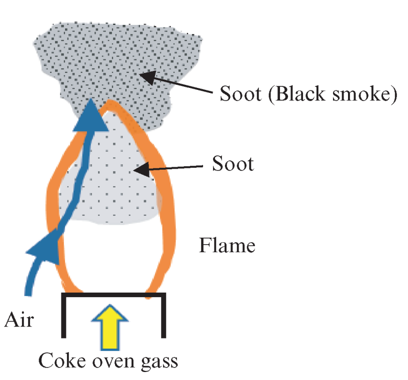


Fig. 2 Structure of diffusion flame

Here, the following Eq. (1) shows the generation speed of soot in a diffusion flame, and Eq. (2) shows the oxidation rate of soot[1]. The amount of black smoke generation is determined by the balance of the soot generation speed and the soot oxidation rate.

$$S_f = 2.54 \times 10^6 \cdot \frac{2gr_B}{u_f^{\,2}} \cdot p_f \cdot \left(\frac{1}{m}\right)^3 \exp\left(\frac{-20\,000}{T}\right) \quad \ldots (1)$$

$$S_b = 3.6 \cdot m_s \cdot \frac{p_0}{\sqrt{T}} \cdot \exp\left(\frac{-20\,000}{T}\right) \quad \ldots\ldots\ldots\ldots\ldots (2)$$

2.2 Smokeless Combustion Method

A combustion method for reducing black smoke was studied. As described in section 2.1, soot is formed when thermal decomposition of a hydrocarbon gas occurs as a result of a lack of air in a high temperature field. Therefore, the following are considered to be effective combustion methods for reducing soot formation.

① Reducing the flame temperature so that a high temperature field is not formed.

② Increasing the supply of oxygen (combustion promotion) so that a lack of air does not occur.

First, ① Effect of flame temperature reduction was examined. **Figure 3** shows the result of a trial calculation of the effect of flame temperature reduction using Eqs. (1) and (2). The flame temperature was assumed to be the adiabatic flame temperature of COG, and the frequency of black smoke was evaluated by (the soot generation speed)/(soot oxidation rate). Assuming the frequency of black smoke at the adiabatic flame temperature in the current condition is 100 %, the frequency of black smoke is decreased by reducing the flame temperature. Thus, it can be thought that reducing the flame temperature leads to a decrease in black smoke.

Injection of steam is one method which reduces the flame temperature, and had already been introduced at

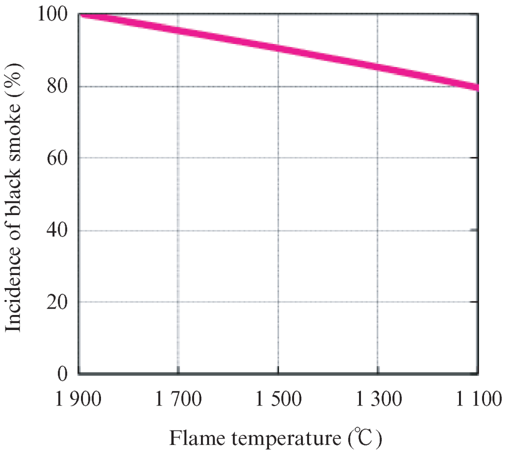


Fig. 3 Relationship between incidence of black smoke and flame temperature

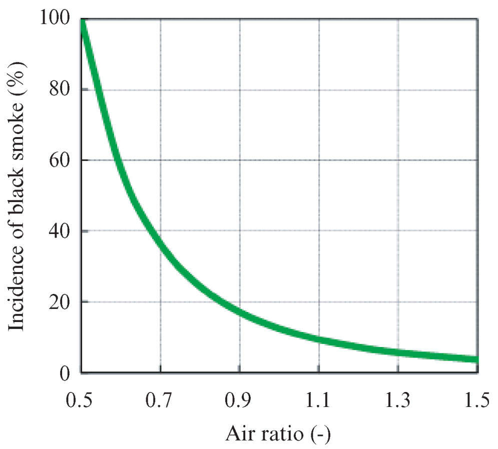


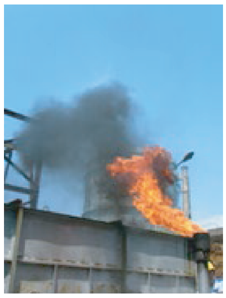
Fig. 4 Relationship between incidence of black smoke and air ratio

