

Characterization of Airborne Particles and Droplets: Relation to Amount of Airborne Dust and Dust Collection Efficiency

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Abstract

Water sprays have been commonly used to suppress airborne dust. Water is doped with surface-active agents to enhance the dust capture efficiency through a reduction of surface tension. Nevertheless, dust collection efficiencies have been less than satisfactory historically. A detailed characterization of freshly generated airborne dust particles and spray droplets was carried out in order to explain this observation. Such properties as the agglomeration state of the freshly generated airborne dust particles and the airborne dust production capacity of various materials were defined and quantified. Electrostatic charges on individual airborne particles and spray droplets were measured. It was demonstrated that freshly generated airborne dust

particles were extensively agglomerated. The magnitude of agglomeration was a function of material type and decided the amount of dust becoming airborne from a given material. This explains why certain materials such as quartz and anthracite produce more dust than some others.

It was demonstrated that surfactants could be employed to charge the spray droplets selectively. The sign and magnitude of the droplet charge was a function of surfactant type and concentration. A strong correlation between the droplet charge and dust collection efficiencies by spray droplets was observed for cationic surfactants, suggesting that surfactants affected collection efficiency in addition to enhancing wetting.

Keywords: characterization, airborne particles, droplets, dust collection

1 Introduction

Surfactants enhance water's ability to wet and engulf dust particles [1–8], hence their use is expected to lead to an improvement in dust collection efficiency. *Hu et al.* [9], who used the concept of the work of adhesion to predict quantitatively the dust collection efficiency, found that it could be correlated well with the collection efficiency for anionic and non-ionic surfactants, but observed no correlation between the two in the case of

cationic surfactants. Similar discrepancies as to the benefits of surfactants in dust suppression are common in the literature. While some researchers have reported results favoring the use of surfactant solutions [10–13], others have questioned their usefulness [1, 4].

The problem may lie in the fact that the efficiency of wetting and engulfment becomes important only after a successful collision between the droplets and particles. Collision efficiency is mainly affected by the flow conditions, number of the particles and droplets, momentum of the particles and the charges on particles and the spray droplets. Hence a knowledge of the physical state of the particles (agglomerated or single particles), their concentrations and the charging level of both the particles and the droplets especially in the presence of surfactants are extremely important in the predicting of the dust collection efficiencies.

This paper presents the results of a detailed characterization study carried out using airborne particles and spray droplets from surfactant solutions. The agglomer-

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ation state of the dust from various materials, their dust production capacities and the charges carried by these particles are discussed. Electrostatic charges carried by the spray droplets of various surfactant solutions and their effect on the dust collection efficiency are also elucidated.

2 Experimental

Various experiments were carried out with particles and droplets to determine the physical properties of airborne dust, electrostatic charges carried by particles and droplets and dust collection efficiencies. Experimental setups utilized in these studies are briefly described below.

2.1 The Fresh Dust Generator

In order to produce dust from freshly broken particles, a fresh dust generator (FDG) was designed and fabricated. The device was a small roll crusher equipped with a sensitive feeding system. A roll crusher-type crushing mechanism was selected to ensure instantaneous and single crushing for each particle. The rolls were enclosed in a Plexiglas box in order to confine the dust in a small volume. The rotation of the rolls created an air flow which gently carried the dust into the observation chamber above the rolls. The pathway to the observation chamber contained two flat baffles located just above the rolls to prevent the coarser particles from entering the dust stream. They leave the FDG from the chute at the bottom. An overall schematic diagram is given in Figure 1. Details of the design are given elsewhere [14].

2.2 The Droplet Charge Analyzer

A charge analyzer was built in the laboratory to measure the electrostatic charges on spray droplets generated from various surfactant solutions. The experimental setup consisted of three main sections (Figure 2);

- (i) a droplet generation cell, where individual droplets were formed by spraying from surfactant solutions;

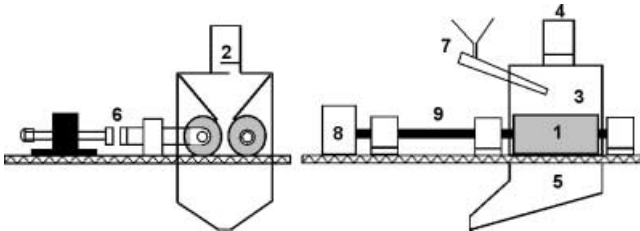


Fig. 1: A schematic view of the fresh dust generator. (1) Crushing rolls; (2) baffles; (3) dust chamber; (4) dust outlet; (5) crushed product chute; (6) spring assembly; (7) feeder; (8) gear box; (9) shaft.

