발전용 미분탄 보일러의 연소 상태 감시를 위한 화염 영상 처리 시스템

Flame Image Processing System for Combustion Condition Monitoring of Pulverized Coal Firing Boilers in Thermal Power Plant

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Abstract : The flame image processing and analysis system has been investigated for the optimal pulverized coal firing of thermal power plant, especially for lower nitrogen oxide generation and more safe operation. We aimed at gaining the relationship between burner flame image information and emissions of nitrogen oxide and unburned carbon in furnace utilizing the flame image processing methods, by which we quantitatively determine the condition of combustion on the individual burners. Its feasibility test was undertaken with a pilot furnace for coal firing, through which the system was observed to be effective for the monitoring of the combustion condition of pulverized coal firing boilers.

Keywords: flame image processing, combustion monitoring, optic acquisition, frame grabber, unburned carbon, nitrogen oxide

I. Introduction

Increased energy costs have placed demands for improved combustion efficiency, high equipment availability, low maintenance and safe operation. Simultaneously low nitrogen oxide modification, installed due to stricter environmental legislation, require very careful combustion management. With the recent installations of large capacity boilers for power generation in particular, increasingly rigorous requirements have come to be imposed on boilers for a significantly lower level of nitrogen oxide, smaller amounts of unburned carbon, and combustion with low excess air in consequence of the measures taken for the safeguarding of the environment[1].

However, the evaluation and judgment of the combustion conditions in the furnace are made by the operator on the basis of his observations of the shape and brightness of the flame, monitoring of the conditions of the flame behavior and the exhaust dust by means of a television system[2-4], and additionally the monitoring of the properties of the emissions performed from the viewpoint of environmental conservation. These circumstances have raised the needs for a combustion monitoring system that would permit instant detection of individual changes for each burner in the combustion conditions[5-6]. To meet these requirements, we aimed at obtaining the relationship between burner flame images and emissions of nitrogen oxide and unburned carbon in furnace by utilizing the flame image processing methods, which quantitatively determines the conditions of combustion on the individual burners. This paper presents a summary description of this system, together with a synopsis of the experimental results obtained from verifying tests conducted on pulverized coal fired pilot furnace, which reveals that a close correlation exists between the changes observed in the flame image data and the emissions of nitrogen oxide and unburned carbon in furnace. As the basic step of the investigation for the system implementation, its feasibility test was undertaken with a bench furnace[7]. In this paper, the test proceeded with pilot furnace for pulverized coal firing, through which the system was observed to be effective for evaluating the combustion conditions monitoring and burner maintenance for pulverized coal firing boilers. This technology may contribute to the saving of burner adjusting times for the changes of the loads and fuels, also to the reduction of the slagging.

II. Flame Image Processing

NTSC image data generally consists of three components such as luminance, hue, and saturation. The first component, luminance, represents gray scale information, while the last two components are mixed to make up chrominance[8]. As hue varies from 0 to 1.0, the corresponding colors vary from red through yellow, green, cyan, blue, and magenta, back to red. As saturation varies from 0 to 1.0, the corresponding colors vary from unsaturated to fully saturated, i.e. from shades of gray to no white component.

1. Quantification of flame image

The Hue level of flame stands for the dominant wavelength of the light area. Regarding a luminous substances, the relationship between wavelength and hue level is as following[9].

$$\begin{aligned} \lambda &= -\frac{\lambda\ \max - \lambda\ \min}{Quantity\ \ Level}\ Hue + \lambda\ \max \\ Hue &= \frac{Quantity\ \ Level}{\lambda\ \max - \lambda\ \min}\ (\lambda\ \max - \lambda\ ) \end{aligned} \tag{1}$$

where, λ is the wavelength, λmax = 700nm, λmin = 400nm, and *Quantity Level* = 256, which is a resolution of video A/D converter imbedded on the image processing unit.

