Flame Diagnosis using Image Processing Technique

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ABSTRACT

Recently the interest for the environment is increasing. So the criterion for the evaluation of the burner has changed. For efficient driving problem, if the thermal efficiency is higher and the oxygen in exhaust gas is lower, then burner is evaluated better. For environmental problem, burner must satisfy NOx limit, soot limit and CO limit. Generally the experienced operator judge of the combustion status of the burner by the color of flame. we don't still have any satisfactory solution against it. the relation of the combustion status and the color of the flame hasn't still been established. This paper is the study about the relation of the combustion status and the color of the flame. This paper describes development of real time flame diagnosis technique that evaluate and diagnose combustion state such as consistency of components in exhaust gas, stability of flame in quantitative sense. In this paper, it was proposed on the flame diagnosis technique of burner using image processing algorithm. the parameter extracted from the image of the flame was used as the input variables of the flame diagnostic system. at first, linear regression algorithm and multiple regression algorithm was used to obtain linear multi-nominal expression. Using the constructed inference algorithm, the amount of NOx and CO of the combustion gas was successfully inferred. the combustion control system will be realized sooner or later.

Keywords : Flame Diagnosis, Image Processing, Correlation Coefficient, HSI Color Model, Burner

1. Introduction

These days, Influence on environmental problems, such as Concentration of NOx or CO in exhaust gas, is referred as one of criteria for the performance evaluation of burners. However, existing burners fall short of satisfaction for criteria mentioned above. Therefore development of on-line combustion monitoring and control system is indispensable for the operation of classical burners to satisfy such issues.

The criteria consists of issue about efficiency and one about influence on environmental problem. The issue about efficiency is thermal efficiency and reduction of oxygen in exhaust gas. The issue about influence on environmental problem is reduction of concentration of NOx and CO. Eventually, making the burner good means that maximize thermal efficiency under the restriction about concentration of oxygen, NOx, and CO. Therefore, the technique about measurement and diagnosis for the state of burner. On the contrary, Existing burners are driven by control action which is made by expert operator who watches flame through window or TV camera. Such a method is neither able to notice abnormality of burner in early stage nor able to drive burner under optimal condition because there is no qualitative resolution. As a result, development of technique of active combustion diagnosis is needed. Though Lee[(1)] introduced image processing technique to the measurement of temperature and concentration of soot in internal combustion engine, there is no study about application of image processing technique to the combustion diagnosis of burner state.

The object of this paper is development of evaluation and diagnosis technique for the combustion state (i.e.

concentration of components in exhaust gas, stability of flame, and notice of ignition) for industrial burner which runs in generation boiler or industrial furnace.

This study focuses on the luminescent wave length from a chemical reaction and measures the luminescence via an optical measuring apparatus and derive correlation with the concentration of the components in the exhaust gas and image processing technique.

In deriving a correlation, a cross correlation method and auto tracking algorithm are used to find image processed quantities and combustion state properties which are strongly correlated.

2. Theoretical Background

2.1 Mechanism of flame luminescence

Flame luminescence consists of chemiluminescence, radical luminescence, and the thermal radiation of soot.

Chemiluminesence is luminescence radiated during a chemical reaction among chemical agencies, oxygen, nitrogen, or other chemical agencies.

Table 1. Wave length of luminescence

Luminescence Source	chemical Species	wave length
radical	OH	306.36nm, 306.7nm, 308.9nm, 312.2nm, 314.4nm
	CH	431.5nm, 438.4nm, 387-396nm, 314nm
	C_2	563.6nm, 285.5-298.7nm 516.5nm, 460-498nm,
	NO_2	600-875nm
soot	CO	430nm
	H_2O	800-1250nm

Radical luminescence is luminescence radiated from the electrons of C2, CH, and OH while they transact from an unstable state to a stable one. Thermal radiation is the black-body radiation of soot. In case of hydrocarbon fuel, flame luminescence is combination of these three ones. Especially, it is impossible to measure chemical luminescence or radical luminescence from luminescence from liquid fuel since thermal radiation is major source of the luminescence.(according to the study by Shin[2], energy from the flame made from liquid fuel is energy of thermal radiation of CO, not chemiluminescence of CH radical because the wave length of these two kinds of luminescence are same.). Dean[3] measured the wave length of radical luminescence using a photometry method, and Stile[4] measured the wave length of radical luminescence and chemiluminescence using Molecular Emission Cavity Detection(MECA) The wave length measured by photometry and MECA are presented in Table. 1.