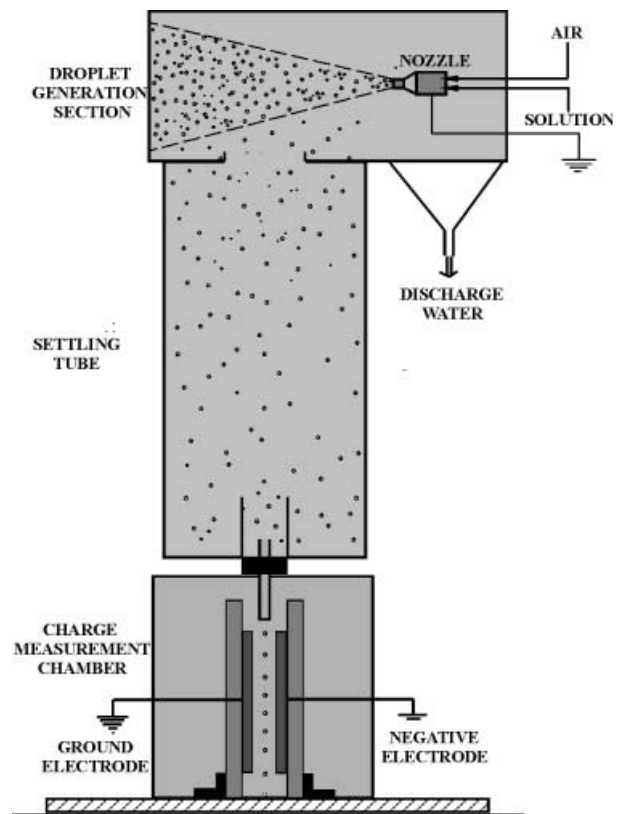


Fig. 2: A schematic view of the droplet charge analyzer.

- (ii) a settling column, where these droplets are allowed to reach terminal velocity; and
- (iii) a charge measurement chamber, where the charges on spray droplets are measured.

The charge was determined by deflection of the droplets from the vertical path in an electric field. To measure the charges, the chamber was placed in front of a long focal length microscope coupled to a high-speed motion analyzer (Spin Physics Model SP2000) (Figure 3). The trajectories of the droplets as they passed through the electric field

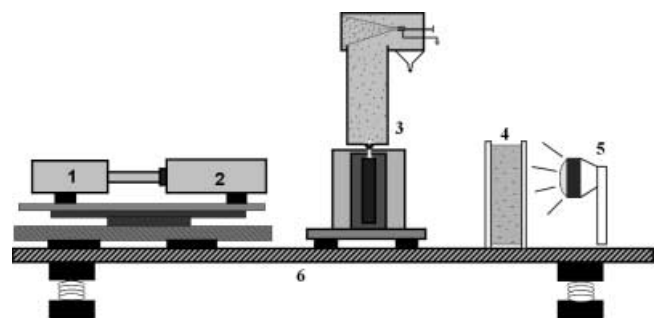


Fig. 3: A schematic view of the set-up used in measuring the droplet charge. (1) High-speed camera; (2) long focal length microscope; (3) the droplet charge analyzer; (4) water tank; (5) light source; (6) vibration-free table.

were recorded on a videotape. These trajectories were subsequently analyzed using appropriate equations of motion to 1–9 determine the charge on the droplets. The details of the procedure are given elsewhere [15].

2.3 The Particle Charge Analyzer

The particle charge analyzer employed the charge measurement chamber mentioned above. Instead of the droplet generation section and the settling column, a sensitive feeder which could feed particles of desired sizes into the charge measurement chamber was utilized. The procedure for determination of charge was same as that for the droplets. In order to control humidity, the particle charge measurement chamber was placed in an enclosed box of $60 \times 9 \times 60$ cm in size and a water-antifreeze mixture at -15°C was circulated inside the metal tubing which was placed inside the box.

2.4 The Dust Suppression Column

The column used for dust suppression studies was made of a Plexiglas tube about 30 cm in diameter and 3 m long. The top of the chamber was covered with a Plexiglas plate through which the connections for the dust inlet and spray nozzle were made. The bottom section was connected to a stainless-steel funnel designed for sludge and air removal. The chamber had two small openings through which in situ measurements of particle and droplet size distributions could be made using the particle size analyzer. A Model 3400 Fluidized Bed Aerosol Generator manufactured by TSI (St. Paul, MN, USA) was used to disperse dust into the chamber. The device consisted of a powder reservoir, a bead chain feeder, a fluidized bed chamber with copper beads, an air plenum chamber and an elutriator. Details of the design are given elsewhere [7, 16].

A 1/8 JJ SS air atomizer, obtained from Spraying Company (IL, USA) was used to spray water and surfactant solutions in both charge measurement and

dust suppression experiments. Liquid and air were internally mixed in the atomizer to produce droplets. The liquid flow-rate was maintained at 0.045 l/min in all the charge and dust suppression experiments. Conditions were chosen so as to obtain droplets of about $90 \mu\text{m}$ in diameter with a standard deviation of $25 \mu\text{m}$.