Luminous flame, such as heavy oil flames and pulverized coal flames, generally emit continuous spectra, the radiating sources of which are the fine particles of pulverized coal, i.e. fine solid particles so called "soot" at a very high temperature in the combus-

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표 1. 광원의 파장과 색도.

Table 1. The wavelength and Hue level of a source of light.

wSource of light	Wavelength (nm)	Hue level (0~256)
OH	306, 308, 312, 314	Unobservable
CH	431, 438	229, 223
C_2	563, 516, 60~498	116, 157, 205~172
	285-298	Unobservable
NO_2	600~875	0~85
CO	430	230
H_2O	800~1250	Unobservable

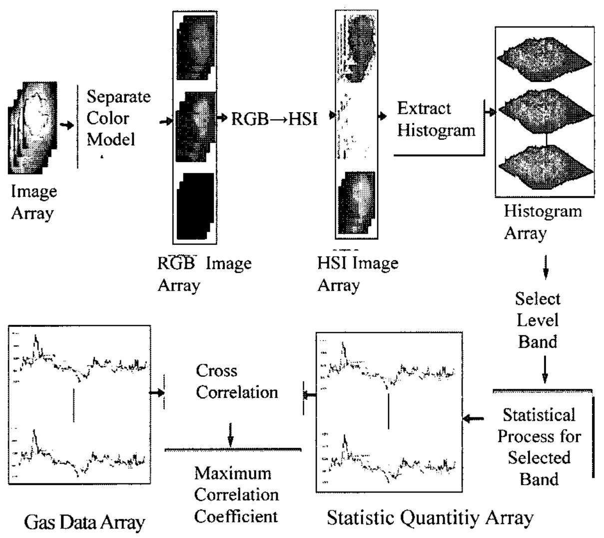


그림 1. 화염영상과 가스 데이터의 상관관계 추적 흐름도.

Fig. 1. Tracking flow diagram of correlation between the flame image and gas data of emissions.

tion process. For judging the condition of a flame, it is frequent practice to depend on the visual perception of the color and brightness of flame. The light has radical luminescence with OH, CH, C_2, NO_2, CO, and, H_2O, the corresponding hue levels of which are summarized in Table 1, calculated by (1).

2. Flame image data processing

The pixel size of the flame image is fixed according to the programmable input scaling of the frame grabber of image processing unit, irrespective of the image pickup area and scanning system supported by the CCD camera. Selection of large pixel size gives us more information on the flame image, but also higher computational cost on the other hands[10]. Hence, we chose 160 x 120 pixels for the flame image processing. The flame light is too bright to be directly handled by CCD camera, which should be properly reduced by the adjustment of shutter and iris control. Simultaneously the flame image is contaminated by some noise such as eddy currents and hot spots due to radiation effects, which should be screened by some filtering process.

3. Correlation between flame images and emissions

The image obtained by CCD camera and frame grabber is stored in TIFF format in image processing unit and the histogram of that is extracted. Statistical processes for properly selected level band are then obtained, while emissions in furnace are repeatedly measured by gas analyzing equipment and stored in ASCII format. The correlation between flame images and emissions is obtained by (2) as illustrated in Fig. 1.

$$\rho_{xy}(n) = \frac{r_{xy}(n)}{\sqrt{r_{xx}(0)r_{yy}(0)}} \qquad n = 0, \pm1, \pm2...$$
$$r_{xy}(n) = \frac{1}{N}\sum_{k=0}^{N-n-1} x(k)y(k+n) \qquad n = 0,1,2... \qquad (2)$$
$$r_{xx}(n) = \frac{1}{N}\sum_{k=0}^{N-n-1} x(k)x(k+n) \qquad n = 0,1,2...$$

where, $0 \le \rho_{xy} \le 1$, if ρ_{xy} is 1, the two signal x and y are identical. It will be shown hereafter that the close relationship exists between specific band of hue level and emissions of nitrogen oxide and unburned carbon in furnace.