2.2 Conversion of Color Model for Flame Analysis

Color model[5] is method of color expression by a linear combination of basic components. Objective to use color model is to classify color according to some criteria. This study introduced HSI model to analyze luminescence in the sense of wave length. HSI model is the method of color expression by components named as hue, saturation, and intensity. Hue is dominant color. It means wave length which has dominant energy in radiation. Saturation is ratio of mixed white to hue. It means distribution of energy to wave length. Intensity is gray level. It means total energy of radiation. Geometric coordinate of HSI model[6] is cylindrical. Hue, saturation, and intensity means angle, distance, and height, respectively. A point in this coordinate represents color. Equation (1) reveals the equation of expression

$$C = H\hat{h} + S\hat{s} + I\hat{i} \tag{1}$$

where C is color and $\hat{h}$, $\hat{s}$, and $\hat{i}$ are the basis vectors for hue, saturation, and intensity, respectively. H, S, and I are the scalar values of hue, saturation, and intensity, respectively. Equation (2) reveals the conversion equation from an RGB model to an HSI model.

$$\begin{aligned} H &= \cos^{-1}\left\{ \frac{\frac{1}{2}[(R-G)+(R-B)]}{\sqrt{(R-G)^2+(R-B)(G-B)}} \right\} \\ S &= \frac{3}{(R+G+B)} \min[R, G, B] \\ I &= \frac{1}{3}(R+G+B) \end{aligned} \tag{2}$$

H has a range from 0° to 360° . S and I have a range from 0 to 1.

2.3 Flame Analysis using HSI Model

Hue is the dominant wave length. It means that hue in flame luminescence has information about the dominant chemical reaction in the area covered by CCD cell. Equations (3) and (4) reveal the relationship between hue and wave length.

$$\lambda = -\frac{\lambda_{max} - \lambda_{min}}{\text{Quantization Level}} \text{Hue} + \lambda_{max} \quad (3)$$

$$\text{Hue} = \frac{\text{Quantization Level}}{\lambda_{max} - \lambda_{min}} (\lambda_{max} - \lambda) \quad (4)$$

λ_{max} and λ_{min} are the range of the wave length which a CCD camera is able to measure. The Quantization Level is the resolution of the video analog / digital converter in an image grabber. The λ_{max}, λ_{min}, and Quantization Level will vary with the camera and grabber. Table 2 reveals the hue value under human vision7) conditions - λ_{max} = 700 nm, λ_{min} = 400 nm, and Quantization Level = 256.

Table 2. measurable wave length with CCD Camera

Luminecense Source	Chemical Species	Hue level in accordance with wave length
radical	OH	unable to measure
	CH	229, 223
	C_2	116, 157, 205-172
	NO_2	0-85
soot	CO	230
	H_2O	unable to measure

The intensity is the ratio of luminescence energy to maximum luminescence energy that a CCD can measure. The luminescence energy can be determined if the intensity, lens diameter, which is uncovered by an iris, viewing angle of the lens, gain of the camera, distance between the CCD and the object, and maximum luminescence energy of the CCD are known. Fig. 2 shows how a CCD cell is matched to an object. Equation (5) is the determination of luminescence strength equation.

$$I = \frac{1}{\alpha}\frac{E_s}{E_{max}}, \quad E_s = E(T)\frac{3}{8}\left(\frac{d}{l}\right)^2 \frac{\cos\theta}{m} \quad (5)$$

where Es is the energy radiated on the CCD cell, Emax is the maximum measurable energy of the CCD cell, E(T) is the radiation energy from the object, m is the magnification number, θ is the directional angle to the light axis of the camera, and α is the gain of the camera. Saturation is index which hue is diluted by white. It means ratio of energy which is generated in region of wave length except wave length represented by hue to that which generated in wave length represented by hue.

3. Experiment Apparatus and Method

3.1 Experiment Apparatus

The burners used in this study is gun - type burner(10ton/hr) which is fueled by Bunker C oil. It has function of a variable coaxial swirl jet flame.