JFE Steel's East Japan Works (Keihin). While it is the most general smokeless combustion technology, it cannot completely prevent black smoke.

Next, ② Effect of combustion promotion was studied as a method for increasing the supply of oxygen. **Figure 4** shows the result of a trial calculation of the effect of combustion promotion using Eqs. (1) and (2). The frequency of black smoke is substantially reduced by increasing the air ratio. Comparing Fig. 3 and Fig. 4, the decrease in the frequency of black smoke when the air ratio is increased is greater than the decrease in the frequency of black smoke when the flame temperature is reduced, indicating that the black smoke reduction effect of combustion promotion is greater than the effect of flame temperature reduction.

Although steam is generally used to reduce the flame temperature, these results suggest that more effective smokeless combustion is considered possible by using air, which is also lower in cost than steam.

Table 2 Experimental results of flame temperature drop

Combustion method	① Normal combustion	② Premixed combustion
Injection	–	Steam
Combustion state (Amount of black smoke)		
Flame temperature	490°C	400°C

2.3 Combustion Experiments

The combustion method with a higher black smoke reduction effect was clarified by lab experiments. A bleeder model with a scale of 1/8 the size of the actual device was used as the apparatus for the lab experiment apparatus, and black smoke generation was reproduced by using a fuel consisting of vaporized benzene mixed in refined COG.

Using the following four combustion methods (① to ④) as the combustion methods, combustion was performed, with steam or air as the injected fluid.

① Normal combustion: No fluid injection (no steam or air injection).

② Premixed combustion: The fluid is injected into the bleeder and mixed with the fuel in advance.

③ Ejector combustion: The fluid is injected, and atmospheric air is drawn in by the ejector effect.

④ Flame mixing combustion: The fluid is injected vertically upward toward the flame from the center of the bleeder tip.

As the evaluation method, the amount of black smoke reduction was evaluated by visual observation, and the combustion condition was confirmed by the flame temperature (at a position 100 mm from the center of the bleeder tip).

First, the effect of flame temperature reduction was investigated. This experiment was conducted using ① Normal combustion and ② Premixed combustion as the combustion methods, and the results were compared. In ②, steam was used as the injection fluid. The experimental results are shown in **Table 2**. In comparison with ① Normal combustion, the flame temperature decreased from 490°C to 400°C with ② Premixed combustion with steam injection. Although the amount of black smoke was also reduced owing to the decrease in the flame temperature, generation of black smoke could not be suppressed completely.

Next, the effect of combustion promotion was investigated. This experiment was carried out using all four combustion methods and air as the injection fluid (the air flow rate was the same in all cases). The experimental results are shown in **Table 3**.

In ② Premixed combustion using air, combustion was not promoted because the flame temperature decreased by 40°C in comparison with ① Normal combustion. Therefore, almost no black smoke reduction effect was obtained.

In ③ Ejector combustion, the flame temperature was 850°C, or an increase of 360°C from that in normal combustion. This rise in the flame temperature can be attributed to promotion of combustion by supplying an adequate amount of air. As a result, black smoke was reduced, and generation could be suppressed completely.

In the case of ④ Flame mixing combustion, the flame temperature increased 110°C in comparison with normal combustion, reaching 600°C. As in ③, this temperature rise is also considered to be due to combustion promotion by supplying air. However, the amount of black smoke decreased, but black smoke could not be suppressed completely.

