FINAL REPORT

Service Contract

Particle Cut-Size Evaluation of Air-O-Cell Sampler

December 1, 1997 – November 30, 1998

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March 27, 1998

SUMMARY

The particle cut-size of the Zefon Air-O-Cell sampler was determined theoretically and measured experimentally with liquid (oleic acid) particles. The experimentally determined cut-size values for different flow rates are 11 % higher than the theoretically calculated ones. The difference is due to somewhat different geometry used in the mathematical model. To confirm the correctness of the experimentally determined cut size different aerosol size spectrometers were used and the instruments were calibrated by different powders.

The particle bounce in the sampler was measured using spherical test particles with smooth surfaces (PSL). Similar experiments were performed with spherical fungal spores of *Penicillium brevicompactum* and spiny fungal spores of *Penicillium melinii*. Both fungal species are presented also as agglomerates of two or more spores. The fungal spores were found to bounce more than solid spherical particles with smooth surfaces. These differences can be explained by the different physical characteristics of the investigated aerosol particles.

TABLE OF CONTENTS

INTRODUCTION

According to the service contract "Particle Cut-Size Evaluation of Air-O-Cell Sampler" the particle cut-size of the Zefon Air-O-Cell sampler was determined theoretically as well as experimentally. The theoretical dependability of cut size versus sampling flow rate was calculated for five different temperatures ranging from 10 F to 130 F.

The cut-size was obtained experimentally by measuring the collection efficiency of the sampler for liquid (oleic acid) particles. The experiments were performed at five different sampling flow rates: 10, 15, 20, 25 and 30 Lpm. The experimentally obtained results were compared with the theoretically calculated ones.

The particle bounce in the sampler was evaluated at the same flow rates with monodisperse solid spherical test particles (PSL) of the following geometric diameters: 1.6, 2.15, 2.43, 2.75, 2.9, 3.5 and 5.1 μm. Particle bounce was also investigated with close-to-spherical fungal spores of *Penicillium brevicompactum* and spiny fungal spores of *Penicillium melinii*. These species cover the range and shape of fungal spores that are typically collected by Zefon Air-O-Cell samplers. The experimental results for all four types of test particles are compared and discussed.

THEORETICAL EVALUATION OF PARTICLE CUT-SIZE FOR THE AIR-O-CELL SAMPLER

The particle cut-size for the Zefon Air-O-Cell sampler was first determined theoretically. The 50 % cut-size, d_{50}, (at that size 50 % of the particles are collected and 50 % penetrate the sampler) was calculated for sampling flow rates, Q_S, ranging from 10 to 30 Lpm. For these calculations a technique described by Marple and Willeke (1976), Willeke (1978), and revised by Rader and Marple (1985) was used.

The principal parameter determining particle capture in an impactor is the Stokes number of a particle having a 50 % probability of impacting, Stk_{50}. The Stokes number is defined as the ratio of the product of the jet velocity in the nozzle, V_0, and the particle relaxation time, τ,

versus the impactor's nozzle diameter (for a round nozzle) or width (for a rectangular nozzle), W, (Willeke, 1978; Sioutas, 1997):

$$Stk_{50} = \frac{\tau V_0}{W} = \frac{\rho_P V_0 C d_{50}^2}{9\eta W}, \quad (1)$$

where ρ_p is the particle density, V_0 is average velocity in the nozzle, C is the size-depended Cunningham slip correction, d_{50} is the particle size for which 50 % of the particles are collected, η is the air viscosity, and W is the width of the nozzle (W=1.055 mm for the Zefon Air-O-Cell sampler).

The average air velocity in the nozzle can be found from:

$$V_0 = \frac{Q_S}{LW}, \quad (2)$$

where Q_S is the volumetric sampling flow rate and L is the nozzle length (L=14.4 mm for the Zefon Air-O-Cell sampler).

Combining equations 1 and 2, we can solve for the 50 % particle cut off size, d_{50}:

$$d_{50}^2 = \frac{9\eta L W^2 Stk_{50}}{\rho_P Q_S C}. \quad (3)$$

In our theoretical estimations, the Cunningham slip correction (Wahi and Liu, 1971) was calculated using the following equation:

$$C = 1 + \frac{0.163}{d_{50}P_2} + \frac{0.0549}{d_{50}P_2}\exp(-6.66 d_{50}P_2), \quad (4)$$

where P_2 is the static pressure (atm) in the impaction region and d_{50} is the particle diameter in μm.

The pressure in the impaction region, P_2, was determined by assuming that the pressure drop in the sampler is equal to the dynamic pressure of the air jet. Thus:

$$P_2 = P_1 - \frac{1}{2}\rho_{AIR}V_0^2 \,, \tag{5}$$

where P_1 is the static pressure at the impactor inlet ($P_1 \approx 1$ atm), ρ_{AIR} is the air density, and V_0 is the average velocity in the jet.

The Reynolds number, Re, for flow passing through the Air-O-Cell sampler was calculated using the following equation:

$$Re = \frac{2\rho_{AIR}V_0W}{\eta} = \frac{2Q_S}{\eta L} \,. \tag{6}$$

The air density, ρ_{AIR}, and air viscosity, η_{AIR}, are parameters dependent on ambient temperature, T. These parameters were determined (Baron and Willeke, 1993) from:

$$\rho_{AIR} = \frac{P}{RT} \,, \tag{7}$$

and

$$\eta = \eta_r\left(\frac{T_r + S}{T + S}\right)\left(\frac{T}{T_r}\right)^{3/2} \,, \tag{8}$$

where P is the atmospheric pressure, T is the absolute air temperature in K, R is the universal gas constant ($R = 8.31\text{x}10^7$ dyn cm/mol K), η_r is the reference viscosity, T_r is the reference temperature and S is the Sutherland interpolation constant (for air S=110.4 K and η_r=182.03 μP when T_r=293.15 K) (Rader, 1990).

The Reynolds numbers for ambient air temperatures ranging from T = 10 F to T = 130 F and sampling flow rates ranging from Q_S = 10 Lpm to Q_S = 30 Lpm were calculated using

equations 6, 7, and 8. The average Reynolds number, Re_{AVG}, for these conditions was found to be equal 3278.

The Stokes number, Stk_{50}, was found from the revised theory by Rader and Marple (1985). This theory describes the effect of jet-to-plate distance, S, throat length, T, and jet Reynolds number, Re, to the impactor's efficiency. The Stokes number, Stk_{50}, for Re=3000, S/W=1 and T/W=1 was found to equal $\sqrt{0.73}$ (Rader and Marple, 1985). This value of the Stokes number and equations 3, 4 and 5 were used to calculate the 50 % particle cut-size, d_{50}, for the Air-O-Cell sampler.

