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EVALUATION OF AEROSOL ASPIRATION EFFICIENCY AS A FUNCTION OF STOKES NUMBER, VELOCITY RATIO AND NOZZLE ANGLE

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Abstract – Inertial effects in the aspiration of aerosols from a moving fluid are described in this experimental study. Aspiration coefficients were determined by comparing concentrations collected by two nozzles simultaneously sampling in a 10 cm wind tunnel. The control nozzle was aligned parallel to the axis of the duct and sampled isokinetically. The test nozzle was inserted at angles of 0, 30, 60 and 90° and sampled at a velocity ranging from one half to two times the isokinetic velocity. Particle size, nozzle diameter and free stream velocity were varied to produce a range of Stokes numbers from 0.007 to 3. Data obtained by Belyaev and Levin (1974) were incorporated with experimental data to develop an empirical expression describing the relationship between the aspiration coefficient and the Stokes number as a function of angle of misalignment and velocity ratio. An adjusted Stokes number is described which takes into account the effect of an apparent change in nozzle diameter due to misalignment of the nozzle to the flow stream. Analysis of the probe wash showed that from 15 to 60% of the total particulate matter entering the sampler inlet was lost on the nozzle walls. Implications of this phenomenon are described.

1. INTRODUCTION

Previous investigations concerning the aspiration of an aerosol into a sampling inlet or nozzle can be categorized into two groups. The first group includes such studies as Watson (1954), Badzioch (1959) and Belyaev and Levin (1972, 1974) on the analysis of errors involved in sampling particles entrained in a moving fluid such as a process stream. The second group includes work by May and Druett (1953), Kim (1974), Davies (1967a, b) and Davies and Subari (1978) on the sampling bias when aspirating aerosols in calm and near calm conditions. Although both areas of study are closely related, as only the magnitude of the particle or free stream velocity differentiates the two, the results from one area cannot always be extrapolated to predict what will happen in the other area. Sampling in calm conditions is identical to flow into a point sink. In this situation, the inertial lag of particles will induce an initial reduction of the concentration of particles entering the inlet. However, this inertial lag also has an effect of increasing the concentration in the vicinity of the inlet so that if sampling is continued long enough, a representative sample can be obtained (Davies and Subari, 1978). This phenomenon of increasing concentration does not occur in a process stream as the parcel of air near the nozzle is constantly being replaced by the moving fluid.

This paper pertains to the first group of studies as it describes the errors involved in the anisokinetic sampling of a process stream. Analysis of the sampling bias will include the effect of nozzle misalignment to the flow stream as well as the effect of unequal free stream sampling velocity.

2. REVIEW OF EXPERIMENTAL WORK ON ISOKINETIC SAMPLING

Due to the inertial characteristics of particles it is necessary to sample isokinetically in order to obtain a representative sample of particulate matter from a moving field. Isokinetic sampling can be defined by two conditions: (1) the suction or nozzle velocity, V_i, must be equal to the free stream velocity, V_0; and (2) the nozzle must be aligned parallel to the flow stream (Wilcox, 1957). Maintaining these conditions will prevent any divergence of streamlines either away from or into the nozzle and thus an inertial sampling bias will be avoided.

The majority of the previous research on an isokinetic sampling has been concerned with determination of the aspiration coefficient only when the ratio of the free stream velocity to the inlet velocity is other than unity. Lapple and Shepherd (1940) studied the trajectories of particles in a flow stream and developed an equation for estimating errors resulting from anisokinetic sampling velocities. Watson (1954) examined errors in the anisokinetic sampling of spherical particles and found that the magnitude of the errors was not only a function of particle size, but also of the velocity and the nozzle diameter. He proposed that the sampling efficiency was a function of the dimensionless particle inertial parameter St (Stokes number) defined as:

$$St = C\rho_p V_0 D_p^2/18\eta D_i = \tau \frac{V_0}{D_i} \tag{1}$$

where
C Cunningham correction for slippage
ρ_p particle density
V_0 free stream velocity
D_p particle diameter
η viscosity of the gas
D_i nozzle diameter
τ $C\rho_p D_p^2/18\eta$. (2)

τ defines the relaxation time which is a measure of how quickly a particle adapts to a change in velocity of the surrounding air (Fuchs, 1964).

