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JIS Performance Evaluation Testing for Automatic Dust Concentration Measuring Instrument: Effect of dust charge on measured value

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Abstract

The automatic measurements of dust concentration emissions is well developed technology which is commonly used in industrial processes. To make public use of such technologies for regulatory compliance purposes, a certification system in Japan is needed, and as a part of such effort, a series of JIS standards were developed in 2020. This study reports on the actual performance evaluation of JIS-compliant test equipment, and useful knowledge and practical issues obtained on the validation and operation to the standard. In particular, the problem of not being able to universally correlate results between gravimetric measurements and probe electrification type dust meters was analysed and found to be caused by variable charging of the test dust. The amount of charge on the test dust is influenced by the dust injection method and the geometry and design of the test section in the ducts was identified. Charging of the test dust, presumably owing to frictional charging between the agitator plate or the rectifying wire mesh, was observed. The dust charge was significantly affected by the dust concentration, although not by the velocity, and this relationship was found to be inversely proportional. While the change in dust charge undermined the linear relationship between the gravimetric measurements and the dust monitor readings, a linear relationship is possible and can be obtained by compensating for the effect of the differences in the amount of charge. For the probe electrification type dust meter, it is necessary to focus on changes in the dust charge when carrying out equivalence tests using a test duct.

Keywords: Particulate emission monitor; Performance evaluation test; Dust charge; JIS B-7996; JIS B-7997

1 Introduction

An automated concentration monitoring instrument (dust meter) is an instrument that can continuously measure the concentration of particulate matter (PM) and is therefore used as a continuous emission monitoring system (CEMS) to monitor pollutant emissions in many different countries. The most commonly used technologies for PM monitoring are opacity, light scattering, beta attenuation, and probe electrification (triboelectric effect, electrodynamic device) (Castellani, 2004). The PM-CEMS developed based on these technologies must be calibrated through gravimetric and isokinetic sampling, which is the only way to obtain the actual concentration and provide a continuous output of the dust concentration (mg/m^3). Therefore, measurement methods and quality standards for the equivalence of devices and gravimetric sampling have been determined, and a certification system has been established and is currently in operation (EN 14181:2014, VDI 4203:2017, U.K. Environment Agency 2012, U.S. EPA 2016, M.E.P. China 2017). CEMSs are being used not only for PM in flue gas, but also for various components, and many countries are actively using such systems for emission control and research (Levy et al., 2002, Jang et al., 2009, Zhao et al., 2010, Krittayakasem et al., 2011, Kristanto et al., 2018, Tang et al., 2020). In Japan, however, these technologies have not yet been officially recognised as methods for PM emission control. The main reasons for this have been an inadequacy of the relevant JIS standards and a lack of scientific evidence to properly assess the reliability of dust meters distributed throughout Japan.

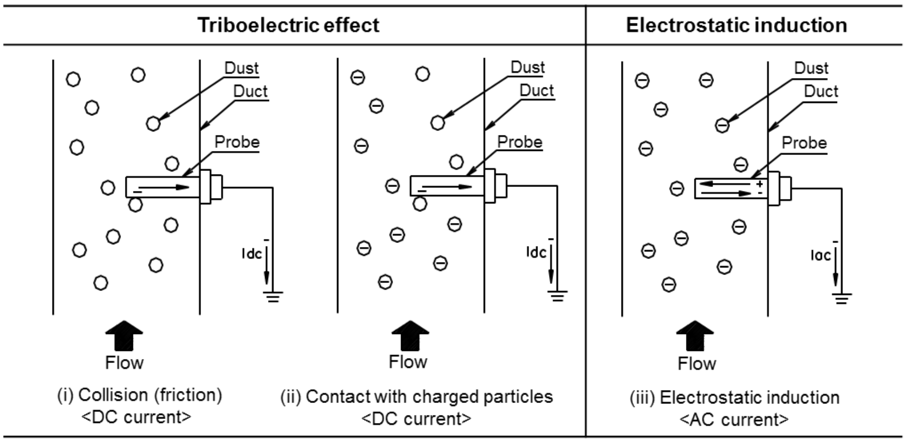
Regarding the former, ISO 10155:1995, i.e. "Stationary source emissions - Automated monitoring of mass concentrations of particles - Performance characteristics, test methods and specifications," has already been established as an international standard. For example, in Europe, EN 14181 has been established in response to this standard, and dust meters are used as CEMS tool for emission monitoring regulations of stationary sources. This situation is similar in many other countries. For these reasons, there have been strong calls for the active use of dust meters in air pollution control systems in Japan. In response to this request, JIS Z 8852:2013 was published based on ISO 10155:1995 to provide an overview of automatic dust measurement technology (Tamori, 2014). JIS B 7996:2020 was established in 2018 for details of the instrumental functions and performance test methods of the instruments. In addition, to allow the method to become an official approach used for emission control under the Air Pollution Control Law, it was necessary to establish a system allowing third parties to recognise continuous measurement data. As a precondition for this, it was considered necessary to establish product standards. In 2020, JIS B 7997:2020, i.e. "Automated concentration monitoring instrument of dust in flue gas," was published, which specifies the measurement principles, composition and structure, specified values, formal tests, and performance tests. For the first time worldwide, provisions for stability under changing flow velocities have been introduced in the standard. With these standards in place, the construction of a certification system is now underway.