The calculated particle 50 % cut point size as a function of sampling flow rate (from Q_S = 10 Lpm to Q_S = 30 Lpm) at different ambient temperatures (T = 10, 40, 70, 100 and 130 F) are presented in Table 1 and Fig. 1. Using the curves presented in the Fig. 1., the theoretical 50 % particle cut-size can be easily determined for sampling flow rate ranging from Q_S = 10 Lpm to Q_S = 30 Lpm.

Table 1. The 50 % particle cut-size diameter d_{50}, μm, determined theoretically for different sampling flow rates, at different temperatures.

Sampling flow rate, Q_S, Lpm	Temperature, T, F				
	10	40	70	100	130
10	2.69	2.76	2.82	2.88	2.94
15	2.18	2.24	2.29	2.34	2.39
20	1.88	1.93	1.97	2.02	2.06
25	1.67	1.71	1.76	1.79	1.83
30	1.52	1.56	1.60	1.63	1.67

It can be seen that when the sampling flow rate is increased from Q_S = 10 Lpm to Q_S = 30 Lpm, the particle 50 % cut point size decreases from d_{50} = 2.82 μm to d_{50} = 1.60 μm when the temperature T = 70 F. It should be pointed out, that these calculations are based on a theoretical model for a 60 degree inlet and for ideal spherical particles. The Zefon Air-O-Cell

sampler has an inlet with an angle of a little more than 30 degrees and the aerosol particles in many cases have a shape different from spherical. It means, that the actual 50 % particle cut point size can be different from the one determined theoretically. Therefore, the 50 % particle cut-size for the Zefon Air-O-Cell sampler has been evaluated experimentally.

EXPERIMENTAL EVALUATION OF PARTICLE CUT-SIZE FOR THE AIR-O-CELL SAMPLER

EXPERIMENTAL SETUP

The test system for the experimental particle cut-size determination is schematically shown in Fig. 2. As indicated in the service contract, three different types of particles – liquid (oleic acid), solid spherical particle (Polysterene particle, PSL, Bangs Laboratories, Inc., Fishers, Indiana), and fungal spores (*Penicillium brevicompactum*, and *Penicillium melinii*) were used in these experiments. For this purpose three different particle aerosolization systems were used. The size-fractionating aerosol generator (Pilacinski et al., 1990) was used for the generation of the oleic acid particles. The Collison nebulizer (BGI Inc., Waltham, Mass) was used for PSL particle aerosolization, and the agar-tube disperser (Reponen et al., 1997) was used for fungal spore generation. In all three cases the aerosolized particles were dried and diluted with filtered, compressed air, Q_{DIL}. The dilution air flow rate ranged from 35 Lpm to 45 Lpm, depending on the generation system used. The dried and diluted aerosol passed through a 10-mCi ^{85}Kr electrostatic charge neutralizer (model 3012, TSI Inc, St. Paul, Minn.) and then entered the sampling chamber. The test aerosol entered a chamber of 2.6 m^3 when the size-fractionating aerosol generator was used for oleic acid particle generation. A sampling chamber of 550 cm^3 was used, when experiments were performed with PSL particles and fungal spores. The air temperature in the sampling chamber was kept at 71 - 73 F and the relative humidity, *RH*, was in the range of 15-20 % in the sampling chamber during all experiments.

The test particles were alternatively sampled through the upstream sampling line, C_{Up} , and the Air-O-Cell sampler being tested (downstream line), C_{Down} , while changing the positions of

valves 1 and 2. The upstream and downstream aerosol concentrations were measured by an aerodynamic particle-size spectrometer (Aerosizer, Amherst Process Instruments, Hadley, Mass.), which was operated at a flow rate, $Q_{AEROSIZER}$, of 5.3 Lpm. The sampling flow rate Q_S equals $Q_{AEROSIZER} + Q_{FM}$. Q_{FM} is the bypass flow monitored by the mass flow meter. Q_{FM} was adjusted from 4.7 Lpm to 24.7 Lpm to have a sampling flow rate through the sampler under investigation ranging from 10 Lpm to 30 Lpm.

The downstream and upstream sampling lines were of the same length (about 40 cm). Therefore, any losses that may have occurred in the upstream and downstream sampling lines were assumed to be same. Grinshpun et al. (1997) reported, that a pressure drop of 0.1 atm can significantly affect the particle size and the concentration measurement results when using the Aerosizer. Our calculations described above have shown that the pressure drop in the Air-O-Cell sampler is about 0.007 atm. The pressure drop in the investigated sampler was measured to be 0.009 atm when the sampling flow rate was 30 Lpm. For smaller flow rates the pressure drop in the Air-O-Cell sampler is less. Such a small pressure drop does not affect the performance characteristics of the aerodynamic size spectrometer.

During each test sequence the particle size distribution was measured upstream and downstream of the Air-O-Cell sampler. The collection efficiency, E_C, of the investigated sampler was calculated as follows:

$$E_C = \left(1 - \frac{C_{Down}}{C_{Up}}\right) \times 100\,\% \qquad (9)$$

Each test was repeated at least three times for each sampling flow rate. The average value and standard deviation calculated from these tests are presented.

EXPERIMENTAL PARTICLE CUT-SIZE DETERMINATION FOR LIQUID PARTICLES

For the experimental evaluation of the Air-O-Cell sampler oleic acid aerosol particles were chosen as non-evaporating liquid aerosol particles. They have been used in many other impactor evaluations. The use of these particles avoids potential bounce-off from the collection surface. The experimental setup described above was used for these investigations.

To avoid coincidence problems which can occur using the Aerosizer when measuring high aerosol concentrations and fast loading of the Air-O-Cell sampler, the oleic acid particle concentration was kept in the range of 1000-3000 particles per liter of air. Solid test particles (PSL) with known geometric diameters (d_{PSL} = 1.6 μm, 2.15 μm, and 2.75 μm and ρ_{PSL} = 1.05 g/cm^3) were used to calibrate the Aerosizer before performing the measurements. It was determined that in this size range the particle diameter was measured with an accuracy of ± 4 %. To confirm the correctness of the experimentally determined cut size different aerosol size spectrometers were used and the instruments were calibrated by different powders.

