

Classification and Quantification of Suspended Dust from Steel Plants by Using Color and Transmission Image Analysis[†]

UMEGAKI Yoshiyuki^{*1} KAZAMA Akira^{*2} FUKUDA Yoshinori^{*3}

Abstract:

A system that analyzes suspended dust from steel plants has been developed. The analysis system takes color images of the dust, extracts particles included in the dust from the image based on the color information and classifies the particles into three color types, black, red, and white. The system ultimately measures the amount of the dust particles and the particle size distribution for each color type. The system has an automatic adjustment scheme of the thresholds for the extraction and classification of the dust particles, enabling the analysis of the dust faster and operator-independent. The system has contributed to the planning and execution of the efficient preventive measures against the dust scattering in JFE Steel's steel plants.

1. Introduction

JFE Steel has made a commitment “To reduce the environmental impact of all business operations” in its environmental policy and is actively conducting technical development and capital investment for that purpose. Countermeasures to reduce dust scattering are one item in those efforts. JFE Steel is working to prevent dust scattering by carrying out various countermeasures, including sprinkling in raw material yards with water, constructing shielding fences around yards, installing dust collectors and increasing the capacity of dust collectors, cleaning the steel works grounds and sprinkling roads with water in its works, etc.¹⁾

In order to implement effective countermeasures to prevent dust scattering, it is important to analyze the existing condition before measures are taken and confirm the effects after measures are in place. In other words, it is important to analyze and measure dust, and to evaluate the types and amounts of dust for which measures should be taken. The dust that originates from a steel works consists of multiple types of particles, such as coke, coal, iron ore, sinter, slag, and lime. Furthermore, when actual measurements are carried out, dust also includes silica sand, and other types of dust which do not derive from iron and steel making. Dust is captured by exposing adhesive tape to the atmosphere or by placing open Petri dishes at observation points. After the adhesive tape or the Petri dishes are recovered from the observation points, the captured dust is measured or analyzed to identify the types of substances and the amount and/or particle size distribution of each substance (what sizes of particles are included in the dust in what amounts). In particular, a knowledge of the amount of dust by type of particle is important for identifying dust sources and dust scattering routes. Conventionally, observation by optical microscope is frequently used to measure the amount of dust by type of particle. In this technique, dust particles are classified into three color types (black particles for coke and coal, red particles for iron ore and sinter, white particles for slag and lime), and the number of particles of each type is counted by visual observation through the microscope. Although this method requires a degree of skill, it has the advan-

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^{*1} Senior Researcher Deputy Manager,
Instrument and Control Engineering Res. Dept.,
Steel Res. Lab.,
JFE Steel



^{*2} Assistant General Superintendent, Steel Res. Lab.,
JFE Steel



^{*3} Dr. Eng.,
Staff Deputy General Manager,
Sensing & Visualization Analysis Center,
Instrument Technology Div.,
JFE Techno-Research

tage that the color classification of the particles and measurement of the amount of particles of each color can be performed at one time. However, because measurements are done by visual observation, the results depend on the operator, and variations may occur. Moreover, with this technique, it is difficult to evaluate the particle size distribution, which is important for estimating the distance from the dust source. For this reason, measurements are sometimes performed using a combination of this technique and another technique, for example, installation of a laser diffraction particle size analyzer, etc. On the other hand, in cases where images of the dust particles can be obtained, image processing is often used as a method for measuring the particle size distribution²⁾. When image processing is performed, it is carried out in steps, namely, extraction of the particle area in the image, measurement of the size of each particle and calculation of the particle size distribution. Although the steps other than the initial step are common to many applications, it is necessary to customize the first step, i. e., extraction of particles, according to the actual application. In application to dust particles that originate from a steel works, it is necessary to segment the particle region from the background of the image and classify the particles by type.

The purpose of this development is to realize measurement of particle size distribution by type of particle by a method which is quick, does not require a high level of skill, and eliminates variations in the results depending on the operator. This paper presents an image processing technique and analysis system which automatically classifies and quantifies dust particles.