Regarding the latter, initially, there was no test duct equipment for evaluating the performance of dust meters in Japan. The authors have been working on the development of a test duct equipment (Wada et al., 2021). To examine the content of the specifications, the JIS drafting committee for preparing JIS B 7997:2020 conducted round-robin tests using two test duct equipment in Japan, including the authors' own equipment. During the tests, there was a good agreement between the results obtained by the two types of device in the case of light transmission and when applying light scattering dust meters. However, the trends of the results obtained for the probe electrification type dust meter were quite different (Wada et al., 2019). In particular, the trend of the results obtained differed when the flow velocity condition was changed, and the reason for the difference could not be identified. Therefore, it was concluded that the test ducts could not be used to make an accurate evaluation. Therefore, we decided to exclude the performance test items from the stability test during the velocity fluctuations in the standard used for the probe electrification type instruments.

With the probe electrification method (Fig. 1), three different effects are detected when particles hit or pass near a conductor placed in the exhaust gas stream: (i) When the particles hit the probe, they rub the surface and cause a frictional charge, (ii) when the particles hit the probe, a charge transfer occurs, and (iii) when charged particles pass near the probe, they induce charges of equal and opposite magnitude in the conductor. The amount of charge generated by the first two effects depends on the velocity of the particle, its mass, and the charge history of the particle. The third effect is the induced charge, and the magnitude of the charge depends on the proximity of the particle to the conductor and the charge history of the particle (Matsusaka et al., 2010). The triboelectric device measures the DC current in such a way that the first two effects are detected.

The electrodynamic device is a method for detecting only the third effect (electrostatic induction), which filters the DC current produced by the particle impact on the rod and measures the RMS signal within an optimised frequency bandwidth resulting from particles passing through the probe (Averdieck, 1995). The signal is independent of the probe surface condition and has a stable and repeatable relationship with dust concentration in many types of industrial applications. Because the signal does not depend on particle collisions (unlike a triboelectric effect), the associated problems of rod contamination and velocity dependence are minimised (Averdieck, 1999). It is known that these probe electrification methods do not work well when the particles are subjected to varying charges (Castellani, 2014). Therefore, they are not recommended to be installed at locations where the dust charge is highly variable, such as in the immediate vicinity downstream of the EP. This means that, even for the same dust concentration, the indicated value will increase in proportion to the dust charge.

Figure 1: Operating principles of probe electrification method



Therefore, the unexplained measurement results that occurred in the round-robin test are suspected to be due to the change in the dust charge in the test duct. However, the confirmation of the phenomenon and the magnitude of the effect are unclear and need to be studied. In this study, the issue in which the equivalence with gravimetric measurements cannot be universally measured was verified when the probe electrification type device, one of the main types of dust monitors, was tested using a test duct. Dust charging in the ducts was identified owing to the structure of the test ducts, and changes in such charging from changes in the test conditions of the flow velocity and dust concentration were measured. The influence of the dust charge change on the evaluation test results of the dust meter was then examined.