In our experiment, swirl was fixed to maximum angle and measured image through CCD camera and concentration of NOx and CO2 through gas analyzer under the condition of 2% to 5% concentrations of O2 with fuel loads of 50%, 75%, and 90%.

Image processing system consists of CCD camera which takes photographs for flame and image grabber which converts image signal in voltage to that in digital code. The cameras used in this study were a wv-CL300 (Panasony), a camera (COSMICA), and a TC270 (Burle) with a Lens Tube (LENOX). Auto iris function of TC270 was not used. The grabber Ultra II (Coreco) converts image formed in YIQ model to that in RGB model. It has 2Mbyte memory for frame buffer and connected to S3 Trio 64V+ video adaptor with native pipe-line bus. In addition to these function, it has expansion slot for JPEG compression for image stream communication.

Gas of interest in this experiment are NOx, CO, CO2, and O2. The gas analyzers used in this experiment were an AUTO STACK MEASURING SYSTEM (Chung Engineering) and MODEL 951A (Rosemount Analytical Inc) for NOx, a CO Analyzer (Thermo Electronic Instrument) of CO, a 1410B (Servomex) for CO2, and a COSMOS O2 Analyzer (COSMOS) and 1420B (Servomex) for O2.

3.2 Experiment Method

The goal of the experiment is to record the images and concentrations of the components in the exhaust gas. If the burner settles within 2% of the desired state, the computer grabs several images and recorded the concentration data from the gas analyzer. The grabbed images is saved in the standard TIFF 5.0 format whereas the concentration data is saved in an ASCII format. Fig. 3 shows a brief block diagram of the experiment. The sizes of the images were inversely proportional to the processing time. In this study, the image size was 160 × 120.

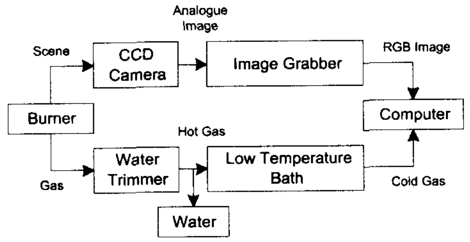


Fig. 1 Structure of measuring apparatus

4. Experiment and Analysis Result

4.1 Correlation Analysis Algorithm

The data measured from each gas analyzer is a 1-dimensional array and the grabbed images is a 3-dimensional array. A statistical analysis (i.e. mean, sum etc) of each image changes the 3 - dimensional image arrays into a 1 - dimensional statistical data array.

Since, after the statistical analysis, the extracted data array has the same dimension and length, it is possible to apply a cross correlation method8) with the concentration data array. A correlation coefficient close to 1 means that the extracted data is strongly correlated with the concentration data array.

4.2 Correlation Analysis Result

Fig. 2 shows work flow of auto tracking algorithm. It searches array set between statistical property arrays and gas data array by cross correlation method.