2. Image Processing Method³⁾

2.1 Acquisition of Color Images and Conversion from RGB to YCrCb

In this method, basically, the work which had been performed visually by a human operator in the optical microscope observation method is replaced by image processing. That is, the flow of the method comprises extraction of dust particles from optical microscope images of dust by image processing, classification into three color types and measurement of the dust by color.

First, an optical microscope image of dust is acquired. In acquiring a color image, adhesive tape with adhering dust is prepared, illuminated from above with a ring light and photographed with a color charge coupled device (CCD). **Figure 1** shows an example of a color image. In this image, the various colors of the dust particles and a sky-blue background, which is the color of the adhesive tape, can be seen. To facilitate particle extraction, as will be discussed in the following, the

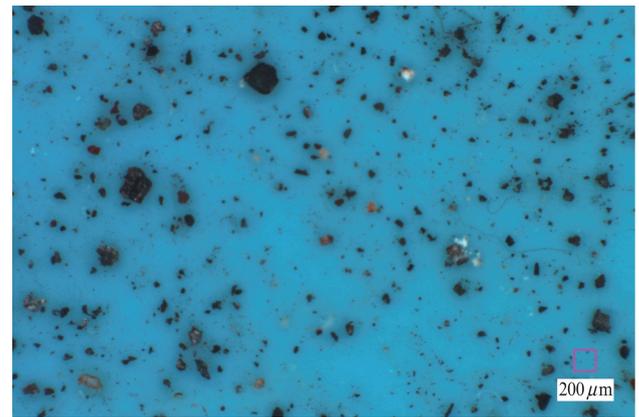


Fig. 1 Microscopic image of dust on adhesive tape³⁾

color of the adhesive tape was selected so that it appears darker than white particles and brighter than black and red particles.

Next, conversion of the color representation is performed. In this method, image process is basically performed in a YCrCb color space. In a YCrCb color space, colors are represented by luminance *Y* and chrominance *Cr* and *Cb*. Luminance represents the brightness of a color independent of its hue. The values of chrominance have hue information; *Cr* expresses redness and *Cb* expresses blueness. On the other hand, the colors of the pixels in an image taken by photography with a CCD camera are represented in an RGB color space. In an RGB color space, colors are represented by a mixture of the three primary colors of light, red *R*, green *G*, and blue *B*. YCrCb and RGB are mutually convertible. Conversion from RGB to YCrCb is performed in accordance with the following equations.

$$Y = 0.298\ 91 \times R + 0.586\ 61 \times G + 0.114\ 48 \times B \dots\dots\dots (1)$$

$$Cb = -0.168\ 74 \times R - 0.331\ 26 \times G + 0.500\ 00 \times B \dots\dots\dots (2)$$

$$Cr = 0.500\ 00 \times R - 0.418\ 69 \times G - 0.081\ 31 \times B \dots\dots\dots (3)$$

For distinguishing red particles, black particles, and white particles, the YCrCb color space is easier to use than the RGB color space. First, because the difference between white particles and dark particles (both black particles and red particles) is mainly brightness, white and dark particles can be distinguished by luminance *Y*. Among the dark particles, redness is one criterion for distinguishing red particles from black particles. This criterion is roughly expressed by the fact that *Cr* is positive and *Cb* is negative. Because RGB and YCrCb are mutually convertible, it is possible to express an equiva-

lent criterion by using RGB. However, as can be understood from the conversion Eqs. (1) to (3), this is difficult to understand, as is necessary to consider conditional expressions represented by linear combination of the three values of R, G, and B.