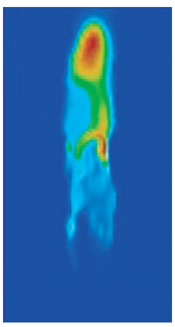
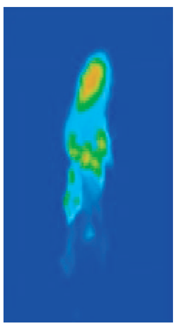
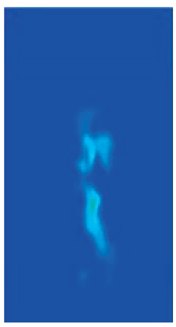
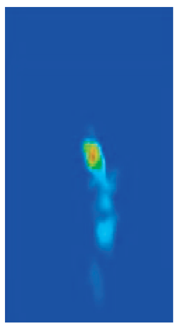
As described above, combustion promotion has a larger black smoke reduction effect than flame temperature reduction, and black smoke can be reduced with high efficiency (i.e., the air flow rate can be reduced) by utilizing ③ Ejector combustion method. These experiments also demonstrated that smokeless combustion is possible by using air, which is more economical than steam, and not by the conventional method using steam.

2.4 Numerical Simulation

In order to verify the black smoke reduction effect of combustion promotion, a simulation of soot generation was carried out using the same combustion methods ① to ④ as in the lab experiments. The amount of soot generation was compared, and the mechanism of black smoke reduction in ejector combustion was elucidated.

In this development, we used the finite volume method code for unstructured grid systems Front Flow Red-Comb (NuFD/FFR extended by Kyushu University, CRIEPI, Kyoto University and NuFD)[2], which has a record of application in combustion simulations in the steel manufacturing process. The governing equations comprised a continuity equation applying a Faver filter, the Navier-Stokes equations, an energy conservation equation and mass conservation equations for each chemical species. Considering the strong unsteadiness of the diffusion flame and soot generation by the diffusion flame, LES was used in the turbulence model and the Dynamic Smagorinsky model was used in the modeling of SGS (subgrid-scale) components [3,4].

Table 3 Experimental results of combustion acceleration

Combustion method	① Normal combustion	② Premixed combustion	③ Ejector combustion	④ Flame mixing combustion
Injection	–	Air	Air	Air
Combustion state (Amount of black smoke)				
Flame temperature	490°C	450°C	850°C	600°C
Soot volume fraction  				

The SMAC method was used in corrections of pressure and velocity. In discretization of advective terms, the second-order central difference and the first-order upwind difference were mixed at a ratio of 95 : 5. The first-order Euler implicit method was used in the time integration algorithm. Statistical quantities were calculated assuming a time step set at $d_t = 1.0$ ms and a run-up section defined as 20 000 steps from the start of calculation, and taking the average from 20 000 steps to 25 000 steps.

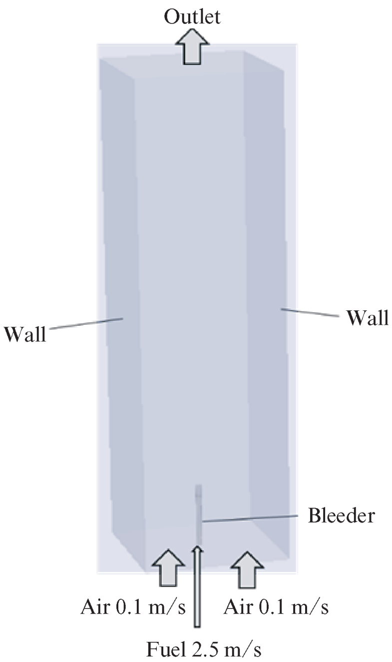


Fig. 5 Geometry of simulation

To consider the effects of the SGS components of LES, a Scaled similarity filtered reaction rate model (SSFRRM)[5] was adopted in the turbulent combustion model. For the soot generation model, the acetylene precursor model proposed by Wen et al.[6] was used. The geometry of the simulation and the boundary conditions are shown in **Fig. 5**. The air injection conditions were the same as in the experiments.