Tests run by Dennis *et al.* (1957) on an atmospheric dust of 0.5 μm MMD produced no detectable concentration changes even while sampling at a 400% variation from isokinetic flow, thus indicating that isokinetic sampling is relatively unimportant for fine particles. Hemeon and Haines (1954) and Whiteley and Reed (1959) observed that for coarse particles the velocity into the nozzle had no important bearing on the quantity of dust collected. They suggested using the product of the nozzle area and the stack gas velocity approaching the nozzle as the gas sample volume, regardless of the velocity of the nozzle.

Lundgren and Calvert (1967) found the sampling bias or aspiration coefficient A to be a function of the inertial impaction parameter St and the velocity ratio ($R = V_0/V_i$). Badzioch (1959) developed equations to define the dependence of the efficiency upon particle inertia and the velocity ratio. In a slightly different terminology, using nozzle inlet concentration, C_i, and free stream concentration, C_0:

$$A = C_i/C_0 = 1 + (R - 1)\beta(St) \tag{3}$$

where $\beta(St)$ is a function of inertia given by:

$$\beta(St) = [1 - \exp(-L/l)]/(L/l) . \tag{4}$$

l is the stop-distance, or the distance a particle with initial velocity V_0 will travel into a still fluid before coming to rest, and is defined by (Fuchs, 1964):

$$l = \tau V_0 . \tag{5}$$

L is the distance upstream from the nozzle where the flow is undisturbed by the downstream nozzle. It is a function of the nozzle diameter and is given by the equation:

$$L = nD_i . \tag{6}$$

Badzioch (1959) observed that the factor n lies between 5.2 and 6.8.

Flash illumination photographic techniques were used by Belyaev and Levin (1972) to study particle aspiration. Photographic observations enabled them to verify Badzioch's claim that L, the undisturbed distance upstream of the nozzle, was between five to six times the diameter of the nozzle. They examined data of previous studies on error due to anisokinetic sampling and concluded that the discrepancy between experimental data was due to the researchers failing to take into account three things: (1) particle deposition in the inlet channel of the sampling device; (2) rebound of particles from the front edge of the sampling nozzle and their subsequent aspiration into the nozzle; and (3) the shape and wall thickness of the nozzle. They also found that the sampling efficiency was a function of the inner diameter of the nozzle, D_i, as well as St and R.

In a more recent article, Belyaev and Levin (1974) obtained experimental data demonstrating that for thin-walled nozzles, the function $\beta(St)$ was a function of both R and St. Equations were developed from the data for values of St between 0.18 and 6.0 and for values of R between 0.16 and 5.5.

$$\beta(St, R) = 1 - \frac{1}{1 + (2 + 0.617/R)St}. \tag{7}$$

Figure 1 shows a plot of equations (3) and (7) for a range of velocity ratios and Stokes numbers. The most significant changes in the aspiration coefficient occur at values of St between 0 and 1. Beyond $St = 1$, the aspiration coefficient tends to asymptotically approach a limit of R. The limit of R is due to the phenomenon observed by Hemeon and Haines (1954) and Whiteley and Reed (1959) that for large particles the inertia of the particles is so great that the particle trajectories become straight regardless of any divergence of the flow streamlines. Since only those particles directly in front of the inlet will enter the nozzle, the inlet concentration, C_i, will be equal to the product of flow stream concentration, C_0, nozzle inlet area, A_i, and flow stream velocity, V_0, divided by the volume of gas sampled, V_iA_i.

$$Ci = \frac{C_0 A_i V_0}{V_i A_i}. \tag{8}$$

The aspiration coefficient A can be found by dividing both sides of equation (9) by C_0 to obtain

$$C_i/C_0 = A = V_0/V_i = R. \tag{9}$$

The values of Stokes number for which equation (9) applies depends upon the accuracy that is required and can be calculated using equations (3) and (7). It can also be approximated by analyzing the definition of Stokes number:

$$St = \tau V_0/D_i = l/D_i. \tag{10}$$

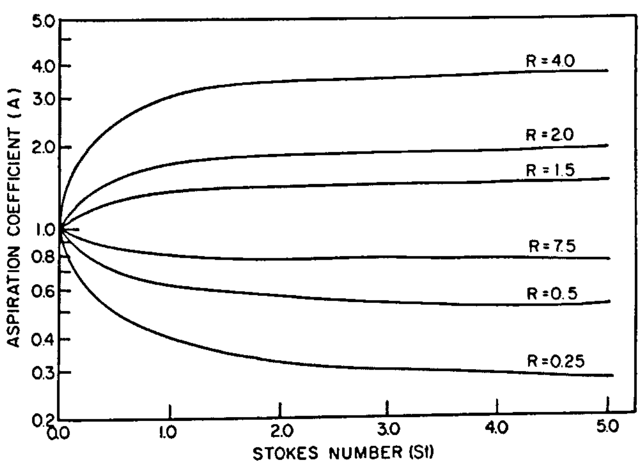

Fig. 1. Aspiration coefficient as a function of Stokes number (St) and velocity ratio ($R = V_0/V_i$) (Belyaev and Levin, 1974).

By definition, Stokes number is the ratio of particle stop-distance to nozzle diameter. Badzioch (1959) and Belyaev and Levin (1972) have shown that the disturbance upstream of a nozzle is proportional to nozzle diameter, and at approximately six diameters upstream the flow is relatively undisturbed. Thus the flow streamlines start to diverge toward or away from the nozzle at approximately six nozzle diameters and this represents the distance available for a particle to change direction. The distance required for a particle to change direction is a strong function of the stop-distance, and the relationship $l > 6D_i$, represents the limiting situation for a particle to have sufficient time to react to changing streamlines. Therefore, for $St > 6$, a particle would essentially have a straight trajectory and equation (9) would apply.

Results of Dennis *et al.* (1957) and Belyaev and Levin (1974) show that for small values of Stokes number a representative sample of particulate matter can be obtained regardless of the velocity ratio. This is due to the fact that the particles have such low inertia they can negotiate sudden direction changes along with the streamlines. Using equations (3) and (7) and an analysis of Stokes number similar to that performed for large values of St, it is possible to show that for $St < 0.01$, the aspiration coefficient will always be close to unity.

3. SAMPLING BIAS DUE TO NOZZLE MISALIGNMENT

Sampling error associated with nozzle misalignment has not been adequately evaluated in past studies because the sampled flow field was maintained or assumed constant in velocity and parallel to the duct axis. The few studies that have been performed do not provide enough quantitative information to understand more than just the basic nature of the problem. The bias due to misalignment of the nozzle with the flow stream is similar to that caused by superisokinetic sampling ($R < 1$). When the nozzle is at an angle to the flow stream, the projected area of the nozzle is reduced by a factor equal to the cosine of the angle. Even if the nozzle velocity is equal to the flow stream velocity, an aspiration coefficient less than or equal to unity will be obtained because some of the larger particles will be unable to make the turn into the nozzle with the streamlines. As in the case of anisokinetic sampling velocities, for large values of St, only particles lying directly in front of the projected frontal area of the nozzle will be collected. Therefore, the limit for the aspiration coefficient when the nozzle is misaligned can be found by substituting $A_i \cos\theta$ for A_i in equation (8) to obtain a value of $A = R\cos\theta$ for large Stokes numbers. The aspiration coefficient would approach unity for small Stokes numbers as in the case of $\theta = 0$.

Figure 2 is a plot of data obtained by Mayhood and Langstroth (as reported by Watson, 1954) on the effect of misalignment on the collection efficiency of 4, 12 and 37 μm particles. In a study on the directional dependence of air samplers, Glauberman (1962) found that a sampler head facing into the directional air stream collected the highest concentration. Although these results coincide with theoretical expectations the data is of little use since two

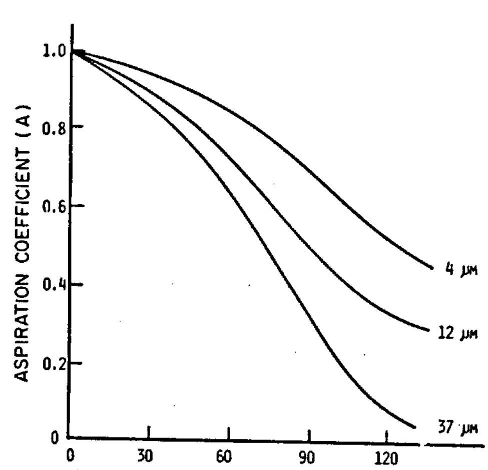

Fig. 2. Error due to misalignment of probe to flow stream (after Mayhood and Langstroth in Watson, 1954).

important parameters, free stream velocity and nozzle diameter, are not included in the analysis.