2.2 Extraction of Particles from Color Images

In this step, dust particles are extracted from a color image. As a precondition, here, the mean value of the luminance Y of the background in the color image is regulated to approximately a set value by using the iris during image acquisition. This regulation can be realized easily by performing regulation while observing the intensity profile of the image on the screen. **Figure 2** shows histograms of the YCrCb values calculated for the image shown in Fig. 1. The distribution of the background color in the YCrCb color space is concentrated around the highest peaks in the histograms. The distribution of the Y value shows a peak in approximately the same range each time because the background luminance is adjusted during image acquisition. Consequently, the pixels corresponding to the background can be distinguished from those belonging to particles by the following condition:

$$Y_{Low} < Y < Y_{High} \dots\dots\dots (4)$$

where, Y_{Low} and Y_{High} are appropriate thresholds, which are represented by the two vertical broken lines in the graph. The background region, except for the area adjacent to the particles, can be excluded by removing the

pixels that satisfy the above conditional expression (4). Because the value of luminance Y is reduced slightly by the shadow caused by illumination of the particle in these adjacent parts, there are parts where the values of Y fall below Y_{Low} . Although the details will be omitted here, this remaining background region is completely eliminated by performing further additional processing. **Figure 3** shows the result when the background region was removed from the input image in Fig. 1. **Figure 4** presents histograms showing the distribution of the YCrCb values calculated for the remaining region of Fig. 3; there is no overlap with the distribution which also included the background region shown in Fig. 2. After the background is removed in this manner, each of the particle areas is detected from the remaining area.

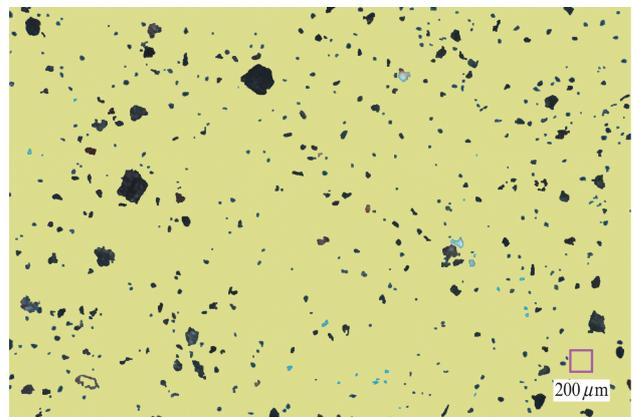


Fig. 3 Image obtained by removing background (Represented by light-yellow) from image of Fig. 1³⁾