The oleic acid particle size distributions upstream and downstream were measured by the Aerosizer. The number concentration in the 165 different size channels was recorded in PC memory after each measurement which lasted 160 s. The collection efficiency was calculated in each size channel in the size range from 1 μm to 4 μm. The experiments were performed for five different sampling flow rates (Q_S = 10 Lpm, 15 Lpm, 20 Lpm, 25 Lpm, and 30 Lpm).

The dependence of the Air-O-Cell sampler collection efficiency on the particle aerodynamic diameter at the different sampling flow rates is plotted in Fig. 3. Each point in these curves is the average value from three measurements and the error bars represent the standard deviation. The 50 % particle cut-size diameter, d_{50}, for the five sampling flow rates was determined from the experimental results, see Table 2. The Fig. 4. shows the calculated and the experimentally determined 50 % particle cut-size. It is seen (Fig. 4), that for all sampling flow rates the experimentally determined 50% particle cut-size values are about 11 % higher than those

obtained theoretically. This difference occurs because the mathematical model, as mentioned earlier, is for an inlet that is different from the one investigated.

Table 2. The 50 % particle cut-size diameter determined experimentally for different sampling flow rates, using oleic acid particles.

Sampling flow rate, Q_S, Lpm	10	15	20	25	30
50 % particle cut point size, d_{50}, μm	3.2 ± 4 %	2.6 ± 4 %	2.2 ± 4 %	2.0 ± 4 %	1.8 ± 4 %

ASSESMENT OF PARTICLE BOUNCE IN THE AIR-O-CELL SAMPLER

The particle bounce in the Air-O-Cell sampler was investigated experimentally using monodisperse, spherical test particles (PSL) with geometrical diameters of: 1.6, 2.15, 2.43, 2.75, 2.9, 3.5, and 5.1 μm (density of these particles is 1.05 g/cm^3). When the measurement was performed with PSL particles of selected size, the sampler collection efficiency was calculated only for that diameter. This means, that, for a given flow rate, the collection efficiency was determined only for the tested PSL particle. The measurement time for all these tests was set to 60 s. A new Air-O-Cell sampler was used for each test with a different particle size and sampling flow rate to prevent increasing bounce because of particle loading in the sample deposition area.

The same experiments were performed with two types of fungal spores: *Penicillium brevicompactum* (mean d_a=2.55) and *Penicillium melinii* (mean d_a=2.84). Because of the different surface characteristics, different collection and bouncing mechanisms are possible for three types of solid test particles (Fig. 5.). The PSL particles are highly monodisperse spherical particles with smooth surface. Such spheres can tightly stick to the surface of the collection plate, and only a small amount of them will bounce. Spiny particles such as *Penicillium melinii* , do not have good contact with the collection plate and can bounce easily. In case of the spiny particle, there are only few connection points with the collection surface and not enough adhesion forces to prevent bounce. Both tested fungal spore species are often

composed of agglomerates of two or more spores. That can also influence the collection efficiency of the sampler for these particles as well as their bounce. An agglomerate of two or more single particles (or spores) has an aerodynamic diameter that is larger than that of a single particle and can be collected at a low sampling flow rate at which single particles would not be collected. When an agglomerate of two particles strikes the collection surface, it can be deagglomerated: one particle may remain on the plate and second one is removed by the rebound energy and penetrates through the sampler. Fig. 5. attempts to schematically explain these processes.

The experimental results are shown in Fig. 6a, 6b, 6c, 6d, an 6e. Each figure shows the experimentally determined collection efficiencies of the Zefon Air-O-Cell at the selected flow rates for all test particles. There is no significant difference in collection efficiency obtained for liquid (oleic acid) and solid, ideal spherical (PSL) particles. The differences can be seen only for highest, close to 100 %, collection efficiencies. When all liquid particles are collected (E_C = 100 %) the collection of the PSL particles is somewhat less, because of bounce. No more than 10 % of these particles bounce at all sampling flow rates investigated. When the sampling flow rate is 15 Lpm, 2.2 % of 3.5 μm particles and 10 % of 5.1 μm particles bounce (Fig. 6b.).

The situation was different when the collection efficiency of Air-O-Cell sampler was measured for fungal spores. When the sampling flow rate was 10 Lpm, about 30 % of *Penicillium brevicompactum* spores and 50 % *Penicillium melinii* spores were collected (Fig. 6a.). The results can be explained by a broad size distribution of fungal spores, because they include agglomerates from two or more single spores. When the sampling flow rate is 15 Lpm, the collection efficiency for all types of particles investigated is about the same (Fig. 6b.). In this case, the mean diameter of the fungal spore collection efficiency coincides with the curve for PSL particles. For sampling flow rates 10 and 15 Lpm, the larger particles (*Penicillium melinii* spores) are collected more efficiently than the smaller ones (spores of *Penicillium brevicompactum*). When the sampling flow rate increases to 20 Lpm and more (Fig. 6c., 6d., and 6e.), bounce is observed for the of *Penicillium melinii* spores. Comparing Fig. 6b. with Fig. 6c. is seen, that the collection efficiency of *Penicillium melinii* is

lower at 20 Lpm than at 15 Lpm. At 25 Lpm, Fig. 6d., the collection efficiency is still lower, i.e. there is more bounce. The dashed line indicates what the curve might look like, if tests could be performed with fungal spores of different size, but the same spinal geometry. At 30 Lpm, significant bounce is also observed for the smaller spores of *Penicillium brevicompactum*.

CONCLUSIONS

The particle cut-size of the Zefon Air-O-Cell sampler was calculated theoretically as well as determined experimentally. Comparison of the calculated values with those measured experimentally with liquid particles shows that the experimentally determined values are about 11 % higher than the calculated ones. This difference is the same for all flow rates investigated. That is because the mathematical model is for a sampler geometry of a somewhat different inlet geometry from the Zefon Air-O-Cell.

The particle bounce in the Air-O-Cell sampler was evaluated for three different solid test particles: ideal spherical test particles (PSL) with a smooth surface, spherical fungal spores (*Penicillium brevicompactum*) and spiny fungal spores (*Penicillium melinii*). Comparison of the experimental data for these different test particles has shown that the fungal spores bounce more than the solid spherical particles with a smooth surface. Almost 45 % of *Penicillium melinii* spores were found to bounce at a flow rate of 30 Lpm, while only 8 % of the solid spherical test particles bounce at the same sampling conditions. These differences can be explained by the different surface characteristics of the investigated particles.

The results obtained in this study show that particle shape and surface characteristics can significantly affect the sampling efficiency.