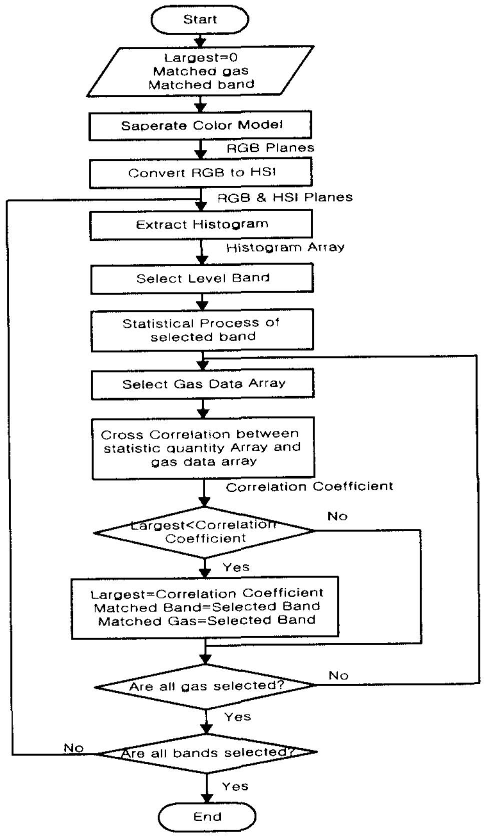


Fig. 2 Auto Tracking Algorithm

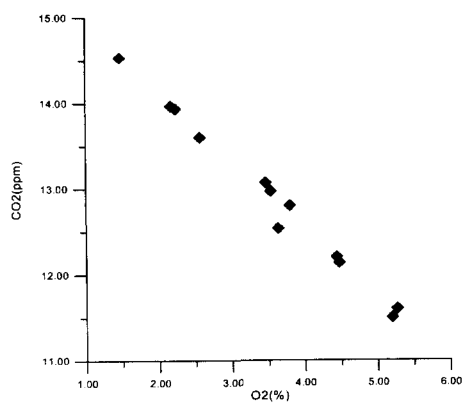


Fig. 3 Concentration of CO_2 according to Oxygen

Fig. 3 is a graph which shows relationship between O2 and CO2 in exhaust gas. It is evident that CO2 is inversely proportional to O2.

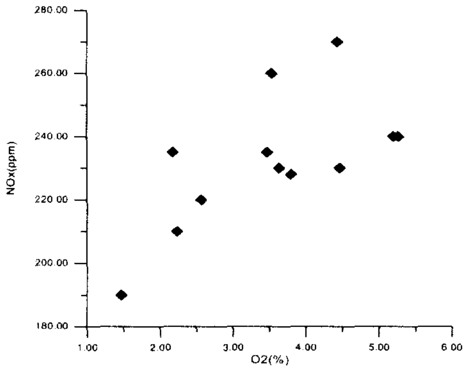
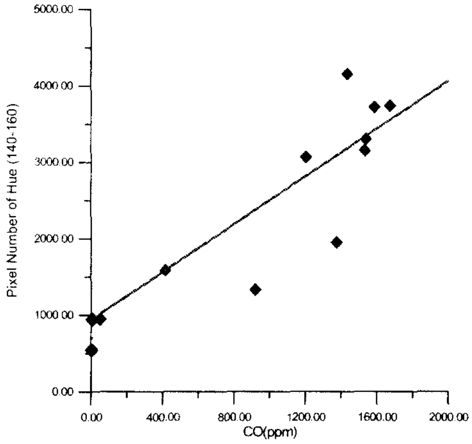


Fig. 4 Concentration of NO_x according to Oxygen(O_2)

Fig. 4 shows relationship between O_2 and NOx. It is evident that NOx has trend proportional to O_2.

Fig. 5 shows relationship between statistical properties and CO and equation derived from regression analysis.

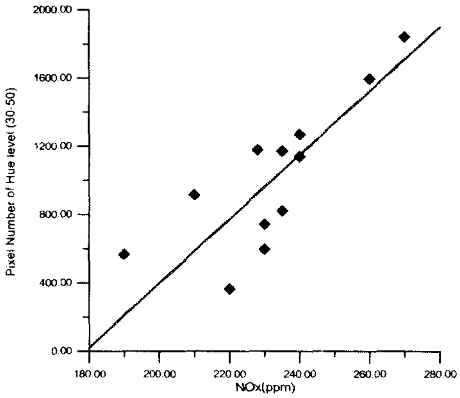


y= 940.91 + 1.56x

Correlation Coeff. = 0.80

Fig. 5 Correlation plot and regression between Concentration of CO and Summary of Hue level from 140 to 160

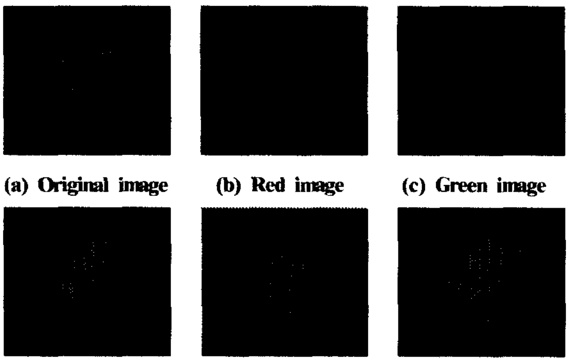
Fig. 6 shows relationship between statistical properties and NOx and equation derived from regression analysis.