Laktionov (1973) sampled a polydisperse oil aerosol at an angle of 90° for three subisokinetic conditions and developed an empirical equation for a range of St from 0.003 to 0.2 and a range of R from 1.25 to 6.25;

$$A = 1 - 3St^{(R)^{-0.5}}. \tag{11}$$

Fuchs (1975) suggests that for small angles the sampling efficiency will be of the form:

$$A = 1 - 4\sin(\theta St/\pi). \tag{12}$$

Raynor (1970) evaluated the aspiration coefficient over a range of particle sizes, velocities, and angles and then used a trigonometric function to convert equation (3) to the form:

$$A = 1 + \beta(St)[(V_i \sin\theta + V_0 \cos\theta)/(V_i \cos\theta + V_0 \sin\theta) - 1]. \tag{13}$$

This function only serves to invert the velocity ratio between 0 and 90° and does not realistically represent the physical properties of the flow stream.

A more representative function has been derived by Lundgren *et al.* (1978):

$$A = 1 + \beta'(R\cos\theta - 1), \tag{14}$$

where β' is a function of the velocity ratio, Stokes number and angle of misalignment. To satisfy the boundary conditions β' must approach 0 for small Stokes numbers and must approach 1 for large Stokes numbers. At first there may appear to be an error in equation (14) because the aspiration coefficient equals 1 whenever $R = 1/\cos\theta$, regardless of the Stokes number. An example of this is when $R = 2$ and $\theta = 60°$. This phenomenon can be explained as follows. Since the projected frontal area of the nozzle is one half the actual area when $\theta = 60°$, in order to sample so that there is not divergence of streamlines into the nozzle, the sample velocity must be one half of the free stream velocity or $R = 2$. Therefore, the situation of $R = 1/\cos\theta$ defines the conditions for obtaining a representative sample when the nozzle is aligned at an angle to the flow stream.

4. EXPERIMENTAL DESIGN

The approach to this study was to first experimentally determine the relationship between the aspiration coefficient and Stokes number as a function of nozzle angle while maintaining an isokinetic sampling velocity ($R = 1$). When this phase was completed, the data would be used along with the data of Belyaev and Levin (1974) (equations (3) and (7)) to develop and test an empirical model to predict sampling error as a function of Stokes number for $R \neq 1$ and $\theta \neq 0$.

The aspiration coefficient was measured by comparing the concentration obtained by two nozzles inserted into a 10 cm dia. wind tunnel. The control nozzle was aligned parallel to the duct and sampled at isokinetic conditions. The test nozzle was inserted at an angle of 0, 30, 60 or 90° and the sampling velocity was set equal to the wind tunnel velocity for the first phase of experiments and was varied from one half to two times the wind tunnel velocity for the second phase.

A spinning disc aerosol generator was used to produce monodisperse particles (90% uranine and 10% methylene blue) from 1.0 μm NMD to 11.1 μm NMD. For a few experiments, 19.9 μm NMD ragweed pollen was mechanically dispersed into the flow stream. Following dilution and mixing, the aerosol stream flowed through a section of pipe containing straightening vanes and into a straight section of clear pipe from which samples were taken. Duct velocity, nozzle diameter and particle diameter were varied to produce a range of Stokes numbers from 0.007 to 3.0.

The sampling systems consisted of stainless steel, thin-walled nozzles connected to 47 mm filter holders. Each filter assembly was connected in series to a dry gas meter, rotameter and pump, fitted with a bypass valve to control sampling rate. Following each test using a uranine aerosol, the glass fiber filter, sampling nozzle and front half of the filter holder were washed in distilled water and the uranine leachate concentration was analyzed using a fluorimeter. A similar procedure was followed for the ragweed pollen except that membrane filters were used and the particles were counted under a stereo microscope.

Two pairs of sampling nozzles were fabricated from stainless steel tubing of 0.465 and 0.683 cm i.d. Each nozzle was approximately 15 cm long to minimize the flow disturbance at the nozzle entrance caused by the filter holders. Belyaev and Levin (1972) observed that the rebound of particle from the tip of the nozzle into the probe was one cause of sampling error. They concluded that if the edge thickness is less than 5% of the nozzle i.d. and the taper angle is less than 15°, then the variation in aspiration due to particle rebound would be less than 5%. The nozzles were designed accordingly.