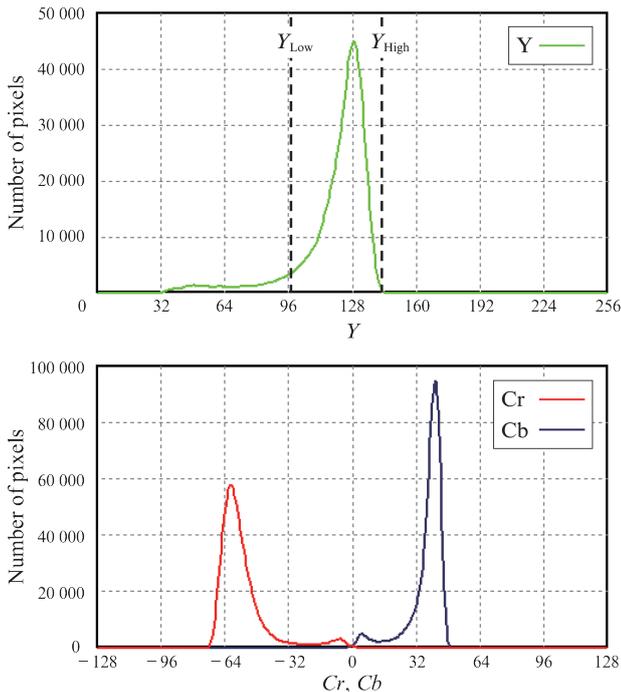


Fig. 2 Histogram of YCrCb values in image of Fig. 1³⁾

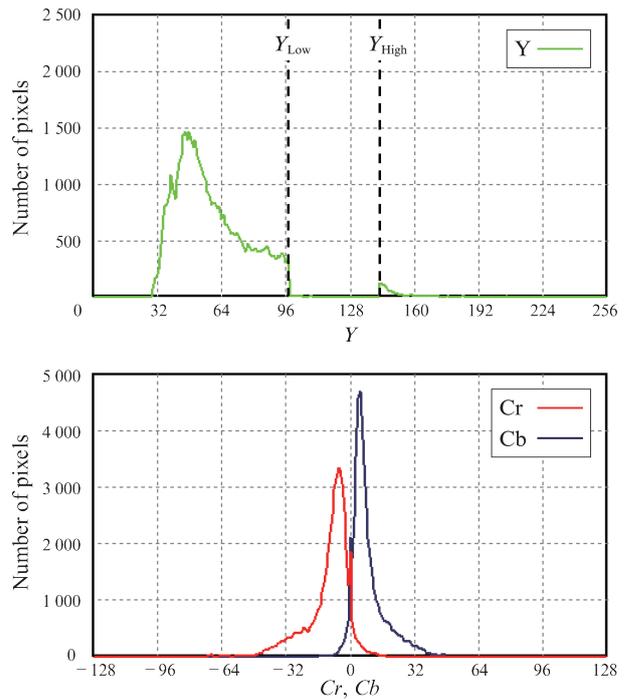


Fig. 4 Histogram of YCrCb values only in area of particles in image of Fig. 3³⁾

2.3 Classification of Particle Color Types

After extraction of the particles from the input image, the particles are classified into the three color types, black particle, red particle, and white particle. First, before classification of the particle color type, the pixels contained in each particle area are classified into the three colors, black, red, and white. Next, the particle color is determined by the distribution of the colors of the pixels contained in the particle area. Basically, however, the color of a particle is determined by the dominant color of the pixels in that particle. **Figures 5 and 6** show the results of determination of pixel colors and determination of particle colors, respectively. White pixels are defined mainly as pixels that have a Y value which is larger than a certain threshold value. This threshold value is set to a value which is obtained by adding a certain offset value to the mean value of Y of the background color. Assuming this threshold value is T_y , pixels which satisfy $Y > T_y$ are determined to be white pixels. Red and black pixels are decided mainly by comparing the Cr values and Cb values of the pixels which were not judged to be white pixels with their respective corresponding threshold values. The threshold values in

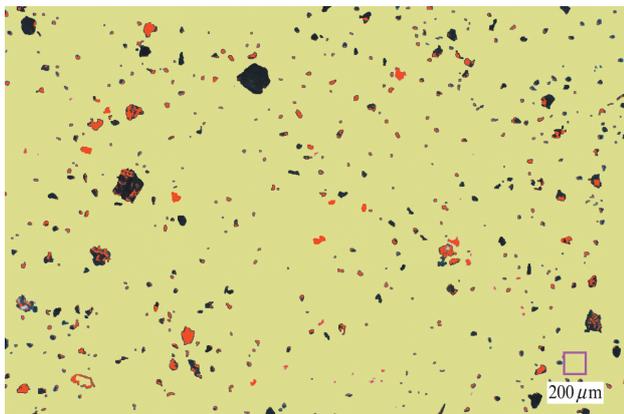


Fig. 5 Results of determination of pixel colors³⁾

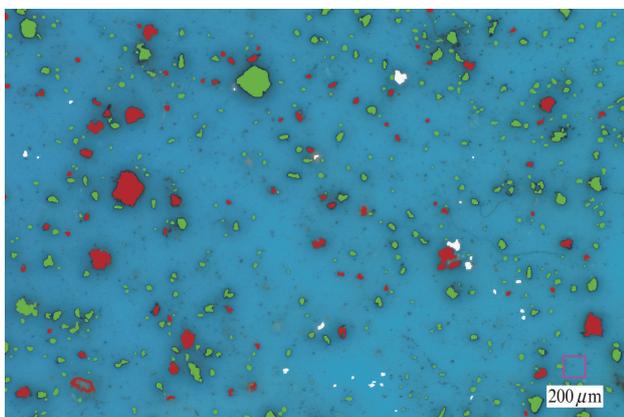


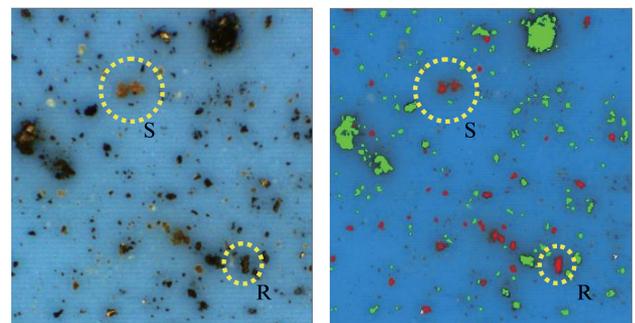
Fig. 6 Result of determination of particle colors³⁾ (Black particles are painted by green.)