3 Materials

Several commercially available surfactants were used. A summary of these surfactants with some common characteristics and structures are given in Table 1.

Four different materials, namely a high volatile A (hvA) bituminous coal sample from the upper Freeport Seam (Lawrence, PA, USA), an anthracite coal sample from Mammoth Seam (Appalachian, PA, USA), a sub-bituminous A coal sample from Colorado Q Seam in Moffat County (Craig Township, CO, USA) and quartz were used in the particle characterization studies. Only the hvA bituminous coal sample was utilized in the dust collection efficiency studies. The quartz was essentially pure SiO_2 with trace elements such as Fe, Cr, Ni, Co and Ca at concentrations less than 50 ppm. The sample was ground and classified into respirable size by means of a Bleuler laboratory mill close-circuited with a Donaldson classifier for the dust suppression experiments. In dust collection efficiency studies, $-10 \mu\text{m}$ particles with a d_{50} value of $4 \mu\text{m}$ were used. For the charge measurement experiments, samples to be studied were ground from a top size of 1.25 cm and were classified into a size fraction of $38 \times 75 \mu\text{m}$ in a glove-box under a nitrogen atmosphere.

4 Results and Discussion

4.1 Characterization of Freshly Generated Airborne Dust

Initial studies were carried out on the dust produced by the FDG in order to determine the characteristics of the

Table 1: Selected properties of the surfactants used in this study.

Commercial name	Hydrophobic group	Hydrophilic group	M.W.	CMC $\times 10^{-3}$ (mol/l)	Surface tension (mN/m)
<i>Anionic surfactants</i>					
Na lauryl sulfate (NaLSO_4)	Lauryl	Sulfate	288	8.25 [18]	–
Aerosol-OT (AOT)	Diocetyl	Sulfosuccinate	444	1.3 [19]	26.0 [19]
<i>Cationic surfactants</i>					
Dodecylamine (DAH)	Dodecyl	Amine	222	13.3 [18]	–
Coco amine (C-10)	Coco	PEO (10 mol)	645	0.16 [16]	38.0 [20]
Tallow amine (T-10)	Tallow	PEO (10 mol)	700	–	–
Tallow amine (T-15)	Tallow	PEO (10 mol)	930	–	–
<i>Nonionic surfactants</i>					
Triton X-100 (TX-100)	Octylphenol	PEO (9.5 mol)	628	0.22 [6]	30.1 [6]
Triton N-101 (TN-101)	Nonylphenol	PEO (9.5 mol)	642	0.033 [6]	30.0 [6]

PEO stands for polyethylene oxide; coco and tallow amines used in this work are known by the trade name Chemeen series.

airborne dust. The dust from the FDG was passed through the beam path of a light scattering size measurement device (Malvern 2600c) in order to determine the size distribution of the airborne dust. A Nuclepore 0.2 μm filter assembly with a pump-flow meter system was employed for collecting the airborne dust particles for further analysis once they had crossed the beam of the size measurement device. By use of this type of a set-up, size measurements for the same population of particles could be obtained while they were in air and after they were collected on the filter and subsequently dispersed in water. A 0.1% aqueous solution of sodium hexametaphosphate (Calgon) and an ultrasonic bath were employed to disperse the particles collected on the filter. The airborne and in-water size distributions of the quartz dust obtained as explained above are given in Figure 4. A large difference between the two size distributions is apparent. The 50% passing size, d_{50} , is 20.3 μm for the airborne quartz particles coming from the FDG. The d_{50} value is 7.3 μm when the same particles are dispersed in water. It should be noted that there seem to be no particles smaller than about 3 μm (when the dust was airborne). Similar results were obtained with the coal samples. The d_{50} and d_{90} values observed in air and in water for all the materials tested are given in Table 2.

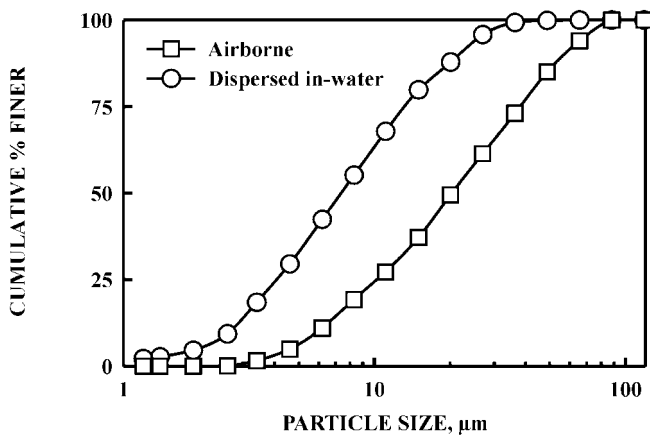


Fig. 4: Size distribution of the airborne quartz dust produced by the fresh dust generator in water and in air.