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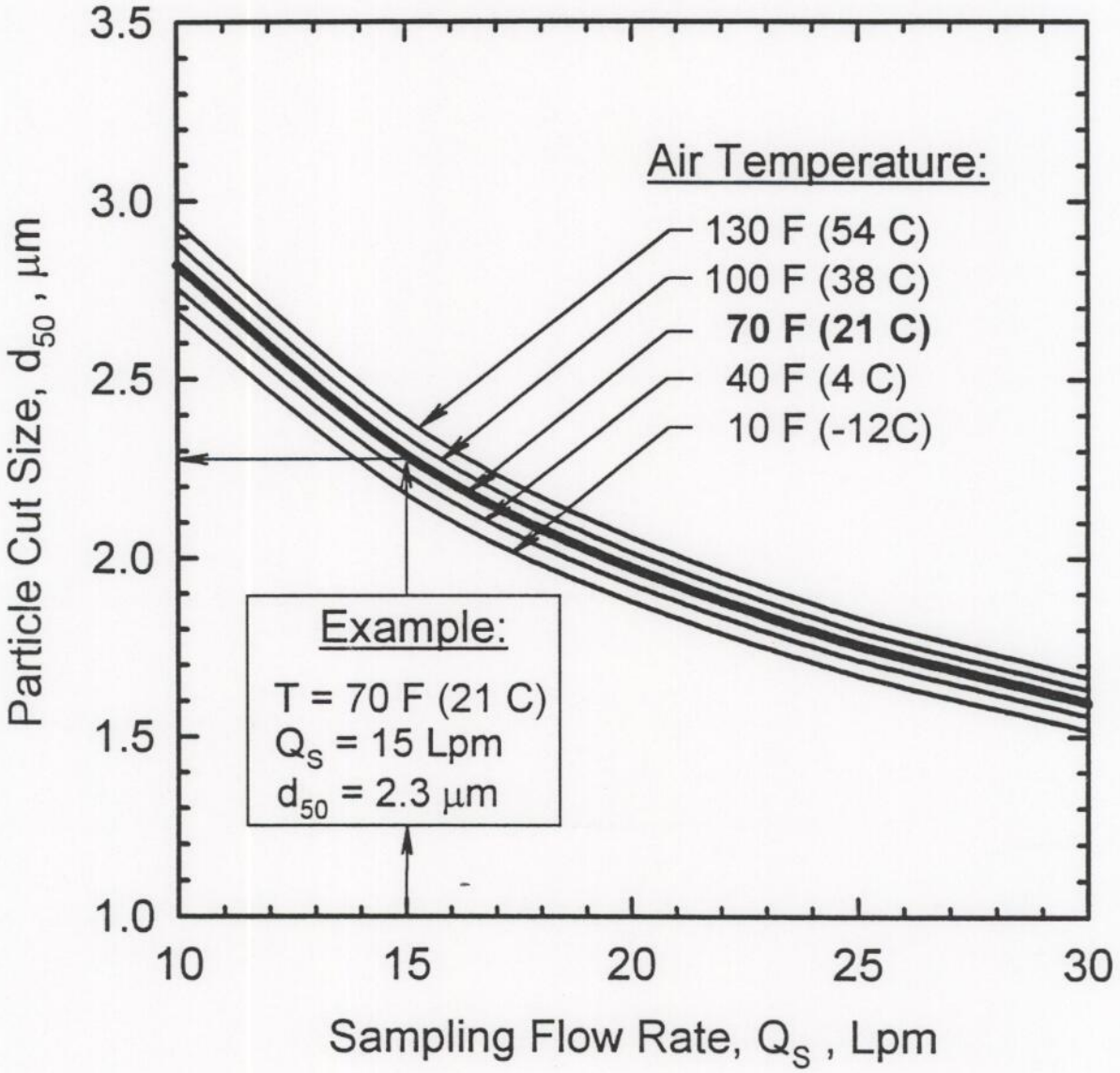

Fig. 1. Calculated particle cut size, d_{50}, for the Zefon Air-O-Cell as a function of sampling flow rate, Q_S, for different ambient air temperatures, T. The cut size, d_{50}, is the particle diameter at which 50 % of the aerosol particles are collected and 50 % pass through the sampler.