2 Experimental Equipment and Methods

2.1 Test duct equipment

In this study, the test duct equipment developed by the authors was used (Wada et al., 2021). This test duct can generate dust-containing air at any flow velocity and dust concentration conditions. A schematic diagram of the test duct is shown in Fig. 2. A blower located downstream of the duct causes air to flow horizontally in the duct at a constant velocity. Dust-containing air is generated at the dust generator upstream of the duct (left side of Fig. 2), and parallel measurements with a dust meter and gravimetric can be conducted at the measurement section downstream. The flow velocity are continuously monitored by a pitot tube. The flow velocity can be set arbitrarily by the inverter control of the blower.

Figure 2: Test equipment for performance evaluation of dust monitors

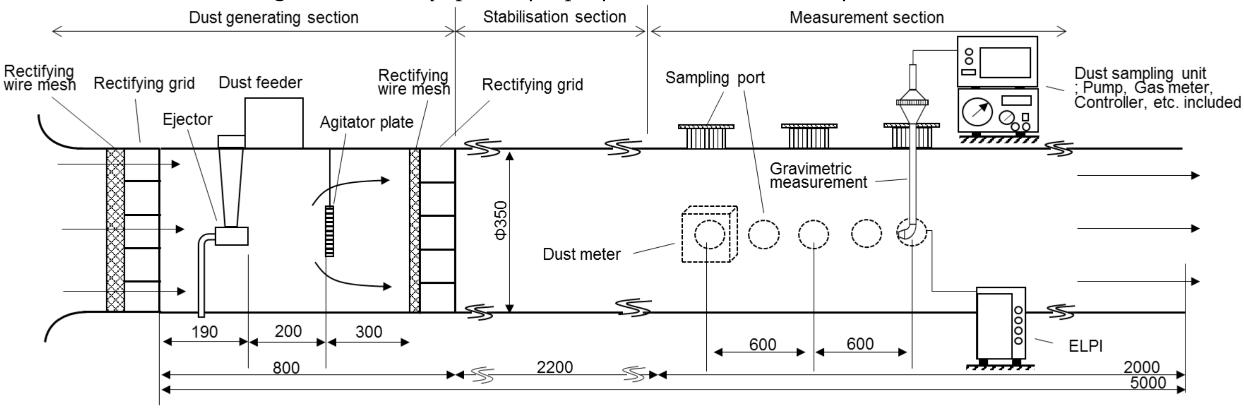
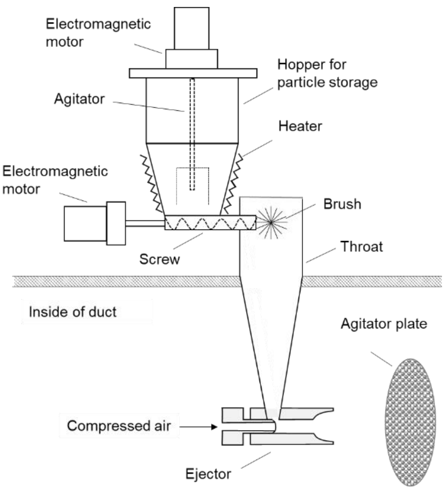


Figure 3: Dust generation mechanism



The dust generation mechanism is shown in Fig. 3. A screw type dust feeder (MF15A-C1.5L, Alpha, Japan) was used to feed the powder. The storage hopper was heated to 100 °C to prevent dust agglomeration owing to moisture absorption during storage. There is a rotating brush at the outlet of the feeder, which allows continuous feeding of powder with minimal pulsation. The dust is fed into a hopper connected to the ejector. The dust suctioned from the top of the ejector is mixed with compressed air, and well-dispersed dust-containing air is ejected from the ejector. The agitator plate (a stainless steel disc with a diameter of 20 cm and numerous round holes of 5 mm in diameter and perforated metal with an aperture ratio of 35.4%) installed in front of the ejector mixes the ejected dust-containing air with the airflow in the duct to generate dust uniformly in the test duct. Furthermore, a wire mesh and a rectifying grid are installed downstream for rectification, which can homogenise the airflow and dust concentration over a short distance. The dust concentration can be set arbitrarily by controlling the screw rotation speed of the feeder. By contrast, during some tests, dust-containing air generated by a fluidized bed dust generator (Model 3216, Kanomax, Japan) was used instead of the above dust generator. A stainless steel suction tube was installed at the same position as the nozzle for a gravimetric measurement and introduced into an electrical low-pressure impactor (ELPI) (ELPI, DEKATI, Finland) to measure the charge of dust in the duct based on particle size.