Table 2: 50% and 90% passing sizes for various materials for airborne and in-water dust.

	Particle size (μm)			
	Dispersed in water		Airborne	
	d_{50}	d_{90}	d_{50}	d_{90}
Quartz	7.3	22.0	21.5	59.5
Anthracite	7.6	22.6	16.1	55.0
High volatile A	18.2	40.0	35.5	85.3
Sub-bituminous A	14.9	41.5	30.2	75.2

The difference between the d_{50} and d_{90} values for the same dust particles depending on whether the particles were airborne or dispersed in water raises the possibility that the particles were agglomerated as they left the dust generator. Once they are dispersed in water the agglomerates broke up and the size distribution belonged to the primary particles which made up the agglomerates. Agglomeration in air was demonstrated by taking the pictures of the dust leaving the FDG by electron microscopy and high-speed camera recordings. Glass microscope slides, which were coated with a very thin layer of grease, were placed above the observation chamber to prepare specimens for electron microscopy. In fact, no single particles could be observed in the electron microscope photographs and in the recordings. All the particles observed were made up of loose agglomerates of different sizes.

4.2 Airborne Dust Production Rates

The amount of airborne dust produced by the FDG was collected by the filter assembly at the outlet of the fresh dust generator for different feed rates for one minute. The results are given in Table 3. A parameter which is called the Airborne Dust Produced) on Breakage (ADP) was utilized to compare the amount of airborne dust produced for different materials. The ADP is simply defined as the ratio of the airborne dust collected on the filter to the amount of feed material to the crusher. Even though the rate of dust production increases with increasing feed rate, the ADP is somewhat independent. Hence the average of the ADP values for the three feed rates can be used.

In addition to the ADP, another descriptive parameter named the Total Amount of Potentially Airborne Dust (TAPAD) can be defined. In calculating the TAPAD, the amount of the particles in the FDG underflow finer in size than the nominal largest particle on the filter-paper was measured. This size was chosen as the d_{90} value in water of the dust collected on the filter. The reason for choosing the 90% passing size dispersed in water was that this could be assumed to be the practical limit for dust particles to become airborne since particles larger than this size failed to reach the filter in significant amounts. For example, the 90% size limit for the quartz material was 22.0 μm (Table 2). The amount of $< 22.0 \mu\text{m}$ material in the crusher underflow was determined to be 9.5%. These amounts were 7.2, 18.5 and 15.3% for anthracite, hvA and sub-bituminous A, respectively. TAPAD is the sum of the amounts (i) collected on the filter and (ii) misplaced in the crusher product and describes the amount of dust which has a potential to become airborne. For example, TAPAD is 10.9% for the quartz feed (9.5 + 1.4%). Dividing the average ADP values by the TAPAD

Table 3: Dust production parameters for various materials.

	Feed rate to FDG (g/min)	Rate of dust production (mg/min)	ADP (%)	Av. ADP (%)	Av. TAPAD (%)	Av. FDR (%)
Quartz	3.8	47.7	1.27	1.41	10.9	12.9
	7.1	111.5	1.56			
	11.8	165.8	1.40			
Anthracite	1.5	13.9	0.93	0.94	8.1	11.6
	3.0	31.0	1.03			
	12.0	103.5	0.86			
High volatile A	2.2	1.2	0.06	0.17	18.7	0.9
	5.9	10.2	0.17			
	10.1	25.9	0.26			
Sub-bituminous A	2.3	2.1	0.09	0.11	15.4	0.7
	9.0	5.9	0.07			
	12.8	20.0	0.16			

values gives the Fraction of Dust Released (FDR). FDR defines the ratio of dust released to become airborne to the total amount of potentially airborne dust. The FDR values are also presented in Table 3. It can be seen that while about 13% of the potentially airborne dust produced by quartz and anthracite actually become airborne, the same amount is less than 1% for the hvA and subbituminous A coal samples. Comparison of Table 3 with Table 2 shows that the FDR seems to be strongly correlated with the agglomerate size. Quartz and anthracite which produce smaller agglomerates release large amounts of dust, whereas the two coal samples which produce larger agglomerates seem to produce smaller amounts of airborne dust. This finding is important since it explains why larger than expected amounts of quartz dust are present in coal mine atmospheres or why very large amounts of dust are present in anthracite mines.