this case are set to values obtained by adding respective offset values to the mean values of Cr and Cb in the particle area. If those threshold values are T_{Cr} and T_{Cb} , pixels which satisfy both $Cr > T_{Cr}$ and $Cb < T_{Cb}$ are determined to be red pixels, and those which do not satisfy these conditions are determined to be black pixels. Since the threshold values are set automatically in this manner based on the mean values, small variations in illumination are cancelled out and substantially the same results can be obtained regardless of the operator performing the analysis.

It shall be noted that the method of classifying the pixel color and particle color described here is the basic method. In actuality, further enhancements in classification accuracy have been achieved by incorporating various innovations in this technique.

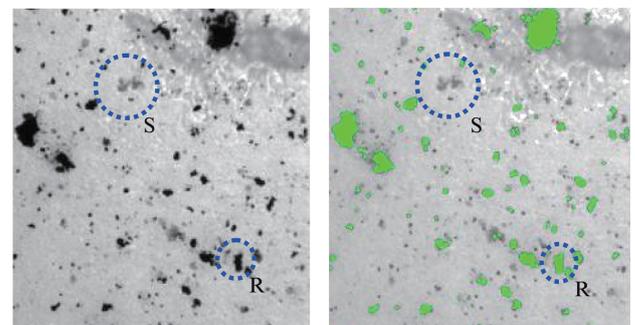
2.4 Exclusion of Silica Sand by Using Transmission Images

Trapped dust also includes silica sand which does not originate from steel manufacturing processes. Because the color of silica sand is red or white, it is difficult to distinguish silica sand from red particles and white particles in a color image. In order to distinguish silica sand from particles derived from steel manufacturing, images



(a) Color image of dust on tape lighted from above (Particle S is silica sand, and particle R is ore.)

(b) Result of classification of particles in (a) into three color types (Black particles are painted by light green.)



(c) Transmission image of the same dust as (a)

(d) Result of detection of opaque particles in (c) (Opaque particles are painted in light green.)

Fig. 7 Exclusion of silica sand by using transmission image³⁾

(hereinafter, transmission images), which are obtained by illuminating dust with a backlight, are used in addition to color images. Although transmission images are monochrome, they can be obtained from color images taken using the same camera as that used to photograph images of dust with lighting from above by converting those color images to monochrome images by Eq. (1). Since the main component of silica sand is quartz, it has the property of transmitting visible light and near infrared light to some extent. Taking advantage of this property, backlit particles with luminance higher than a predetermined threshold are reclassified as semi-transparent particles. An example of this processing is shown in Fig. 7. Particles S and R in the color image in Fig. 7 (a) are both classified as red particles, as shown in Fig. 7 (b). On the other hand, particle S is semi-transparent in the transmission image shown in Fig. 7 (c) but is not detected in Fig. 7 (d), which shows the results of detection of opaque particles by threshold processing of the transmission image. Therefore, particle S is recognized as being a semi-transparent particle, i. e., silica sand.

3. Analysis System³⁾

The authors developed a new analysis system which acquires images of dust and performs image processing by the method described above⁴⁾. The equipment composition of the developed analysis system, as shown in Fig. 8, consists of a personal computer (PC), a color CCD camera with an USB connection, a fixed focal lens with an extension tube, a ring light with an RGB color LED (light emitting diode) and a stage with a backlight. The authors also developed software which performs image processing and outputs the results and incorporated that program in the PC.

The analysis procedure using this system is as follows. First, adhesive tapes with adhering dust are prepared. Dust is captured by exposing the adhesive tapes in the atmosphere at observation points. At this time, the adhesive tape is wrapped around a pipe with the adhesive side out and placed at the observation point. This method makes it possible to identify the approach direction of the dust from the position where the dust adheres.