2.2 Charge measurement of the test dust generated in the test duct

The charge of the dust in the measurement section of the test duct was measured using an ELPI. The ELPI is an instrument that can measure the particle size distribution and the number of particles in real time, and is composed of three main parts: a particle charging part, a classification part (cascade impactor), and a high-sensitivity current detection part. Particles are charged to saturation in the corona charging section, and then collected based on the particle size (6 nm to 10 µm in 11 stages) in a cascade low-pressure impactor consisting of multiple electrically insulated collection stages. The number concentration can be measured by measuring the amount of charge carried by the particles in each impactor stage with an extremely sensitive ammeter. In addition, by turning off the charging section, the charge distribution of the particles can be measured. For the test dust, JIS Class 10 fly ash (JIS Z 8901:2006) was dried at 110 °C for 1 h and then cooled in a desiccator. The test conditions are listed in Table 1. The measurements were conducted at the same velocity and dust concentration, with and without the use of an ejector, with and without a rectification wire mesh (downstream side), and with different dispersing air pressures introduced into the ejector. Measurements were also conducted when the dust generation mechanism was changed from the ejector system to the fluidized bed system.

Table 1: Test conditions for measuring the amount of charged dust generated in the test duct

	Test No.	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Comparison conditions	Dust generator	Screw type						Fluidized bed type	
	Ejector	None		Yes				None	Yes
	Dispersion air pressure (Mpa)	-	-	0.2	0.2	0.4	0.4	-	0.2
	Rectification wire mesh	Yes	None	Yes	None	Yes	None	None	Yes
Common conditions	Measurement point: Center of the duct in the measurement section; flow velocity, 12 m/s; dust concentration, 10 mg/m^3								

2.3 Measurement of changes in the status of dust charge owing to changes in the test conditions

The charge of the test dust, which varied with changes in the test condition settings (flow velocity and dust concentration), was measured at different flow velocities and powder feed rates. Among the facilities of the test ducts, the rectifying wire mesh on the downstream side was not installed here.

The test dust used was JIS Class 10 fly ash. The gravimetric measurement was conducted in accordance with JIS Z 8808:2013. A Type II dust sampler (ERH-A-32H, Okano, Japan) equipped with a 90° stainless steel vent nozzle and an automatic dust sampling device (ESA-703, Okano, Japan) was used. A quartz fibre circular filter (3200QAT-UP, 32 mmφ, ~60 mg, Advantec, Japan) was used as the collection filter. Before and after dust sampling, the filters were dried at 110 °C for 1 h and kept in a thermostatic room (room temperature, 21 ± 1.5 °C; relative humidity, 35 ± 5 %) for 1 day. The filters were weighed on an electronic balance (XS-205, maximum capacity, 81 mg; minimum display, 0.01 mg, Metler Toledo, Japan). Both the laboratory blank and travel blank were 0.02 mg.

A nozzle was inserted at the centre point of the duct, and dust was collected using isokinetic sampling. The diameter of the nozzle and the sampling time were determined by the following factors: dust collection volume of 2.5 mg or higher (0.5 mg or more for each square centimetre collection area, i.e. 5.3 cm^2 collection area).

The charge of the dust was obtained as follows.

(1) Total charge (q)

Turn off the particle charger of the ELPI, measure the detection current of each impactor stage, and then integrate the detection current with the measurement time t to obtain the dust charge of stage i. Then, sum the total charge of the 11 stages to obtain the total charge q.

$$q_i = \int_0^t I_i dt \tag{1}$$

$$q = \sum_{i=1}^{11} q_i \tag{2}$$

(2) Total amount of particles collected using the ELPI (m).