4.3 Electrostatic Charge on Airborne Particles

The charges on individual particles were measured using the charge measurement device. It was observed that particles carried significant amount of charges of both sign. The charge data will be presented on the basis of a few statistical parameters for sake of brevity. These are the *root mean square (RMS) charge*, which gives the extent of charging for a population of particles irrespective of sign, and *total positive or total negative charges*, which are obtained by separately summing the positive and negative charges in the system based on 200 particles. The measured electrostatic charges on individual particles are presented in Figure 5 as a function of the relative air humidity for the four materials used. The 90% passing sizes of the airborne dusts produced by the FDG for these materials are given in Figure 6 also as a function of the relative air humidity.

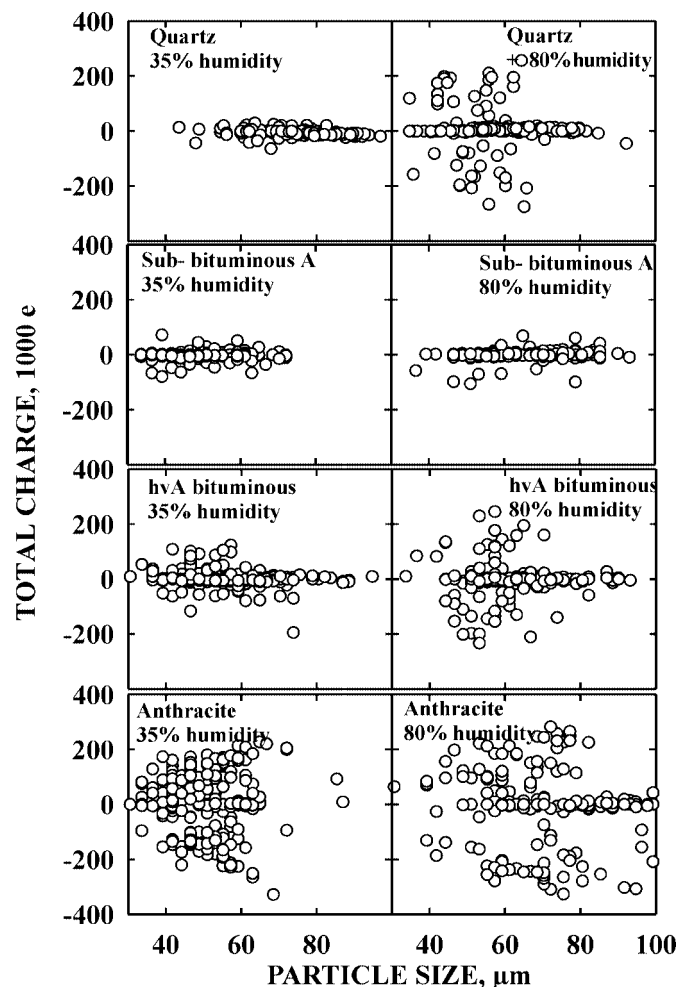


Fig. 5: Electrostatic charge on quartz, anthracite, high volatile A and subbituminous A coals.

The above data suggest that the extensive agglomeration observed for the airborne dust particles is strongly affected by both the particle charge and humidity. The

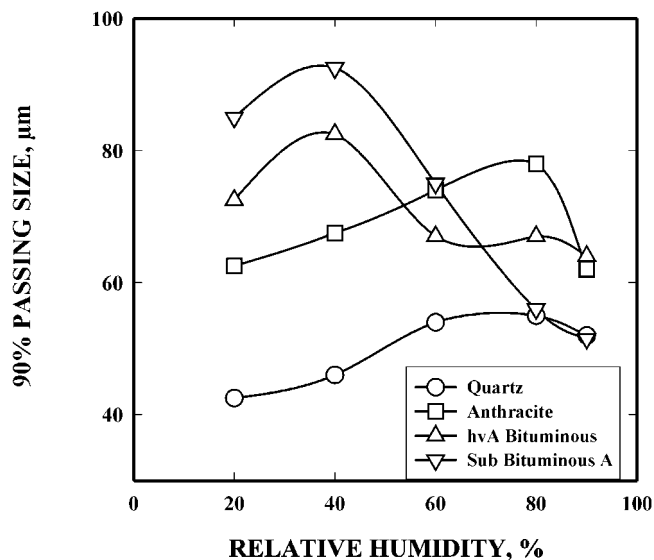


Fig. 6: Change in the mean airborne particle size for various materials as a function of relative air humidity.