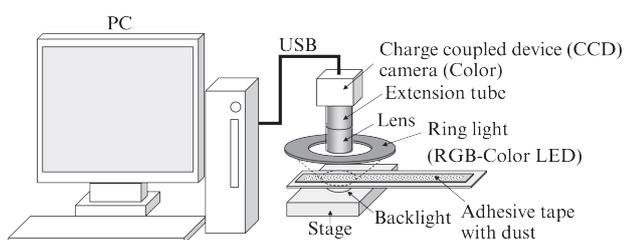


Fig. 8 Analysis system of dust on adhesive tape³⁾

After the adhesive tapes are recovered from each observation point, the tapes are straightened and fixed on a transparent plate such as glass, acryl, etc., and placed on the stage. Next, the adhesive tape is lighted from above with the LED ring light, and a color image of the dust particles is photographed. The lighting is then switched from the LED ring light to the backlight, and a transmission image is taken. When this pair of images (color image and transmission image) is taken, the analysis system automatically analyzes the two images and performs extraction and color classification (3 colors and semi-transparent) of the dust particles. The size (area and diameter) of each particle and the number of particles of each color classification are also measured. Photography and analysis of the color images and transmission images is then repeated for eight points on the adhesive tape, corresponding to the eight dust approach directions (north, northeast, east, southeast, south, southwest, west, northwest).

Finally, statistical results are output in the form of graphs and charts. The results include the number of particles and the particle area calculated by color classification, the approach direction and the particle diameter of the classified particles. This series of operations and processing can be performed easily by the developed software. The work that must be done by the operator is limited to photography of the dust images. With the exception of the photography, the entire analysis is performed automatically by image processing, including adjustment of the threshold values.

4. Analysis Results³⁾

A tape with adhering dust was analyzed using the developed analysis system. Color images and transmission images were photographed and analyzed from eight directions. The photography and analysis of all the images could be completed within 10 minutes. Figure 9 shows the images photographed from all directions, and images of the results of analysis of those images and classification of the dust particles into three colors and semi-transparent. The statistical results are shown in Fig. 10. Figures 9 and 10 are examples of the images which are output of the developed software. By looking at the entirety of the images in Fig. 9, it is possible to confirm at a glance the condition of the adhesive tape that captured the dust, for example, the amounts and colors of the particles. The colors assigned to each particle can be understood by comparing the color images in the upper row and the results of image processing in the lower row. Figure 10 (a) is a radar chart arranged by particle color classification, and provides a quantitative grasp of the amount of airborne dust from each direction during the observation period. Figure 10 (b) shows the