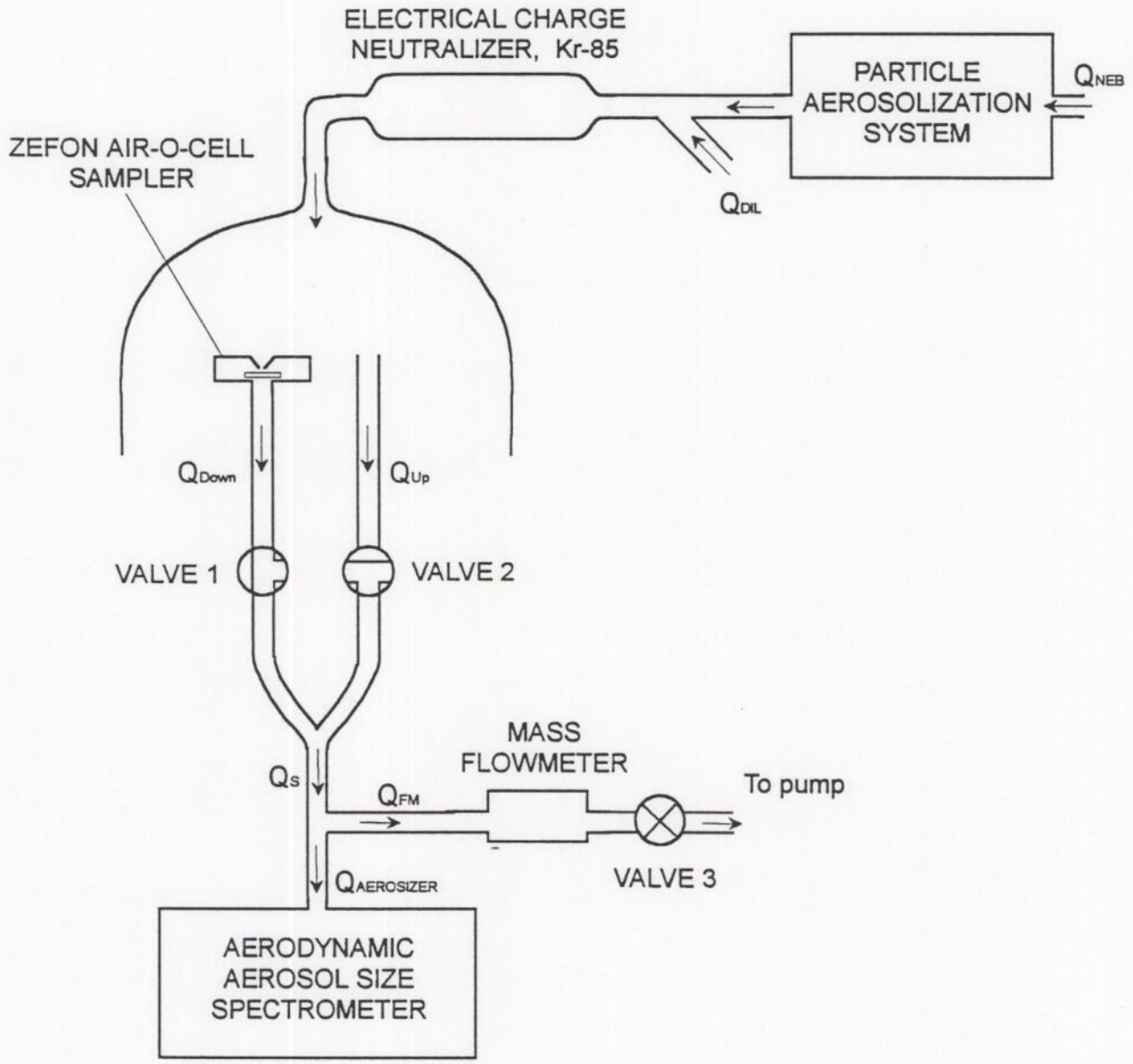

Fig. 2. Schematic diagram of the experimental setup.

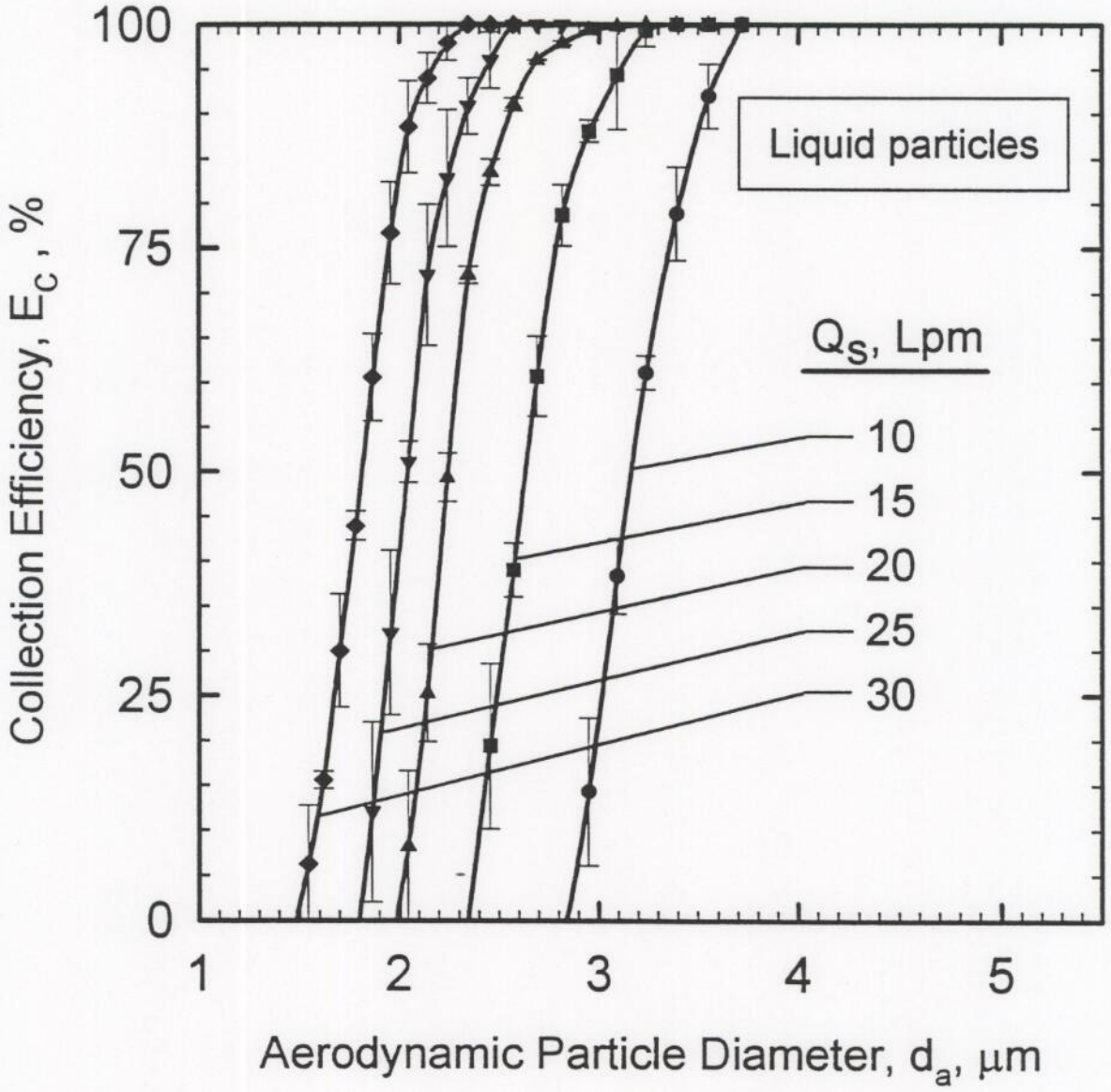

Fig. 3. Collection efficiency of the Zefon Air-O-Cell for liquid (oleic acid) particles sampled at flow rates, Q_S, ranged from 10 to 30 Lpm (T=73 F, RH=15 %).