III. Flame Analysis System

For quantitative evaluation of the combustion conditions of nitrogen oxide and unburned carbon, a CCD camera is mounted for each burner, as shown in Fig. 2. The flame images are led as a video signal from the cameras to the multi-viewer and displayed in real time on the control room monitor. Compressed images can be monitored on one screen simultaneously to compare the different burners, thus allowing the control of the combustion process at each burner.

1. System hardware

The system hardware as shown in Fig. 3 is divided into two part of optic acquisition units and flame monitoring panel. The first part, which is for obtaining the flame image, consists of optical probe, CCD camera, air cooling housings, automatic retraction equipment as shown in Fig. 4, and local rack for control cooling air for protecting optical probe under high temperature.

The second part, which is for monitoring and analyzing the flame image, consists of muliplexer, TV monitor, routing switcher, flame detection unit, computer, frame grabber, and LAN card.

2. System software

The System software can be divided into two parts: the image processing program and the diagnostic result display program, as shown in Fig. 5. The image processing program captures flame images of each burner and calculates constitution of nitrogen

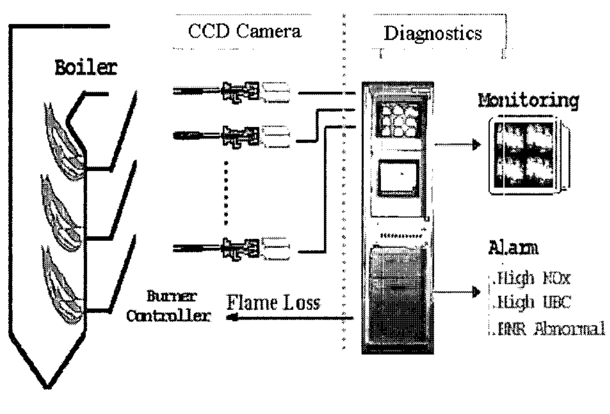


그림 2. 시스템 구성 개략도.

Fig. 2. Schematic diagram of system configuration.

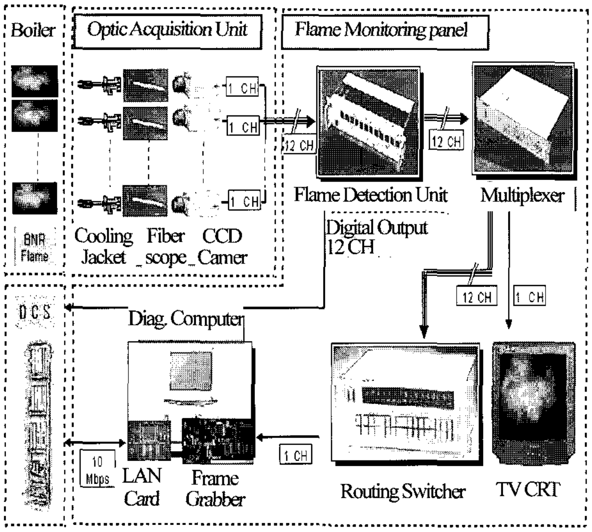


그림 3. 화염영상 감시를 위한 기기 구성.

Fig. 3. Apparatus configuration for the flame image monitoring.

oxide and unburned carbon through color analysis and filtering process.

The diagnostic result display program shows the result from the image processing program through a computer monitor in real time, providing alarm functions and historical trending, which is composed with 7 screens. Additionally it sets parameters for image processing and communicates with external machines.

The resulting system produces flame parameters at an interval of 10 seconds. This provides information to the operator on changes in direct numeric and graphic presentation of the flame stability, which enables the operators to observe trends and to prevent future loss of ignition

This also provides continuous monitoring of the quality of the combustion of unburned carbon and nitrogen oxide concentration, which enables to reduce combustible ash and nitrogen oxide.