The amount of particles collected using the ELPI was determined from the dust concentration value through a gravimetric measurement. In this calculation, it was assumed that there was no loss in the ELPI ($\alpha = 1$).

$$m = \alpha C Q_{ELPI} \tag{3}$$

where m is total mass of particles collected by ELPI (mg), α is loss in the ELPI (-), C is dust concentration by gravimetric measurement (mg/m^3), and Q_{ELPI} is suction rate of ELPI (m^3/s)

(3) Charging amount per unit mass (q)

The amount of charge per unit mass was calculated by dividing the total charge q measured using the ELPI by the amount of collected dust.

$$\bar{q} = q/m \tag{4}$$

The test conditions are listed in Table 2. The dust concentration to be generated was set to three different concentration ranges from 5 to 30 mg/m^3, considering the dust concentration at the actual source.

Table 2: Test conditions for measuring changes in the status of dust charging owing to changes in test condition settings

Item	Description	Total number of measurements
Flow velocity	Low (8 m/s), standard (12 m/s), high (16 m/s) × 3	3
Dust concentration	Low (5 mg/m^3), medium (10 mg/m^3), high (20 mg/m^3) *The value is the reference concentration at 12 m/s. The setting for each concentration range is controlled by the feeder voltage, and the same setting value is used for each concentration range.	×3
Number of measurements	3	×3 = 27 times

2.4 Measurement of the effect of change in charge of the test dust on the readings of the dust meter

The gravimetric and dust meter measurements were carried out in parallel. A probe electrification type dust meter (an electrodynamic device) manufactured by Kansai Automation (VIEW 370) was used. The dust meter is a measuring instrument used in a relative concentration indication method, and does not directly measure the mass concentration. Therefore, it is necessary to conduct parallel measurements with gravimetric measurements to obtain the conversion factor for the mass concentration. For the the detected AC current, the dust concentration is expressed through the following equation; where C is dust concentration (mg/m^3), I is AC current (A), V is Flow velocity (m/s), Z is factor, d_p is particle size (µm), and k is particle-specific coefficients.

$$C = \frac{d_p}{k\ v^Z} I \tag{5}$$

The AC current and dust concentration have a proportional relationship when the velocity, particle size, and particle-specific coefficients do not vary. Therefore, when using the dust meter, the readings converted using Eq. (6) can be obtained by setting the reciprocal of the sensitivity ratio (dust concentration meter indication (primary value) divided by gravimetric measurement) obtained by the user at each site as the conversion factor; where K_u is conversion factors to be set by the user, K_m is manufacturer's device constant, R is indicated value of dust meter (primary value) (mg/m^3 RC), and R' is indicated value of dust meter (mg/m^3 RC).

$$C = K_u K_m I = K_u R = R' \tag{6}$$

The value used to convert the indicated value includes the conversion factor K_u, which is set by the user using the gravimetric measurement value in the field, and the device constant K_m, which is set by the manufacturer, the latter of which is a black box in most cases. The readings of the dust meter during this test indicate the amount (primary value) of dust. (Hereinafter, the readings refer to the indicated value (primary value) of the dust meter, i.e., the value measured without setting a conversion factor (Ku = 1). The unit of the measured value in this study is milligrams per cubic meter of relative concentration (RC), because the measured value of the dust meter is a relative concentration and does not represent the actual concentrated mass.)

The measured value output (output at 4–20 mA) of the dust meter installed upstream of the measurement section of the test duct was recorded using a data logger. The sampling period of the data logger was set to 1 s, and the average value of the trend indicated during the sampling period of the gravimetric measurement was taken as the readings of the dust meter. The dust concentration through gravimetry, the value output by the dust meter, and the electrostatic charge using the ELPI were measured simultaneously in parallel and treated as one set of measurement data.