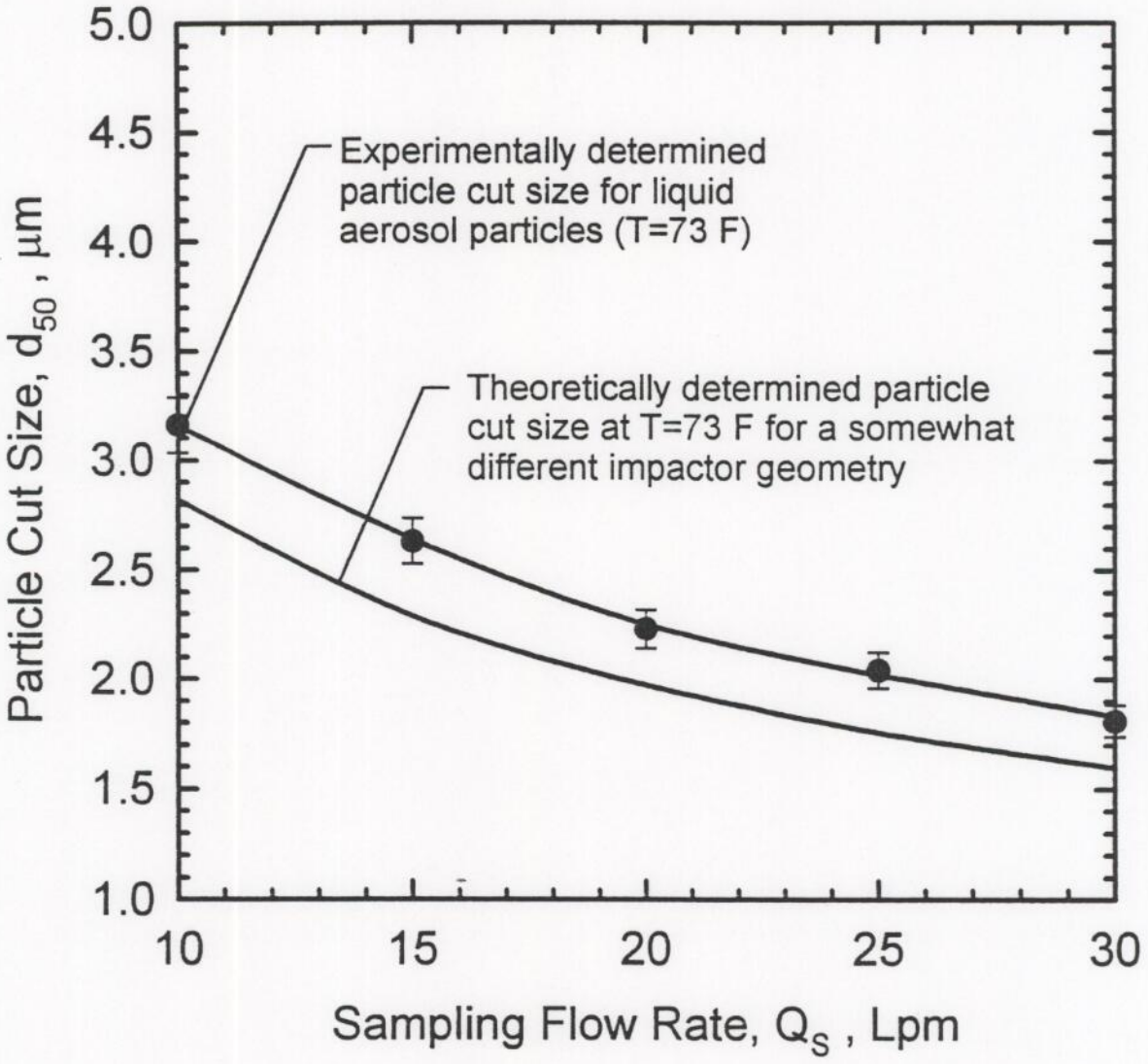

Fig. 4. Experimental and theoretical cut size of the Zefon Air-O-Cell at flow rates, Q_S, ranged from 10 to 30 Lpm (T=73 F, RH=15 %).

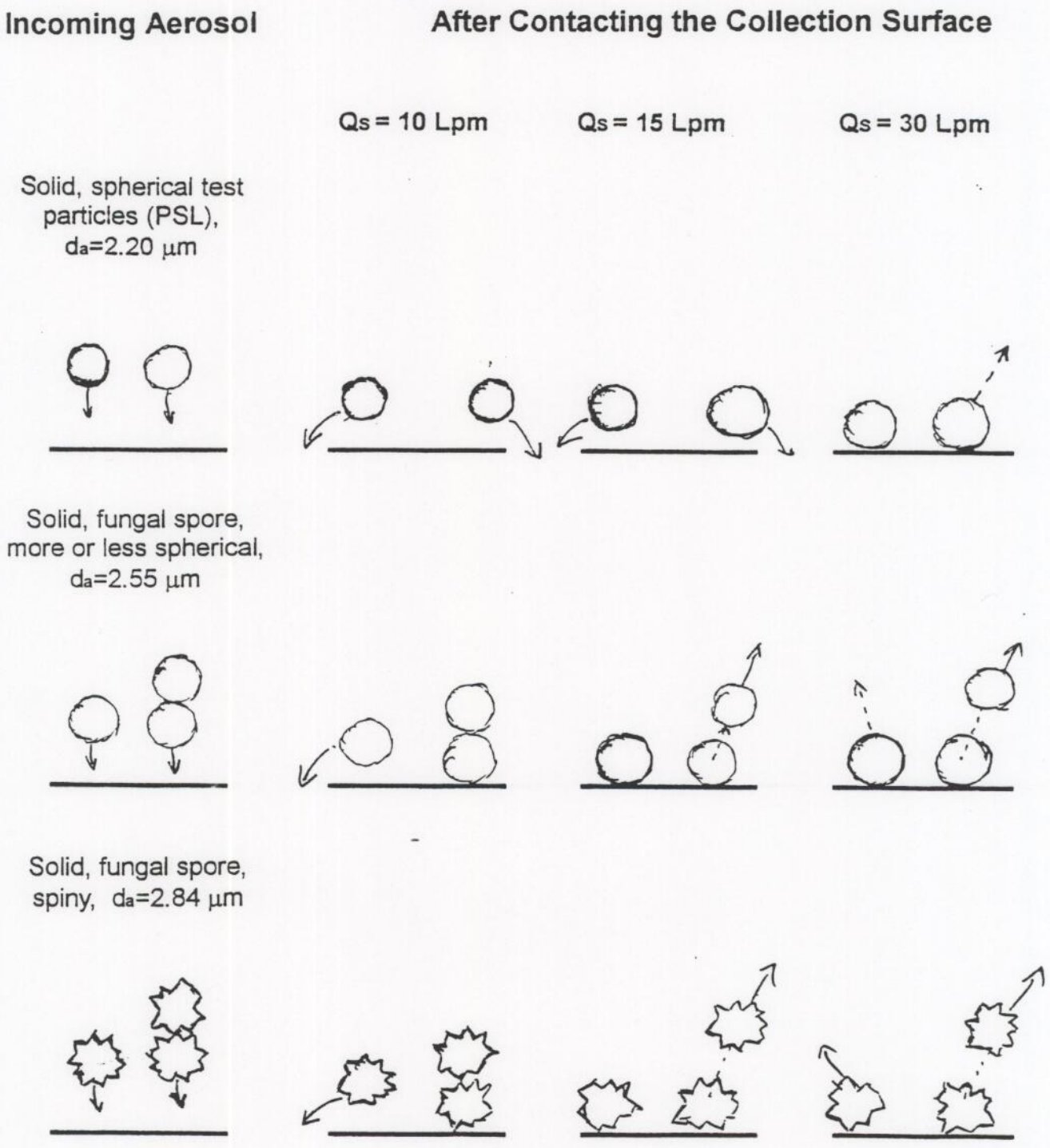

Fig. 5. Schematic representation of collection and bounce mechanisms at different sampling flow rates.