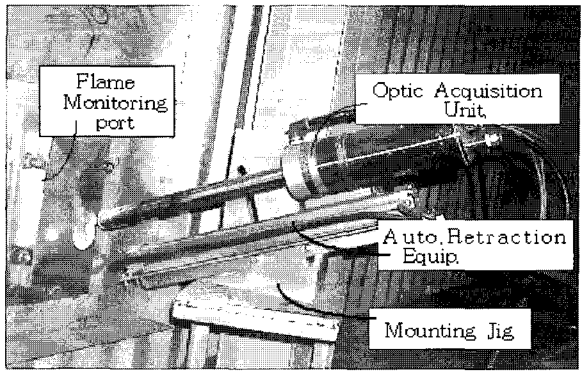


그림 4. 화로에 장착된 화염 수광부와 자동후퇴장치.

Fig. 4. Optic acquisition unit and automatic retraction equipment mounted at burner side of coal firing furnace.

IV. Experimental results

The 1MW$_{th}$ pilot furnace as shown in Fig. 6 consists of coal feeding system, firing system, and fuel treatment system.

A top-fired externally air staging burner is adopted in order to avoid influence of gravity on the coal particles and for easy maintenance. Distribution of temperature and chemical species concentration of coal flames can be measured in vertical pass of furnace.

The furnace dimension is ψ 2.10 x 7.60 m, coal firing rate is 180 km/h, and main fuel of Australian high bituminous coal is pulverized by 83.4% less than 80μm. From variety of test conditions, overall excess air ratio is selected at 1.2 i.e. 20% excess air. The experiments were executed under the condition of 100% load, fixed swirl number, while varying excess air ratio from 0% to 20%. When emissions of nitrogen oxide and carbon monoxide and unburned carbon were measured by analyzing equipment, the flames were simultaneously captured by the optic acquisition units. The relationship between nitrogen oxide and hue is shown in Fig. 7.

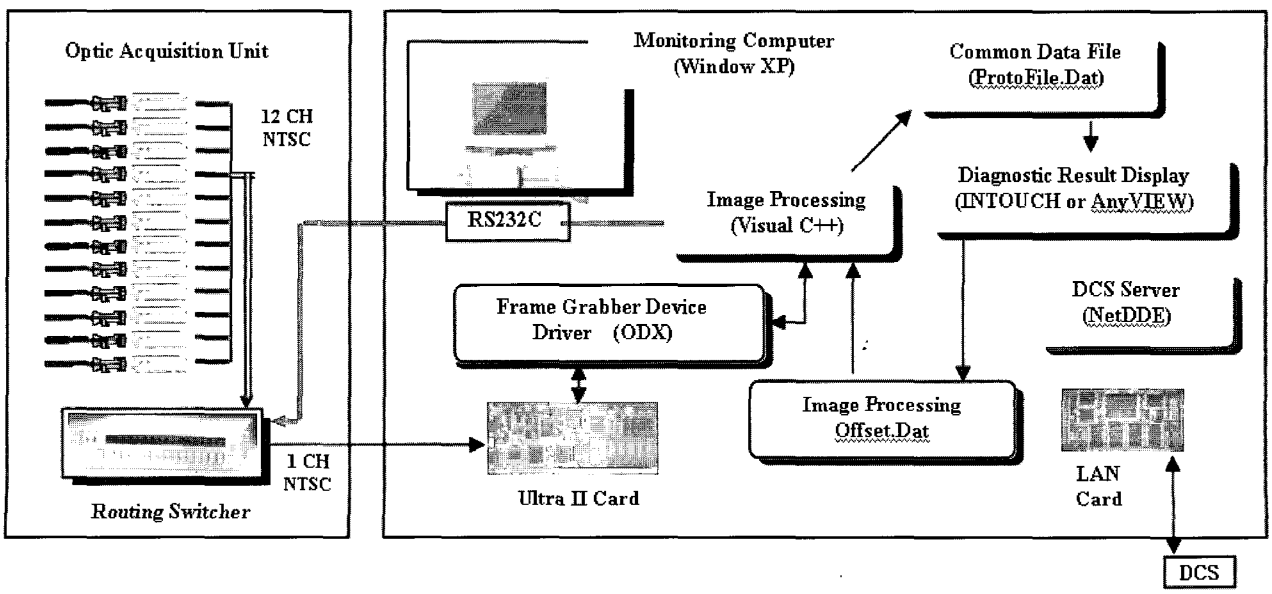


그림 5. 시스템 소프트웨어 구성 및 영상처리 데이터 흐름도.