charges present on the surface of non-conducting or semiconducting materials are most probably in the form of positive and negative patches. The magnitudes of charge given in Figure 5 are determined from the contributions of both the negative and positive patches. Therefore, a highly charged particle should have an abundance of patches of one polarity whereas a slightly charged particle might contain surface patches of both polarities. If only the patches of single polarity are abundant the collision efficiency may be reduced since similar charges will repel such that the agglomerates have less chance to grow. In addition, as the humidity of the environment is increased, the amount of water molecules adsorbed on the particle surface will increase owing to the increased partial pressure of water vapor. The adsorbed water molecules create a water film, which may be uniform, in the case of quartz, or in patches, in the case of coals. If the bodies are not in contact the water increases the magnitude of van der Waal's forces since it contributes to the total mass of the system [17]. When two bodies are in contact, however, the water film reduces the magnitude of the van der Waal's forces. Nevertheless, when two bodies are in contact a meniscus is formed because of condensation of water at the point of contact. This meniscus leads to an attraction force between two particles due to the direct effect of surface tension and the reduction in the pressure of the liquid by virtue of its concave shape. This creates a pressure which pushes the particles together, resulting in a compact agglomerate. In later stages the particles might chemically bond with the help of water to produce very strong agglomerates. However, obtaining a correlation as to how particle charge and humidity influence the agglom-

eration among airborne particles is not easy to establish. It seems that the airborne agglomerate size would be determined by an interplay between the electrostatic and capillary forces, which themselves depend on many parameters.

4.4 Electrostatic Charge of Spray Droplets from Surfactant Solutions

Charges on individual droplets generated in the droplet generation section were measured using the droplet charge measurement set-up given in Figures 2 and 3. The experiments were carried out for anionic, cationic and nonionic surfactants. The results are presented below.

Anionic Surfactants: Addition of anionic surfactants increased the droplet charge at low concentrations significantly. The RMS charges for the anionic sodium lauryl sulfate (NaLSO_4) displayed a maximum at very low concentrations and subsequently decreased with further surfactant addition (Figure 7). The RMS charge became almost as low as that of the distilled water at 3.5×10^{-3} M and remained constant at higher concentrations. It should be noted that this concentration is very close to the critical micellar concentration (CMC) of this

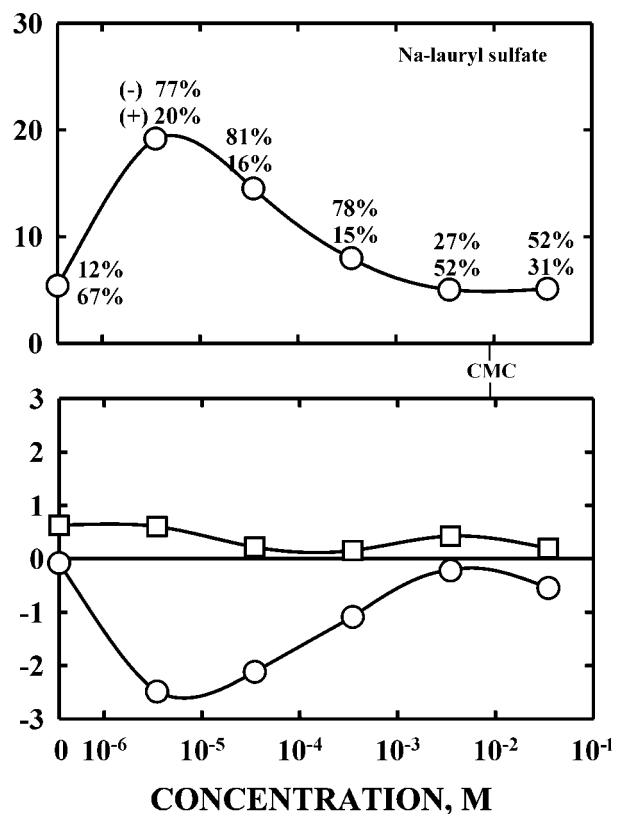


Fig. 7: The RMS and total charges on spray droplets as a function of sodium lauryl sulfate concentration. The numbers on the symbols refer to the fractions of positively and negatively charged droplets in the population.

surfactant. The total negative charges displayed a behavior very similar to the RMS charge whereas the total positive charges seemed to be fluctuating at low values. This demonstrates that negative charges are dominant on the droplets generated from the solutions of this surfactant. This can be better seen from the percentages of the positively and negatively charged droplets. While the fraction of negatively charged droplets was significantly low in the case of distilled water (12%), it increased to 77% upon addition of this negatively charged surfactant. The percentages became somewhat closer around the CMC.

The other anionic surfactant, Aerosol-OT (AOT), showed similar charging character even though its droplets were less strongly charged than those of NaLSO_4 at low concentrations. The similarity in the root mean square charges for the droplets from the NaLSO_4 and AOT solutions at high concentrations should be noted, however.

Cationic Surfactants: The results for dodecylamine hydrochloride (DAH) are presented in Figure 8 in terms of the RMS and total charges. The general trend for this cationic surfactant was similar to that observed with the anionic surfactants. The RMS charge displayed an initial

increase, but began to decrease with further surfactant addition and seemed to level off at a concentration close to the CMC. However, it should be noted that the RMS charges are considerably higher for this cationic surfactant than the anionic surfactants. It should be noted that the RMS charges are still fairly high around the CMC. The negatively charged droplets are almost completely eradicated at high concentrations of this surfactant, as seen from their very low percentages.