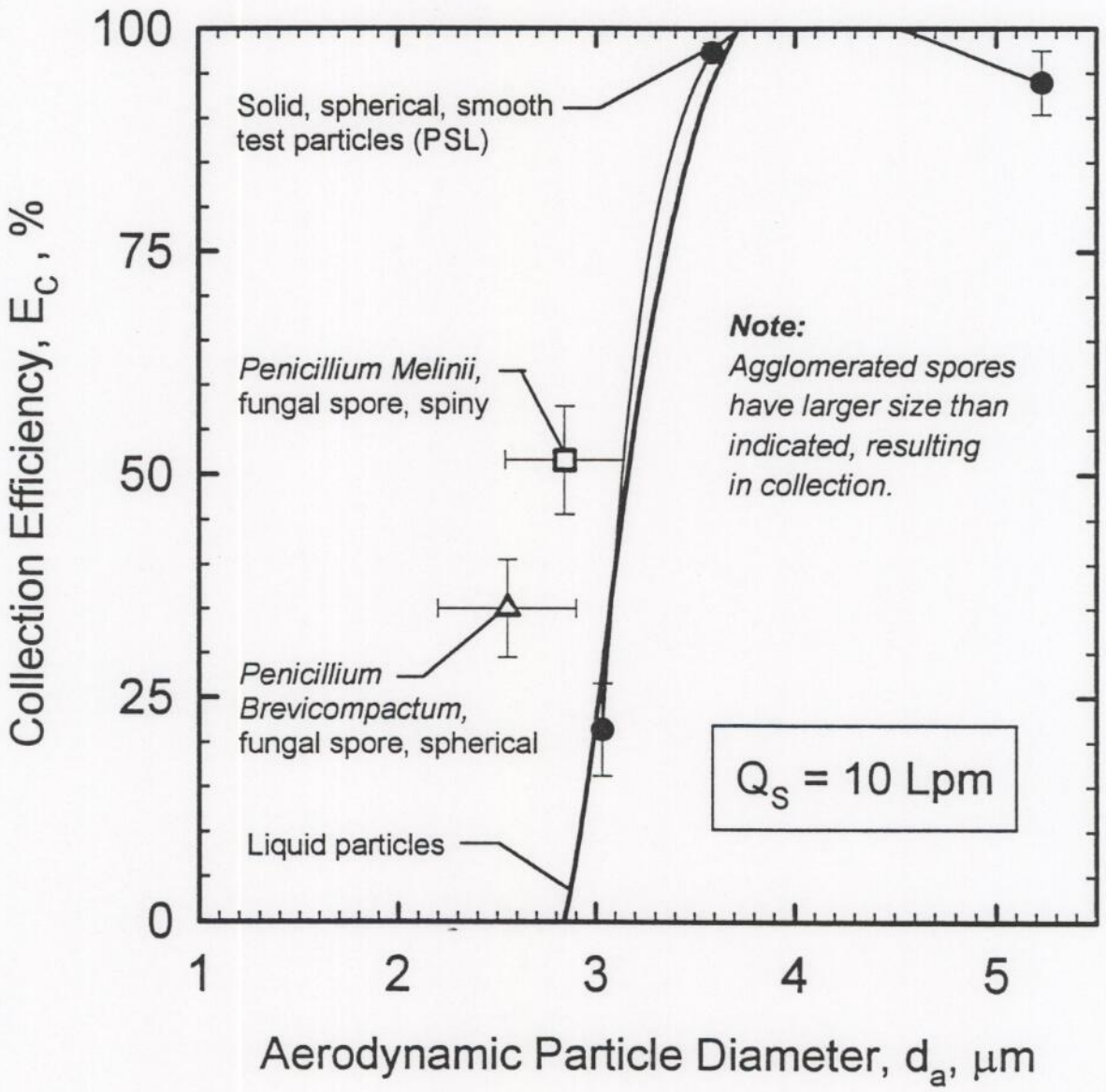

Fig. 6a. Collection efficiency of the Zefon Air-O-Cell for liquid and solid particles at Q_S=10 Lpm, (T=73 F, RH=15 %).