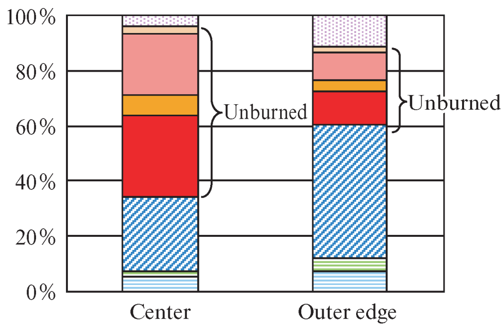
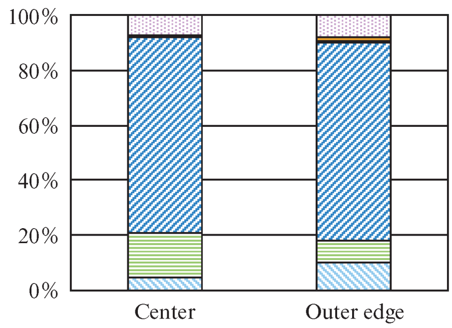
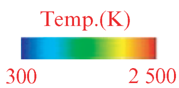
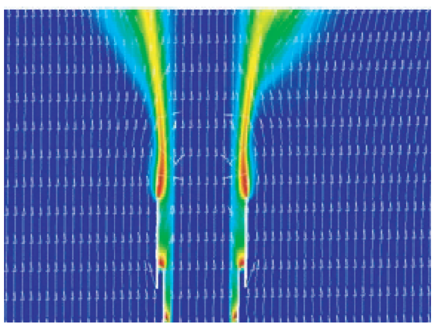
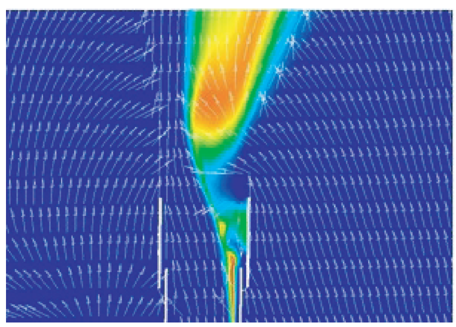
Table 4 shows the instantaneous values of the volume fraction of soot in the simulation results. As in the experimental results, the simulation results also showed that ejector combustion achieves the smallest amount of soot generation. Moreover, in all the combustion methods except ejector combustion, the peak position of soot was separated by some distance from the bleeder tip. This shows the phenomenon that black smoke is generated from the flame tip, as observed in Tables 2 and 3.

Based on these results, this numerical simulation model can reproduce the experiment.

2.5 Mechanism of Black Smoke Reduction (Smokeless Combustion)

The mechanism of black smoke reduction in ejector

Table 4 Experimental results and analysis results of simulation

	Smoke combustion	Smokeless combustion
Gas component H_2O C_nH_n CH_4 CO H_2 N_2 O_2 CO_2	 	
Flame temperature	Center : 490°C Outer edge : 500°C	Center : 850°C Outer edge : 580°C
Temperature distribution and flow direction vector  		

combustion was clarified by the lab experiments and numerical simulation. Table 4 shows a summary of the mechanism of black smoke reduction.

From the results of the flame temperature measurements and the gas analysis in the lab experiments, when black smoke is generated (normal combustion), the amount of unburned ingredients is particularly large at the flame center position, and the flame temperature is also low. On the other hand, in smokeless combustion, that is, when black smoke generation is suppressed in ejector combustion, the flame temperature at the flame center position is high, and the amount of unburned ingredients decreases to zero. Based on these facts, in smoke-generating combustion, incomplete combustion occurs in the interior of the flame, and soot is formed and causes black smoke. In contrast, black smoke generation can be suppressed by complete combustion extending to the central part of the flame, which is possible by combustion promotion.