The RMS charges obtained with the ethoxylated coco amine C-10 are also very similar to those observed with DAH. The RMS charge goes to a maximum initially before dropping and leveling off at high concentrations. There is one important difference, however. The concentrations where maximum RMS charges are observed are very close to the CMC values of these three surfactants.

Nonionic Surfactants: The charging behavior of the nonionic Triton X-100 (TX-100) was markedly different from that obtained with the ionic surfactants. The RMS charge showed a linear increase with increasing surfactant concentration. Also, the general magnitude of the RMS charges was significantly smaller for these surfactants (Figure 9). The behavior of Triton N-101 (TN101)

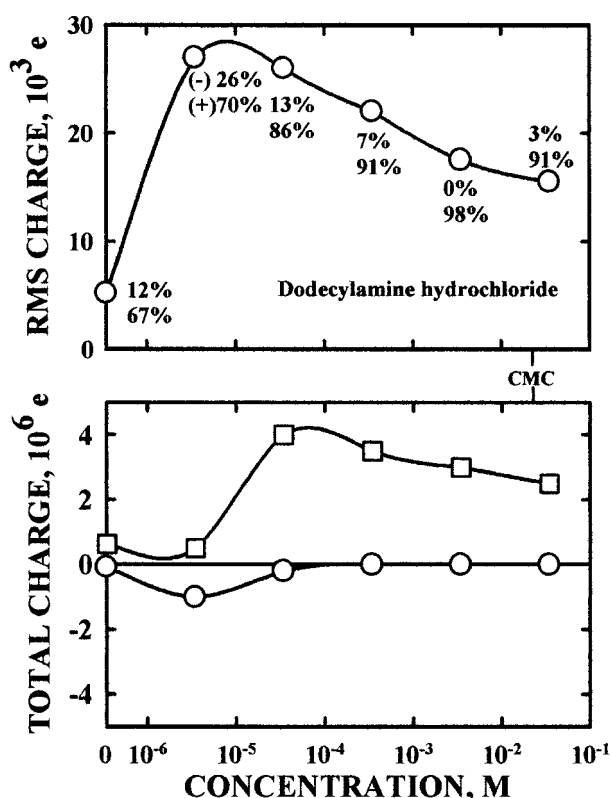


Fig. 8: The RMS and total charges on spray droplets as a function of dodecylamine hydrochloride concentration. The numbers on the symbols refer to the fractions of positively and negatively charged droplets in the population.

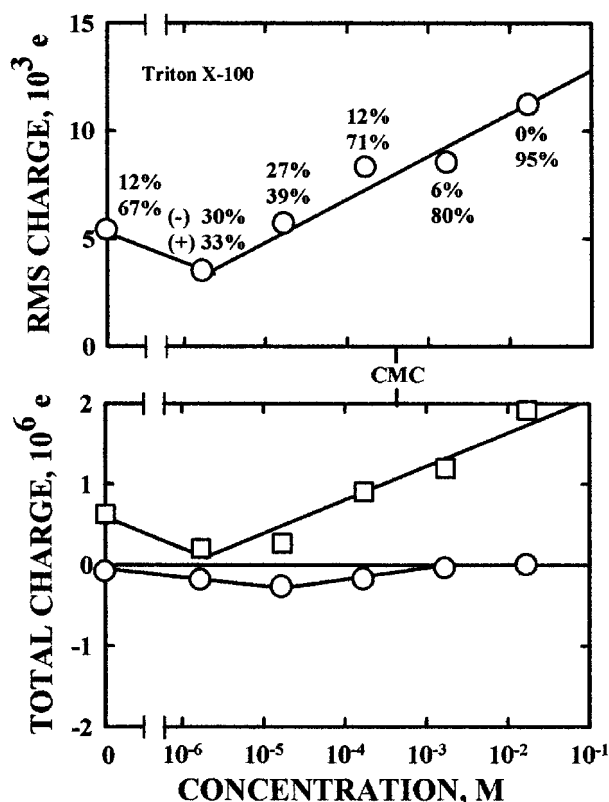


Fig. 9: The RMS and total charges on spray droplets as a function of Triton X-100 concentration. The numbers on the symbols refer to the fractions of positively and negatively charged droplets in the population.

was identical with that of Triton X-100. It is important to note that the increase in the RMS charges results from the generation of positively charged droplets, as seen from the percentages given in Figure 8.