3 Results

3.1 Charging status of the test dust generated in the test duct

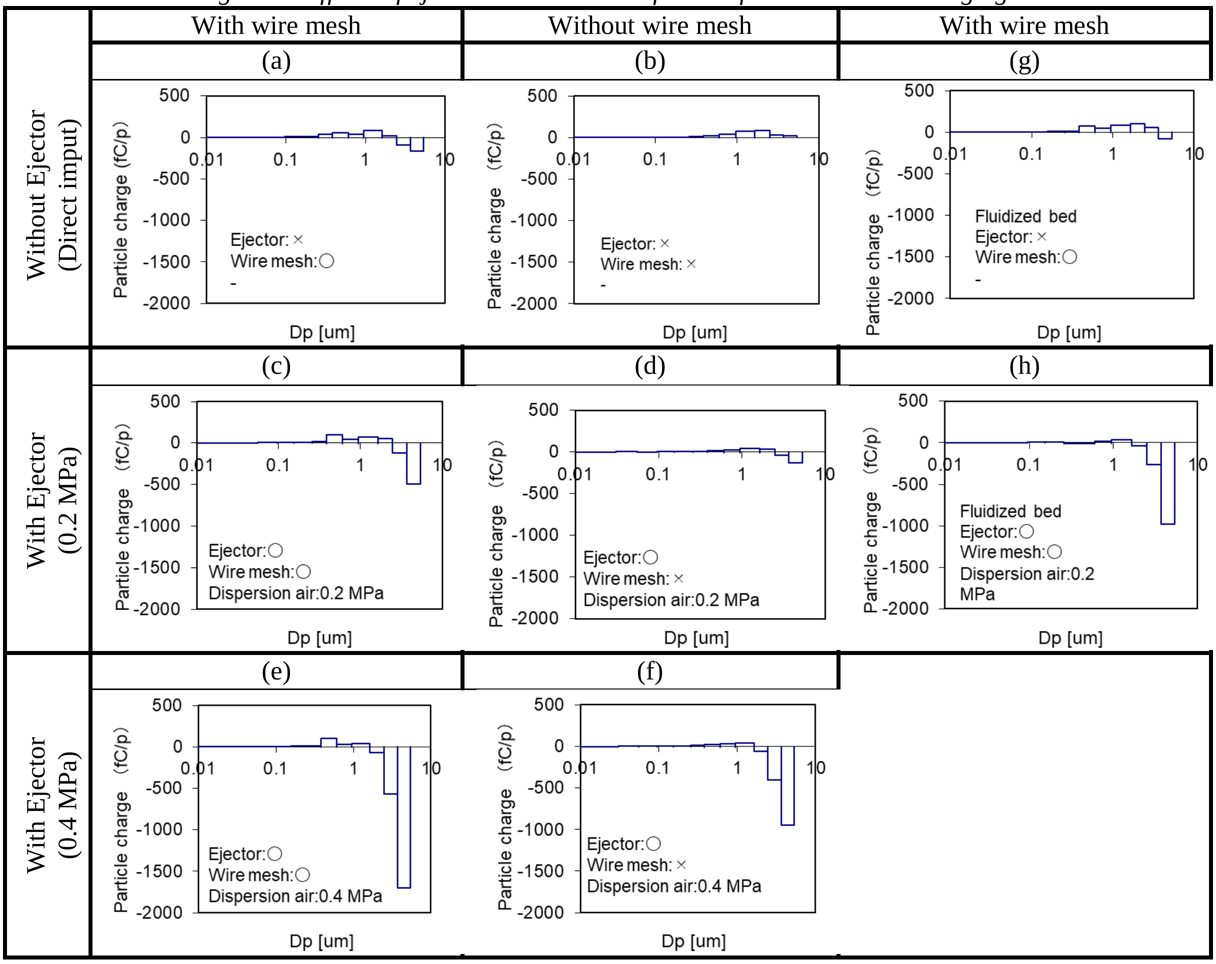
It is known that the readings of the dust meter in the probe electrification method are affected by the charge of the dust in addition to the dust concentration. It is necessary to investigate the charging conditions and causes of the dust in the test duct. Therefore, the charging of the test dust was measured using the ELPI under different dust generation conditions.