Fig. 5. System software configuration and data flow diagram for the image processing.

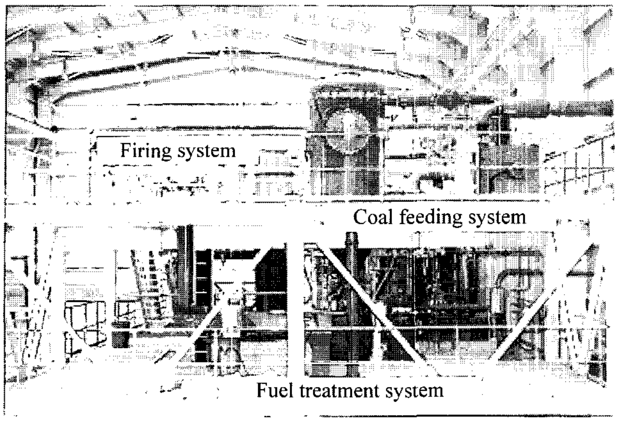


그림 6. 시험용 미분탄 연소로.

Fig. 6. Pilot furnace for pulverized coal burning.

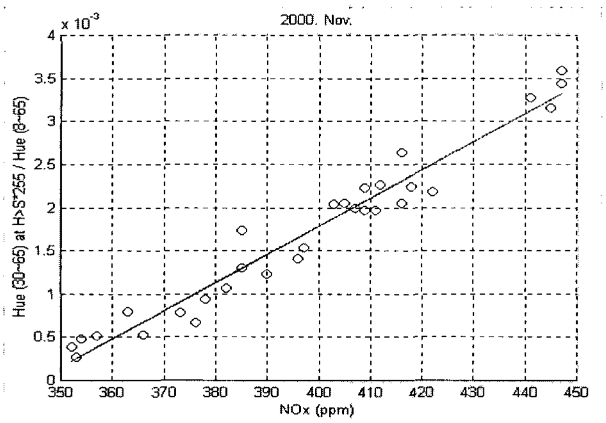


그림 7. 질소산화물과 색도레벨의 상관관계.

Fig. 7. Relationship between nitrogen oxide and the hue level.

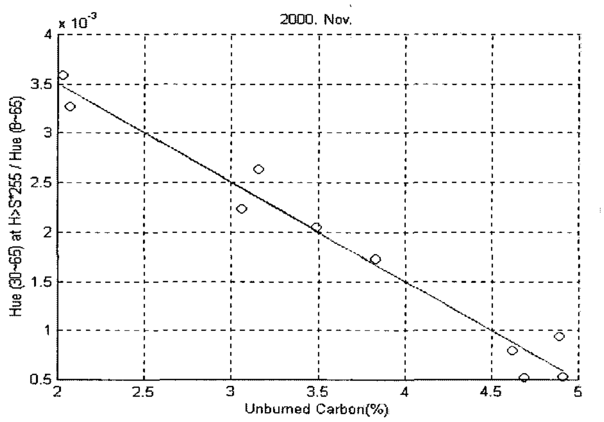


그림 8. 미연 탄소와 색도레벨의 상관관계.

Fig. 8. Relationship between unburned carbon and the hue level.

It is observed that the specific band of hue level of 30 to 65 is directly proportional to the concentration of nitrogen oxide. As shown in Fig. 8, it is observed that the band is inversely proportional to the unburned carbon.