4.5 Dust Suppression with Water Sprays from Surfactant Solutions

The relationship between the droplet charge and dust suppression efficiency is presented in Figure 10 for the Chemeen series cationic surfactants. It can be seen that both the droplet charge and the dust suppression efficiency vary in a non-linear manner with surfactant concentration. However, it should be noted that the dust suppression efficiency reaches a maximum at a concentration where maximum droplet charges are observed. Similar results have been obtained with other cationic surfactants but are not presented here for the sake of brevity. These results demonstrate that the efficiency of dust suppression is clearly affected by the electrostatic charges on spray droplets. However, this relationship was observed only with the cationic surfactants. A similar correlation cannot be observed with anionic and non-ionic surfactants. This points to the fact that the thermodynamic relationship suggested by *Hu et al.* [9, 16] holds for anionic and nonionic surfactants which produce smaller charges on droplets. However, for

cationic surfactants which lead to very large charges on droplets, a thermodynamic relationship does not hold, but the effect of charge dominates. This means that increasing the dust collection efficiency by means of reducing the surface tension using surfactants is only possible with those surfactants which do not impart high charges on droplets. That is, a mention of the effect of the surfactant on wetting is only possible after considering its effect on the collision. In other words, thermodynamically favored conditions can be achieved only after a successful collision.

The reason for not obtaining a relationship between the particle charge and dust suppression efficiency is attributed to agglomeration of particles in air. It is clear that the relationship between the dust collection efficiency and the total electrostatic charge for agglomerates will be very complex.

5 Conclusions

A detailed characterization of airborne particles and spray droplets was carried out and the following observations were made:

1. Freshly generated respirable dust particles always form agglomerates in air irrespective of the material. This is very important in modeling of the transfer, capture and sedimentation processes of dust particles.
2. The extent of agglomeration is different for different materials and at different relative air humidities. These factors seem to determine the amount of dust released into air. Those materials which generated smaller agglomerates (quartz and anthracite, for example) released large amounts of dust into air. This explains the relatively higher fractions of quartz in airborne coal dusts and the extremely dusty atmospheres in anthracite mines.
3. Particles carry a significant amount of electrostatic charges in air which is a function of both the material type and the humidity of the environment. Although electrostatic charge must also affect the agglomerate size as does humidity, establishing a correlation was not possible.
4. Airborne spray droplets also carry electrostatic charge. More importantly, the sign and magnitude of this charge could be manipulated by the addition of minute amounts of surfactants. Statistically, the droplets acquired the charge of the ionic head, cationic surfactants lending more charge to the droplets than anionic surfactants. Nonionic surfactants were mostly positively charged. There are indications that some positive charge from air was acquired by the hydrocarbon chains. This explains the

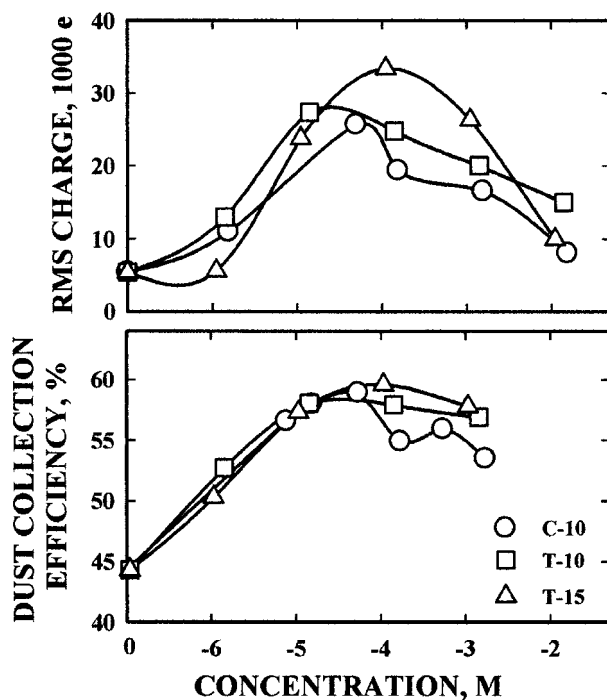


Fig. 10: Change in the electrostatic charge on droplets and the dust collection efficiency as a function of surfactant concentration: hvA bituminous coal, 45 ml/min water flow-rate.

stronger charging of the cationic surfactants and positive charging of the nonionic surfactants.

5. How the use of surfactants in water sprays to suppress dust influences the dust collection efficiency depends on the type and concentration of the surfactant. A strong correlation between the droplet charge and dust collection efficiencies was observed for the cationic surfactants, but not for the anionic and nonionic surfactants. Large amounts of charge imparted on droplets by the cationic surfactants affect dust capture via their impact on the collision process. Anionic and nonionic surfactants which charge the droplets to lesser extents, on the other hand, cannot influence the collision, but perform mostly through the adhesion and wetting sub-processes.

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