Fig. 4 shows the measurement results of the amount of charge based on the particle size. Focusing on the coarse particles (right side of the graph), where the dust charge (absolute value) is large, it can be seen that the charge is larger for particles (c)–(f) with an ejector than for particles (a) and (b) without an ejector, and that it increases as the dispersion air pressure of the ejector increases. In addition, when comparing those with the same ejector conditions, it can be seen that the amount of charge is larger when the wire mesh for rectification is present (comparison of (a) and (b), (c) and (d), and (e) and (f)). When a fluidized bed is used, the charging is comparable to that of direct injection (comparison of (a) and (g)). By contrast, the aerosol generated using the fluidized bed also shows an increase in charging when passed through the ejector (comparison of (c) and (h)). It is considered that the dust generated using the fluidized bed can be tested in a close to uncharged state, and is less affected by fluctuations in the amount of charge.

To summarise the confirmed phenomena, (ⅰ) the amount of charge of fine particles is small, and changes depending on the generation conditions are also small. (ⅱ) The charging amount of coarse particles increases when the dispersion air pressure of the ejector increases. (iii) The presence of a wire mesh for rectification in the flow path of the test dust increases the amount of charging. Based on these phenomena, the confirmed charging of dust is assumed to be as follows. The dust is mixed with the ejected air in the ejector, ejected at high speed with the ejected air, and blown to the agitator plate. Coarse particles with high inertia collide and rub against obstacles owing to inertia. The dust particles collide, and friction with the obstacle is charged through frictional static electricity. The amount of charging is correlated with the collision speed of the dust. The same phenomenon occurs in the rectification wire mesh.

From the above results, it was confirmed that the test dust generated in the test duct was electrically charged, and it was assumed that this was due to frictional charging by the agitator plate and rectifying a wire mesh.

Figure 4: Effects of ejector and wire mesh for rectification on dust charging status



3.2 Status change of dust charging by changing the settings of the test conditions

The test duct was used to evaluate the equivalence between the dust meter and gravimetric measurements by setting the dust concentration and flow velocity. Fig. 5 shows the relationship between the concentration and charge of the test dust generated by changing the flow rate and the dust supply rate. Fig. 4 shows the relationship between the dust concentration and dust charge of the test dust generated at different flow velocities and dust feed rates. The equation in the figure is an approximation obtained after a logarithmic conversion. Within the range of −5 to −15 μC/g, the higher the dust concentration, the lower the dust charge. This trend was also observed in a report that investigated the particle charging in a pipe. Suzuki et al. (2001) reported that the specific charge was larger when the feed rate was smaller and when the flow velocity was higher. It is thought that the specific charge increases not only because the probability of individual particles colliding with the collision plate or tube wall increases, but also because the collision area also increases as the spatial concentration of the powder decreases with a decrease in the feed rate, which is consistent with the results obtained in this study. Similar results were obtained when the amount of electric charge in a pipe was measured using JIS 10 type fly ash (Masuda et al., 1997). By contrast, the dust concentration and amount of charge, regardless of the flow velocity, are on the same curve. Frictional charging owing to collisions is inversely proportional to the collision speed because the contact area changes with the collision speed (Masuda et al. 2002). During this measurement, the rectifying wire mesh in the downstream was not installed, and the collision between the particles and the agitator plate downstream of the ejector was the main cause of the dust charging. These collisions were not affected by the velocity of the flow in the duct because the velocity of the exhaust gas from the ejector was constant.

It was found that when the dust feed rate was adjusted to change the dust concentration, the dust charge was also unchanged. For the relationship between the dust concentration value and the amount of charge, a relationship equation specific to this test duct was obtained.

$$q_a = \frac{27.0}{{C_m}^{0.4}} \tag{7}$$

where qa is the actual charge (μC/g), and Cm is the dust concentration based on the gravimetric measurement (mg/m^3).