Sehmel (1970) observed that non-uniform particle concentrations existed across the diameter of a cylindrical duct, and that the magnitude of the concentration gradient varied with particle size. To account for these radial variations, the two sampling points were located symmetrically about the center of the duct at a radius of 2 cm. Simultaneous isokinetic samples were taken at the two points and compared. Tests were repeated for different particle sizes and no concentration differences were found to exist at the two sampling points. The velocity was also checked at both points using a standard pitot tube and was found to be essentially identical.

5. RESULTS

The aspiration coefficient was determined by comparing the particulate concentration determined when sampling with a control nozzle at $R=1$ and $\theta=0$ with the concentration determined with a test nozzle at $R=1$ and $\theta=30$, 60 or 90°. These results confirm the theoretical prediction. For all sampling angles the aspiration coefficient approached one for small Stokes number, decreased as St increased, and leveled off at a value equal to $\cos\theta$ for large St. The most significant changes occurred between $St=0.01$ and $St=1.0$.

The curves for 30, 60 and 90° shown in Fig. 3 are all similar in shape except for the values of Stokes number where they approach their limiting value. As the angle of misalignment increases, the aspiration coefficient reaches its maximum error at a lower Stokes number. This can be accounted for as an apparent change in nozzle diameter, because it is the only parameter in the Stokes number that is affected by the nozzle angle to the flow stream. As described before, the nozzle diameter is important because it determines the amount of time available for the particle to change directions (approximately $6D_i/V_0$). As the nozzle is tilted at an angle to the flow stream the projected frontal area, and therefore the projected nozzle diameter, are reduced proportional to the angle. Therefore, as the angle of misalignment increases, the time available for the particle to change direction decreases leading to increased sampling error for a given value of St. To normalize these curves for angle to the flow stream, it is necessary to define an "adjusted Stokes number" (St') which takes into

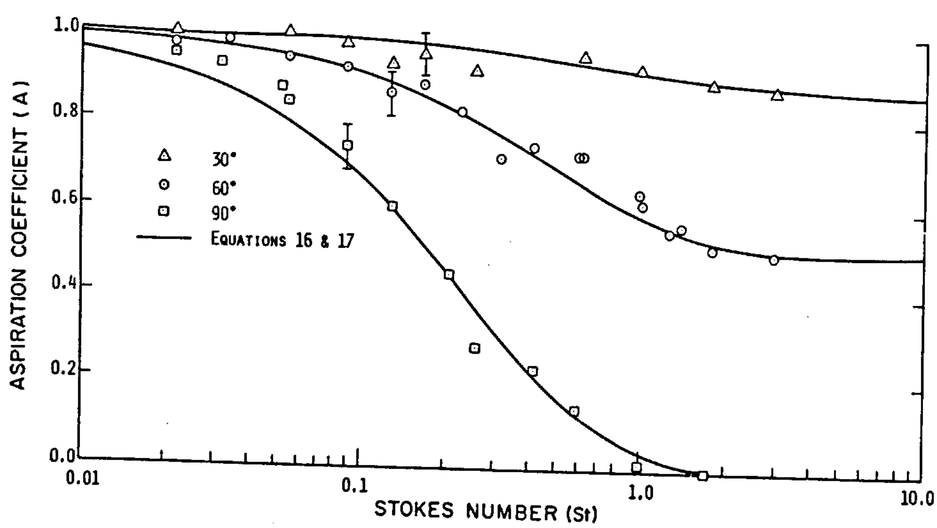

Fig. 3. Aspiration coefficient vs Stokes number for 30, 60 and 90° when $V_i=V_0$.