Next, the mechanism of combustion promotion in ejector combustion was clarified. From the results of flow measurements, in normal combustion, the air supplied by natural suction from the space between the bleeder pipe and the hood is equivalent to an air ratio of 0.05, and it can be said that this is a condition of incomplete combustion. The air supply rate in ejector combustion is equivalent to 0.05, and ejector effect increases the amount of suction from the space between the bleeder pipe and the hood to the equivalent of an air ratio of 0.2. However, this is still an inadequate amount of combustion air.

The temperature distribution and vector showing the flow direction around the bleeder tip in the simulation of normal combustion and ejector combustion were shown in bottom of table 4 In normal combustion, a high temperature zone occurs above the edge of the hood. This shows that the combustion reaction is only occurring at the interface between the fuel and the surrounding air, and the fuel inside the combustion zone rises without combustion reaction (i.e., incomplete combustion occurs). In ejector combustion, a condition in which the surrounding air is entrained by the air sucked in as a result of the ejector effect can be observed. The effect of entrainment by this sucked-in air jet causes the surrounding atmosphere to flow in toward the flame, and this supplies combustion air as far as the center of the hood, where the supply of combustion air had been inadequate, and as a result, a high temperature zone is generated in the central part of the hood. The difference in the temperature distributions in normal combustion and in ejector combustion is consistent with the temperature trends obtained in the lab experiments.

Accordingly, as the mechanism of smokeless combustion in ejector combustion, due to the ejector effect, the flow of the surrounding atmosphere can reach the center of the flame, where combustion was incomplete in smoke-generating combustion (normal combustion). This supply of combustion air to the flame center accelerates combustion, thereby suppressing the formation of soot.

3. Results of Actual Machine Introduction

The effect of ejector combustion was verified by a combustion experiment with an actual machine. As shown in **Table 5**, the black smoke reduction effect of air suction can also be obtained with the actual machine. Moreover, because the results of flame temperature measurements showed that the flame temperature was higher than in normal combustion, it is considered that black smoke was also reduced by promotion of combustion in the actual machine, as in the lab experiments.

When this technology was applied to actual coke ovens and the dissipation bleeder actually operated, combustion discharge could be performed without generation of black smoke, as shown in **Photo 1**.

Table 5 Experimental results of actual machine test

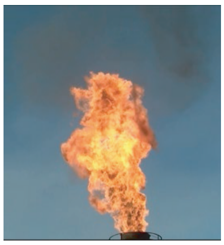
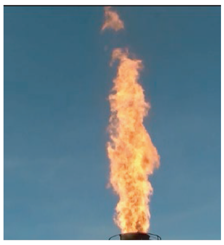
Combustion method	① Normal combustion	③ Ejector combustion
Injection	—	Air
Combustion state (Amount of black smoke)		
Flame temperature	634°C	925°C

Photo 1 Operational status of actual machine

4. Conclusion

Generation of black smoke occurs in dissipation bleeders because incomplete combustion in the interior of the combustion discharge flame causes thermal decomposition of hydrocarbons, which form soot particles that grow into aggregates and are discharged without being oxidized. Based on equations expressing the generation speed and oxidation rate of soot and the results of lab experiments and a numerical simulation, promotion of combustion is effective for reducing black smoke.

Until now, the general technology for smokeless combustion was reduction of the flame temperature by steam injection. However, this development clarified the fact that the black smoke reduction effect of combustion promotion is greater than the effect of flame temperature reduction. As a method for accelerating combustion, the ejector combustion method generates a flow that supplies air from the surrounding atmosphere to the flame by air suction by the ejector effect, and that this method had the highest black smoke reduction effect, as well as the highest efficiency (reduced air flow), among the methods studied here. Moreover, because ordinary air can be used to achieve completely smokeless combustion when this method is applied, the cost of operation can be substantially reduced in comparison with the conventional method using steam injection.

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