3.3 Effect of change in charge of the test dust on the dust meter readings

The results are shown in Fig. 6. An approximate line was added as an eye guide. There was no linear relationship between the gravimetric measurements and the dust meter readings, but rather a curvilinear relationship where the higher the concentration, the lower the indicated value. With the regression curve at a flow rate of 12 m/s as a reference, the regression curve at a flow rate of 16 m/s was comparable, whereas the regression curve at a flow rate of 8 m/s tended to be slightly lower. These were most likely caused by the difference in dust charge during the test. Therefore, because there is a relationship between the dust concentration and the dust charge during the test, as shown in Eq. (7), and according to the detection theory of the electrostatic detection method shown in Eq. (5), the indicated values of the dust meter and charge have a proportional relationship, i.e. the relationship between the readings obtained under the standard charging conditions (qs = −10 μC/g is used) and the readings obtained from the actual test can be expressed as follows:

$$R_a = \frac{|q_a|}{|q_s|} R_s \tag{8}$$

where Rs indicates the dust meter reading obtained under the reference charging condition (mg/m^3 RC), Ra is the dust meter reading obtained during the actual test (mg/m^3 RC), qs is the reference charge (μC/g), and qa is the actual charge (μC/g).

Fig. 7 shows the results of removing the effect of charge variation from the respective readings using the correction equation for removing the effect of the charge variation, i.e. Eq. (8). A linear relationship between the gravimetric measurements and the converted dust meter readings was found to be normal. It can be seen that the change in the charge of the test dust caused by the change in the test condition settings of the test duct has a non-negligible effect on the dust meter readings. It was found that the higher the dust concentration, the lower the charge per particle, and the curvilinear nature of the relationship made it impossible to evaluate the equivalence through a gravimetric measurement. It was thought that if the relationship between the amount of charge of the test dust and the dust concentration specific to each duct was obtained in advance, it would be possible to evaluate the equivalence based on gravimetric measurements by measuring the amount of charge of the test dust during the test and removing the effect of any charge fluctuations from the dust meter readings.

Figure 7: Relationship between dust concentration and dust meter readings with the effect of charge variation removed

Figure 5: Relationship between dust concentration and dust

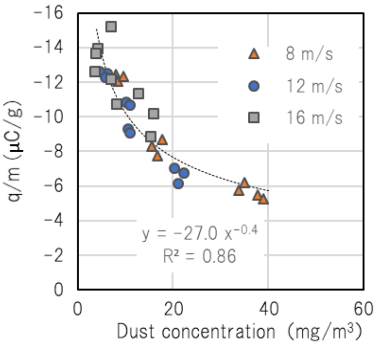
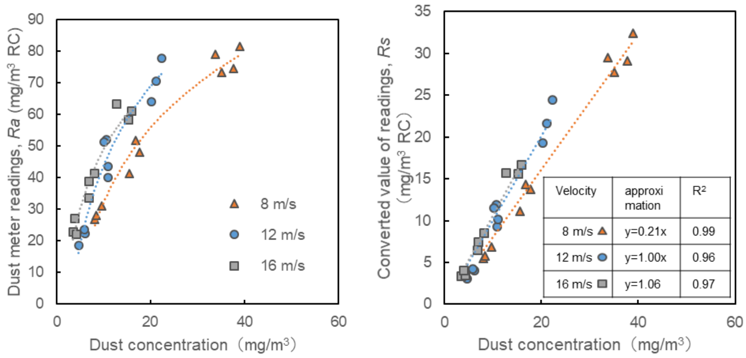


Figure 6: Relationship between dust concentration and dust meter readings



4 Conclusion

In this study, the relevance of the standard and operational considerations for the performance evaluation of dust meters using the test ducts specified in the newly developed JIS standard are discussed. In this paper, we focus on the issues in the measurement of a probe electrification type dust meter. As a result, the following points are found:

- It was confirmed that the test dust in the test duct was electrically charged. The cause of this was assumed to be the structural origin i.e. the frictional charging of the agitator plate and the rectifying wire mesh.
- The dust charge changes as the test conditions are changed. The effect of changing the dust concentration was larger than that of changing the flow rate, and there was an inverse proportional relationship between the dust concentration and the charge.
- The change in the dust charge undermined the linear relationship between the dust meter readings and the gravimetric measurement, and a curvilinear relationship was observed in which the higher the dust concentration, the lower the dust readings.
- By removing the effect of the difference of dust charges, a linear relationship was obtained.

In summary, it was found that it is necessary to measure the dust charge and compensate it appropriately when conducting the equivalence test when using this test duct. In addition, it is desirable to take measures to fundamentally reduce the dust charge generated.

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