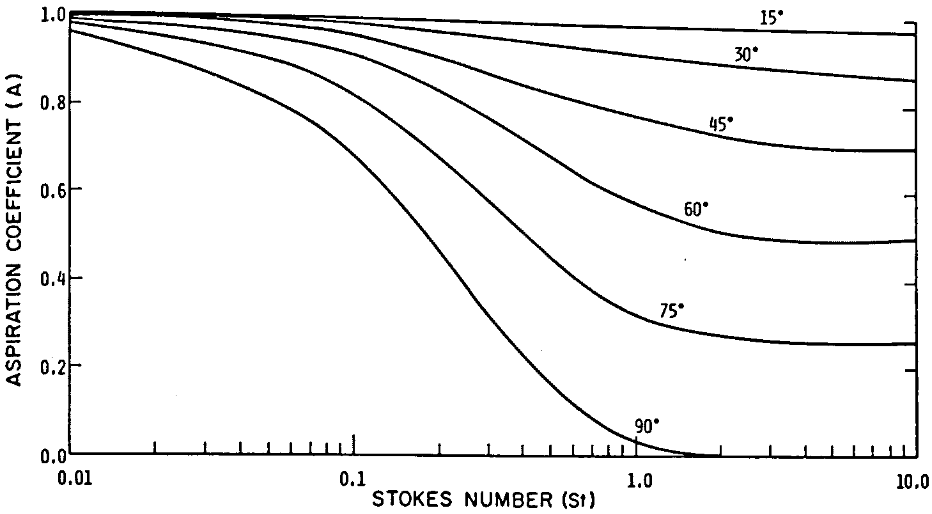

Fig. 4. Predicted aspiration coefficient vs Stokes number for angles of 15, 30, 45, 60, 75 and 90° (from equations (16) and (17)).

account the change in projected nozzle diameter with angle. The following equation was developed to account for this by plotting as a function of θ in degrees, the value of St where the aspiration coefficient reached a value that represented 95% of the maximum error:

$$St' = St \exp(0.022\theta) \tag{15}$$

for

$$0 \leq \theta \geq 90°.$$

It can be determined from equation (15) that the Stokes numbers for 30, 60 and 90° must be multiplied by 1.93, 3.74 and 7.24 respectively to account for the effect of nozzle angle to the flow stream. Using these adjustment factors the following equations were empirically derived to fit the experimental data for $R=1$:

$$A = 1 + (\cos\theta - 1)\beta''(St', \theta) \tag{16}$$

where

$$\beta''(St', \theta) = 1 - \frac{1}{1 + 0.55St' \exp(0.25St')}. \tag{17}$$

This set of equations is plotted in Fig. 3 and fits the data within experimental accuracy. Figure 4 is a plot of the sampling efficiency for angles between 0 and 90° in 15° increments calculated using equations (16) and (17).

To complete the analysis of anisokinetic sampling, it is necessary to know what is the combined effect of both a nozzle misalignment and an anisokinetic sampling velocity. Since an attempt would be made to use the data of Belyaev and Levin (1974) along with the data observed in the first phase of this study, it was first necessary to see if the two different sampling methodologies (photographic observation vs comparative sampling) gave similar results. Four sets of tests were performed at two Stokes numbers ($St=0.154$ and $St=0.70$) and two velocity ratios ($R=2.3$ and $R=0.51$). As can be seen in Fig. 5, the aspiration coefficients obtained by comparing the anisokinetic sample with the isokinetic sample agree within experimental accuracy with the values predicted by equations (3) and (7).

Tests were then run to evaluate the equation derived by Lundgren *et al.* (1978). An attempt would be made to fit the data by developing an expression for $\beta'(St', R, \theta)$ in equation (14) that was some function of $\beta(St', R)$ (equation (7)) and $\beta''(St', \theta)$ (equation (14)). It was assumed that the effect of the reduced projected nozzle diameter would have to be accounted for by the use of the adjusted Stokes number St' in both expressions. Tests were performed by placing a control nozzle parallel to the flow stream and sampling isokinetically. The test nozzle was inserted through the duct wall at angles of 30, 45, 60 and 90° and the sampling velocity was set to be either one half or twice the stream velocity. Tests were run for a range of Stokes numbers