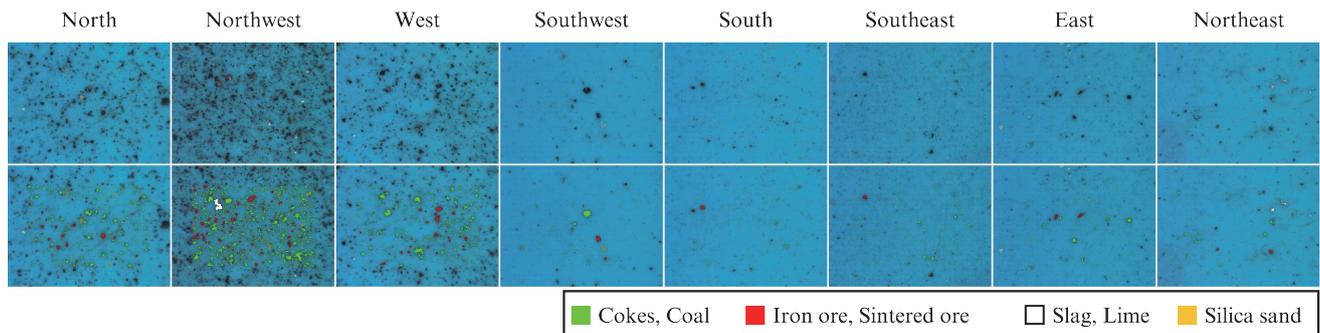
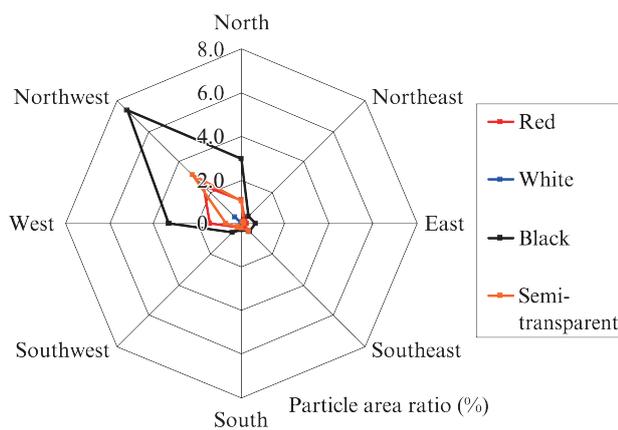
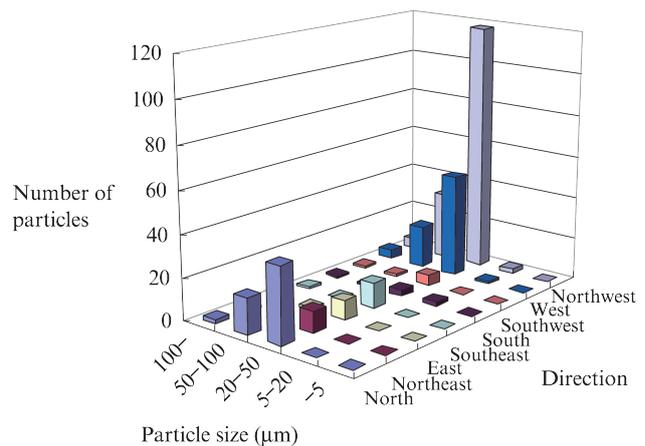


Fig. 9 Raw images (Upper row) and result images (Lower row) of color type classification for eight directions³⁾



(a) Radar chart showing the particle area ratio for each direction and particle color calculated from the images in Fig. 9



(b) Particle size distribution of the red particles for each direction calculated from the images in Fig.9

Fig. 10 Example of statistical data output by the analysis system³⁾

particle size distribution by approach direction for particles classified by designated colors. Here, the main sizes of the particles included in the dust can be understood. These results are also output simultaneously as numerical data.

The results obtained with this analysis system are used to identify the sources and scattering routes of dust. For example, estimation of the dust source, evaluation of the influence of each dust source on the amount of dust fall, evaluation of the influence of wind velocity on the particle size distribution, etc. are possible. These various types of evaluations are performed by comparison of the analysis results and weather conditions such as the wind velocity, etc. during the observation period, comparison with simulations of dust scattering under the same weather conditions, and so on. The analysis system is also used for validation after implementing countermeasures to prevent dust scattering.

5. Conclusion

The development of a technology and analysis sys-

tem for automatic classification and quantification of dust particles originating from a steel works by analysis of color images and transmission images was described.

- (1) Dust particles are extracted from color images acquired by photographing adhesive tape with adhering dust lighted from above, and are classified into the three colors, black, red, and white. Particle extraction and particle color classification are performed based on YCrCb values. Because the thresholds for color classification are regulated automatically based on the mean values of the YCrCb values, variations due to individual differences among operators are eliminated and analysis is possible within a short time.
- (2) Focusing on the light transmission property (semi-transparency) of silica sand, silica sand which does not derive from steel manufacturing is excluded by using transmission images photographed by back-lighting the dust. This improves the accuracy of measurements of particles related to the steel manufacturing process.
- (3) It is possible to obtain statistical data for the number

of dust particles and the particle area calculated by color classification, approach direction, and particle diameter. The obtained data are used in identification of dust sources and scattering routes, and also in planning and implementation of effective measures to prevent dust scattering.

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