y=228.11 + 146.49x

Correlation Coefficient = 0.85

Fig. 6 Correlation plot and regression between Consistency of NO_x and Summary of Hue level from 0 to 85



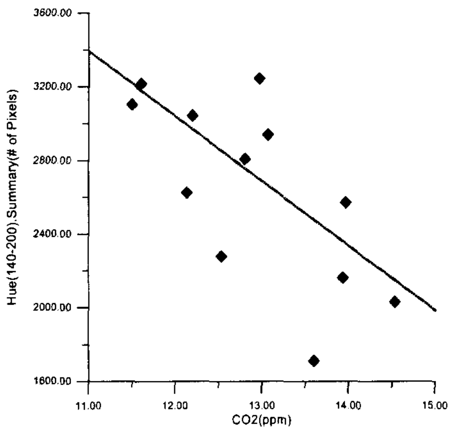
(a) Original image **(b) Red image** **(c) Green image**

(d) Hue image (e) Saturation image (f) Intensity image

Fig. 7 shows separated image by component of color model.

The auto-tracking algorithm read that the concentration of NOx and temperature of exhaust gas is strongly correlated with the number of pixels whose range of level in the hue plane was between 0 and 85 and that of CO was with number of pixels whose range of level in the hue plane was between 140 and 160. The result of the auto tracking analysis for case of NOx is acceptable since the range of 0 to 85 is coincident with the range of NO2 in Table. 2.

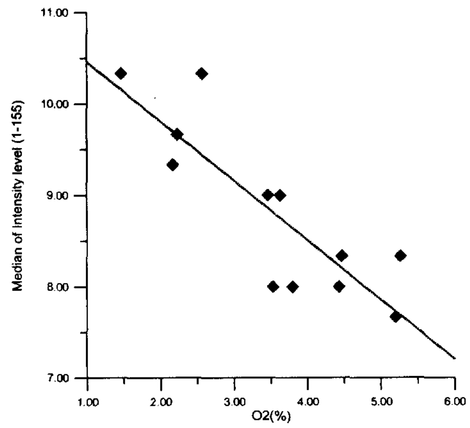
The hue level range of the estimated CO was 230 in Table. 2. However, the result of the auto tracking analysis, range of 140 - 160, is not coincident but included the range of C2. CO is made from C2 radical. Therefore, the luminescence of C2 radical is related to the concentration of CO. Fig. 6 shows the correlation plot and result of the regression analysis.



$y= 7261.40 - 351.83x$

Correlation Coeff. = 0.69

Fig. 8 Correlation plot and regression between Concentration of CO_2 and Summary of Hue level from 140 to 160



$y= 11.11 - 0.65x$

Correlation Coeff = 0.85

Fig. 9 Correlation plot and regression between concentration of O_2 and Median of Intensity level from 1 to 255

Fig. 8 shows the correlation plot and result of the regression analysis.

The luminescence of CO2 is invisible. Therefore, it is of no use to find the correlated image processed data. However, studies report that the concentration of CO2 is inversely proportional to that of CO. In this study, it was confirmed that the concentration of CO is inversely proportional to the image processed data which correlates with the concentration of CO.

Fig. 9 shows the correlation plot and result of the regression analysis between the concentration of O2 and the median whose range of level in the intensity plane was between 1 and 255. It is evident that there is inversely proportional relationship. The concentration of O2 is the key parameter for flammability. Inverse proportionality between concentration of O2 and median value means change of flame state from air diluted state to fuel diluted.

5. Conclusions

Through this study, the following conclusion were derived.

First, it is possible to diagnose a combustion state by using only data extracted from a flame image.

Second, the concentration of NOx is strongly correlated with the number of pixels whose range of level in the hue plane is between 30 and 50 and that of CO with number of pixels whose range of level in the hue plane is between 140 and 160.

Third, the concentration of CO2 is inversely proportional to the data correlated with CO.

Fourth, the concentration of O2 is strongly correlated with the median whose range of level in the intensity plane is between 1 and 255.

These results show possibility for derivation of properties which has more accurate relationship with concentration of NOx and CO. This approach will enables real - time combustion diagnosis system and combustion state control system for burner.

Acknowledgement

This study is performed on the support of project about development of industrial fundamental Technology in 1998 (managed by Samsung Heavy Industry).

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