Nitrogen oxide, unburned carbon, the flame stability and the firing spot delay distance as shown on the right side of Fig. 9. are used for the firing index, which is represented in shape of diamond,

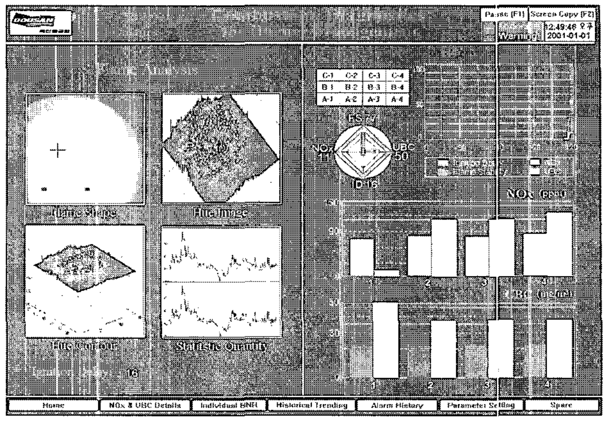


그림 9. 개별버너 화염의 감시화면.

Fig. 9. A screen for the individual burner flame monitoring.

while real time trend of 2 minutes' interval are displayed. Nitrogen oxide and unburned carbon value is described by bar graphs. The left side of the screen displays the calculation processing of index conversion for the firing spot delay distance and the flame stability. If we want to view another burner, we can click the burner selection button at the center of screen.

We can analyze historical data of the firing index of the each burner by selection of the area and the time interval through the historical trending screen. Additionally we can review abnormal combustion records through the alarm history screen.

V. Conclusion

An experimental study was conducted for obtaining the correlation between combustion conditions and flame image captured by CCD camera. As the result, it has been found that the specific band of hue level is closely related to the concentration of nitrogen oxide and unburned carbon in the furnace. By using this, it is possible to perform continuous monitoring of the combustion conditions and instant detection of individual changes for each burner to prevent future loss of ignition, thus demonstrating the possibility of adopting this band of hue level as practical index for evaluating the combustion conditions. The test will be continued under industrial service conditions soon.

References

[1] F. Griffiths and J. A. Barnard, "Flame and combustion," *Blackie Academic & Professional*, Glasgow, pp. 108-112, 141-142, 1995.

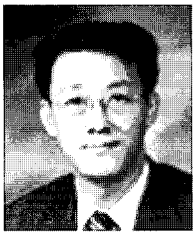
[2] K. Kawamura, A. Saito, T. Yaegashi, and Y. Iwashita, "Measurement of flame temperature distribution in engine by using a two color high speed shutter TV camera system," *SAE Technical Paper Series*, 890320, 1989.

[3] J. M. Char and J. H. Yeh, "The study on propane flame temperature measurement with infrared technique," *Experimental Heat Transfer, Fluid Mechanics and Thermo dynamics*, pp. 1122-1129, 1993.

[4] A. C. Eckbreth, P. A. Bonczyk, and J. E. Verdick, "Combustion diagnostics by laser raman and fluorescence techniques," *Energy combust. Sci.*, vol. 5, pp. 253-322, 1979.

[5] T. W. Lee, S. B. Lee, and J. Y. Ha, "A study on a technique of the measurement of flame temperature and soot using the two-color method in diesel engines," *Trans. of the KSME (B)*, vol. 20,

no. 9, pp. 3007-3014. 1996.
[6] T. Y. Lee, S. H. Kim, and S. R. Lee, "Flame diagnostics using image processing techniques," *KSPE*, vol. 16, no. 7, pp. 196-202, 1999.
[7] W. B. Baek, I. C. Hwang, and S. J. Lee, "A study on the flame monitoring system development," *KSPE* , vol. 21, no. 2, pp. 60-66. 2004.
[8] R. K. Hanson, "Combustion diagnostics: Planar imaging techniques," *Twenty First Symposium on Combustion*, pp. 1677-1691, 1986.
[9] J. louis and J. Galbiati, *Machine Vision and Digital Image Processing Fundamentals*, Prentice-Hall International, 1990.



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