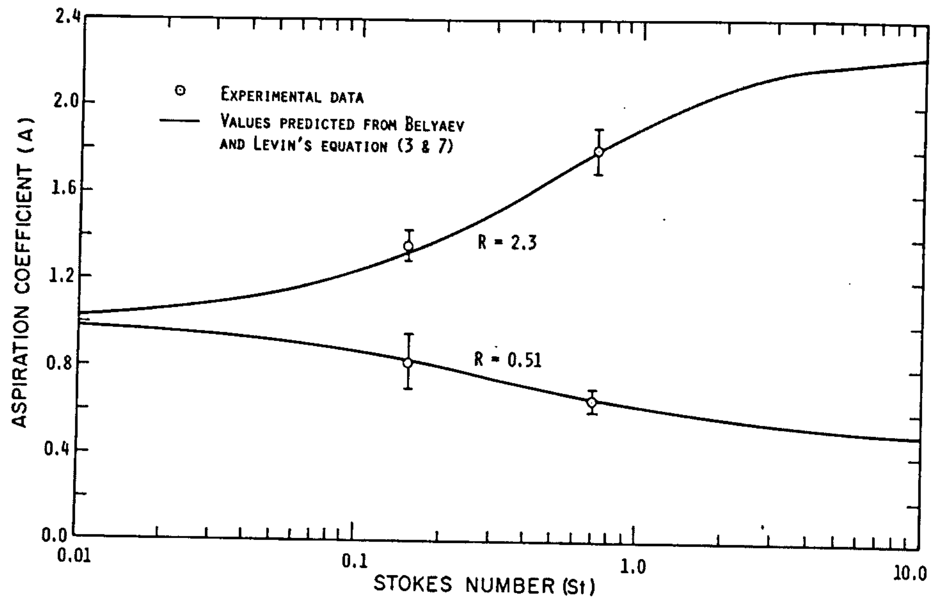

Fig. 5. Comparison of experimental data with results from Belyaev and Levin (1974).

from 0.1 to 1.0. This range was selected because this was expected to be the area where the greatest change in aspiration coefficients occurred. The data plotted in Figs 6 and 7 shows that the aspiration coefficient approaches a limit of $R \cos \theta$ for large St and appears to be unity when $R = 1/\cos \theta$ as in the case of $R = 2$ and $\theta = 60°$.

Equation (18) was found to best fit the data

$$A = 1 + (R \cos \theta - 1) \frac{\beta(St', R)}{\beta(St', R = 1)} \beta'(St', \theta). \tag{18}$$

The term in the denominator is used because β in equation (7) does not become unity at $R = 1$. By incorporating this term in the expression, equation (18) is identical to equation (16) when the velocity ratio is unity. The equation fits all the data within the experimental accuracy except for the tests run at $\theta = 90°$, $R = 2.1$, and $St = 0.19$. Equation (18) predicted an aspiration coefficient of 0.49, while values obtained during the tests averaged 0.015. It appears that the model falls apart at 90° for $R \neq 1$. This is due to the fact that when $\theta = 90°$ there is 0 projected frontal area of the nozzle. This means that subisokinetic sampling could in no way produce an increase in concentration as it does when particles lie in front of the projected nozzle area.

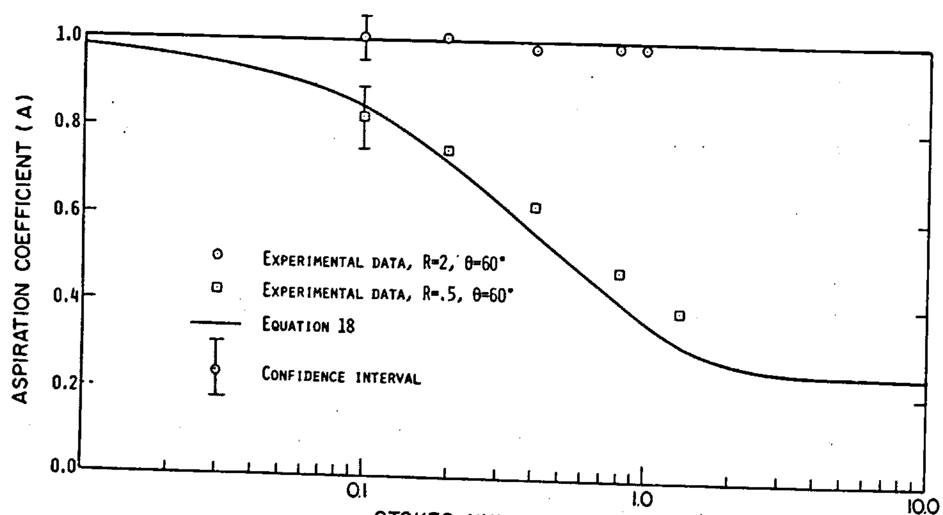

Fig. 6. Aspiration coefficient vs Stokes number for a 60° misalignment at $R = 2.0$ and $R = 0.5$.

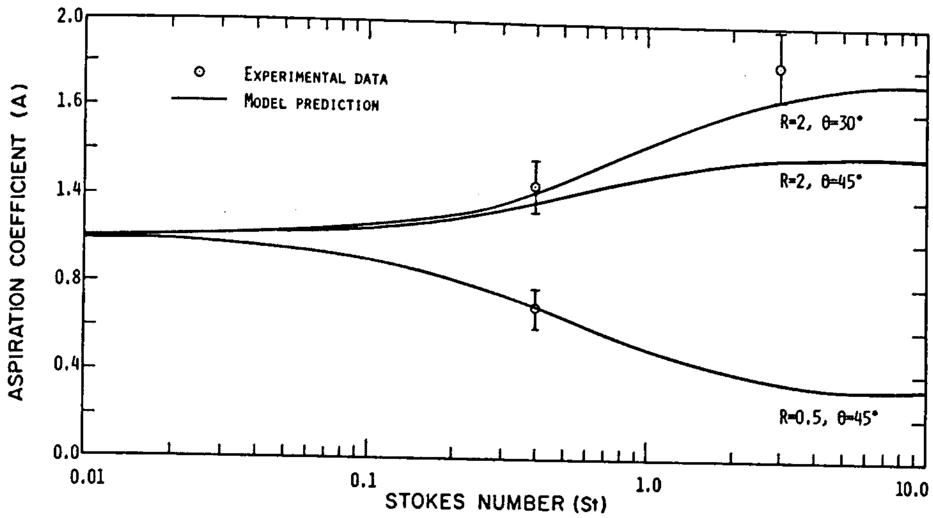

Fig. 7. Aspiration coefficient vs Stokes number for a 45° misalignment at $R=2.0$ and $R=0.5$, and for a 30° misalignment at $R=2.0$.

Because of this it is necessary to put the restriction $\theta < 90°$ on equation (18). These results do compare favorably with the results of Laktionov (1973) (equation (11)). For the identical conditions, his equation predicts an aspiration coefficient of 0.039. This comparison is closer than would be expected considering the fact that two completely different sampling schemes were used and Laktionov did not analyze the amount of particles collected in the probe.

6. ANALYSIS OF PROBE WASH

During the analysis of the tests using ragweed pollen, the filter catch and probe wash were counted separately, allowing for the determination of the importance of including the probe wash as collected particles. An average of 40% of the particles entering the nozzle were collected on the walls of the nozzle-filter holder assembly during parallel sampling and 54% were collected on the walls while sampling at 60°. Davies and Subari (1978) also found large losses to the walls while sampling at an angle to the flow stream. The probe wash for eight tests using 6.7 μm uranine particles were also analyzed separately for comparison with the results of the ragweed pollen tests. While parallel sampling, from 15 to 34% of the total mass was collected in the nozzle and front end of the filter holder. During further testing, it was qualitatively observed that the percent in the probe wash increased with particle size and decreased with increasing nozzle diameter.

7. SUMMARY

Particle sampling errors due to anisokinetic sampling velocity and nozzle misalignment were analyzed and a model was developed to describe the sampling efficiency as a function of the velocity ratio (R), misalignment angle (θ) and Stokes number (St). It was found that the maximum error for $R=1$ approached the value $(1 - \cos\theta)$. When both a nozzle misalignment and anisokinetic sampling velocities are involved, then the maximum error approaches $|1 - R\cos\theta|$.

The Stokes number adequately describes the inertial characteristics of aerosol sampling. However, when the nozzle is aligned at an angle to the flow stream, there is an apparent change in the flow characteristics which is due to a reduced projected nozzle diameter. A correction factor was developed to adjust the Stokes number to take this into account.

When the probe wash was analyzed separately from the filter, it was found that as much as 60% of the total particulate matter entering the nozzle was collected on the nozzle walls. This has implications not only on the importance of using the probe wash in the analysis but more importantly it implies that there may be possible problems in obtaining accurate particle size data using a device such as an impactor. Since the collection of particles in the nozzle is most likely particle size dependent, then losses in the probe could lead to particle sizing errors.

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