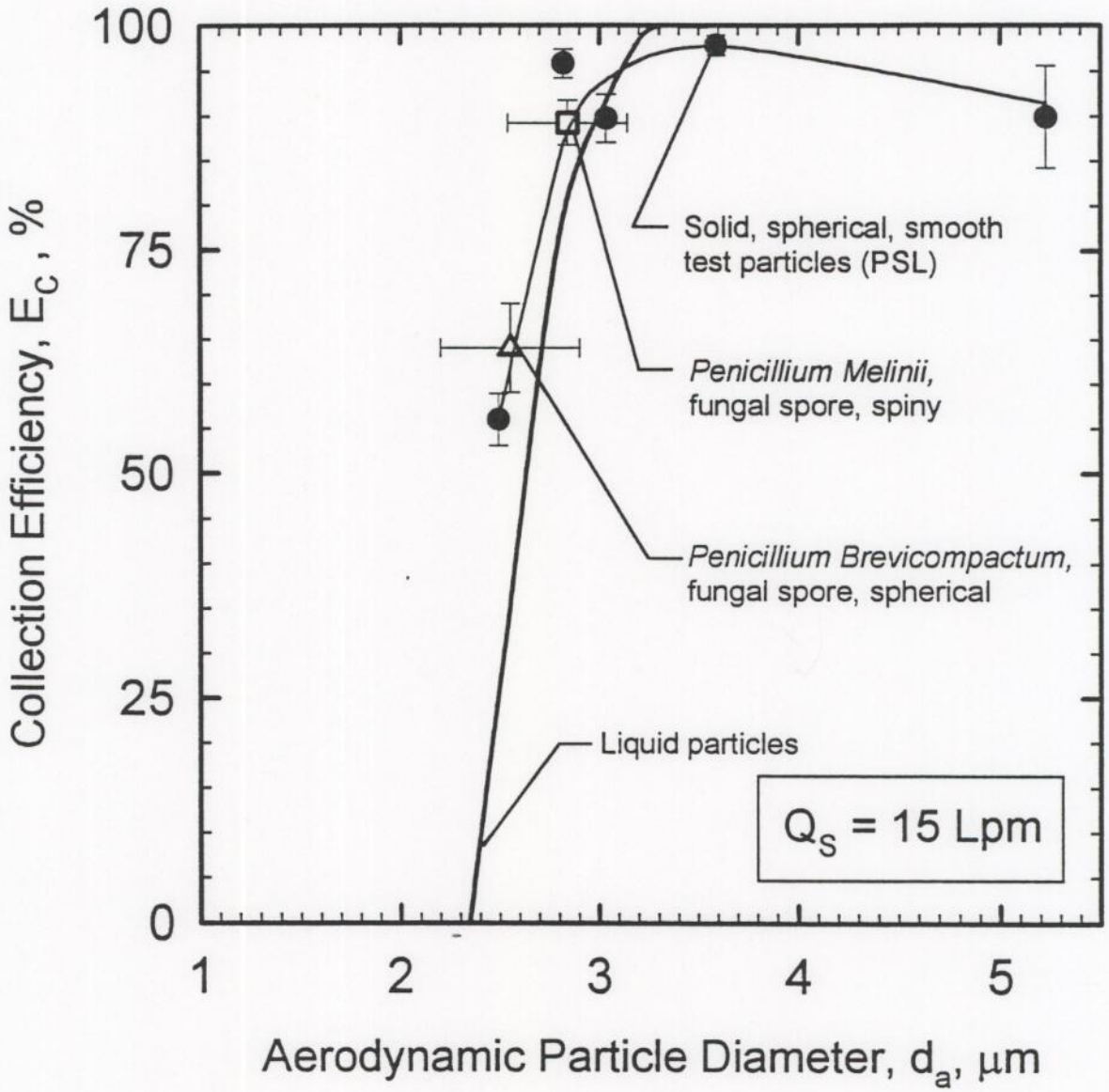

Fig. 6b. Collection efficiency of the Zefon Air-O-Cell for liquid and solid particles at Q_S=15 Lpm, (T=73 F, RH=15 %).

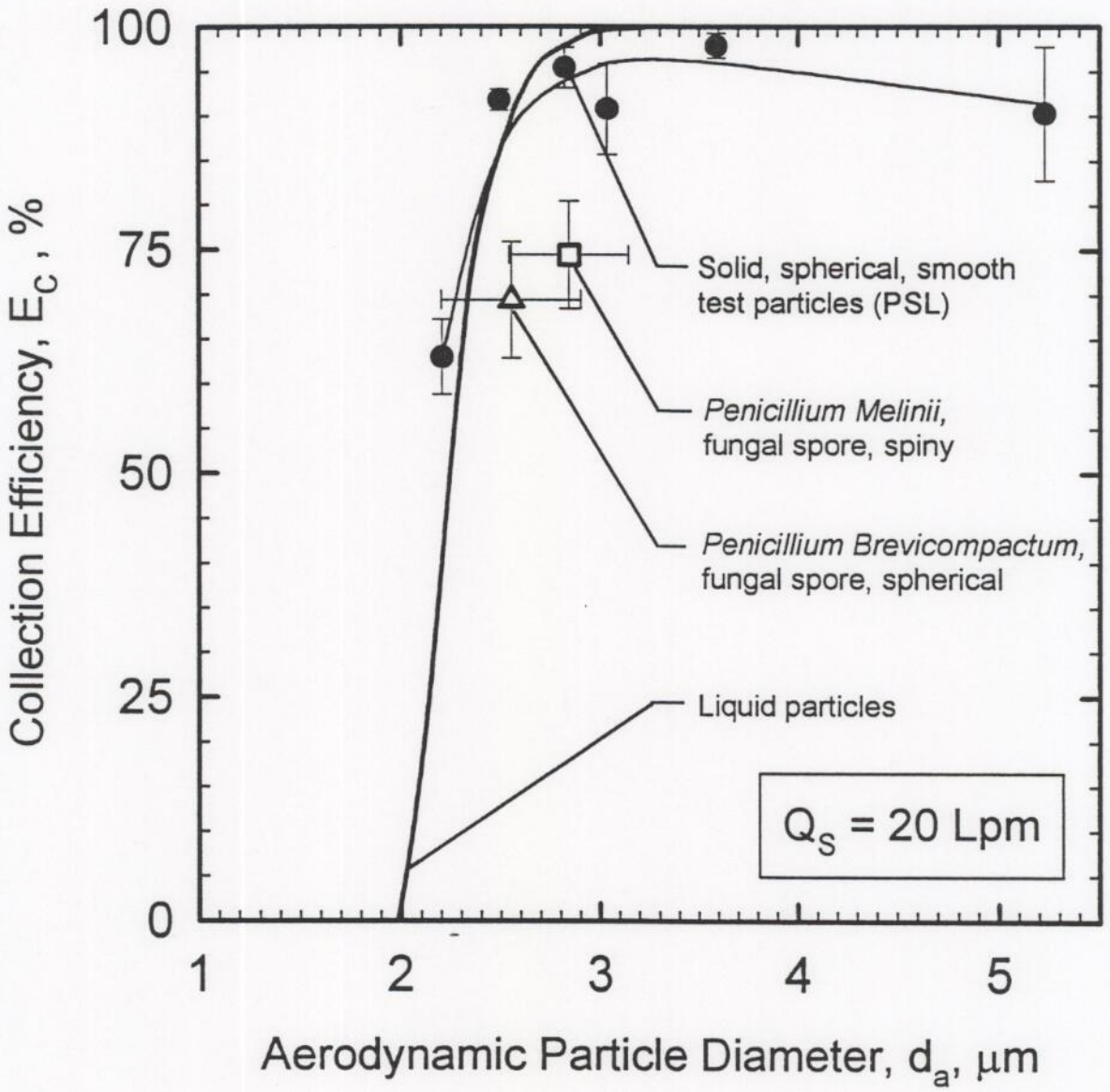

Fig. 6c. Collection efficiency of the Zefon Air-O-Cell for liquid and solid particles at Q_S=20 Lpm, (T=73 F, RH=15 %).

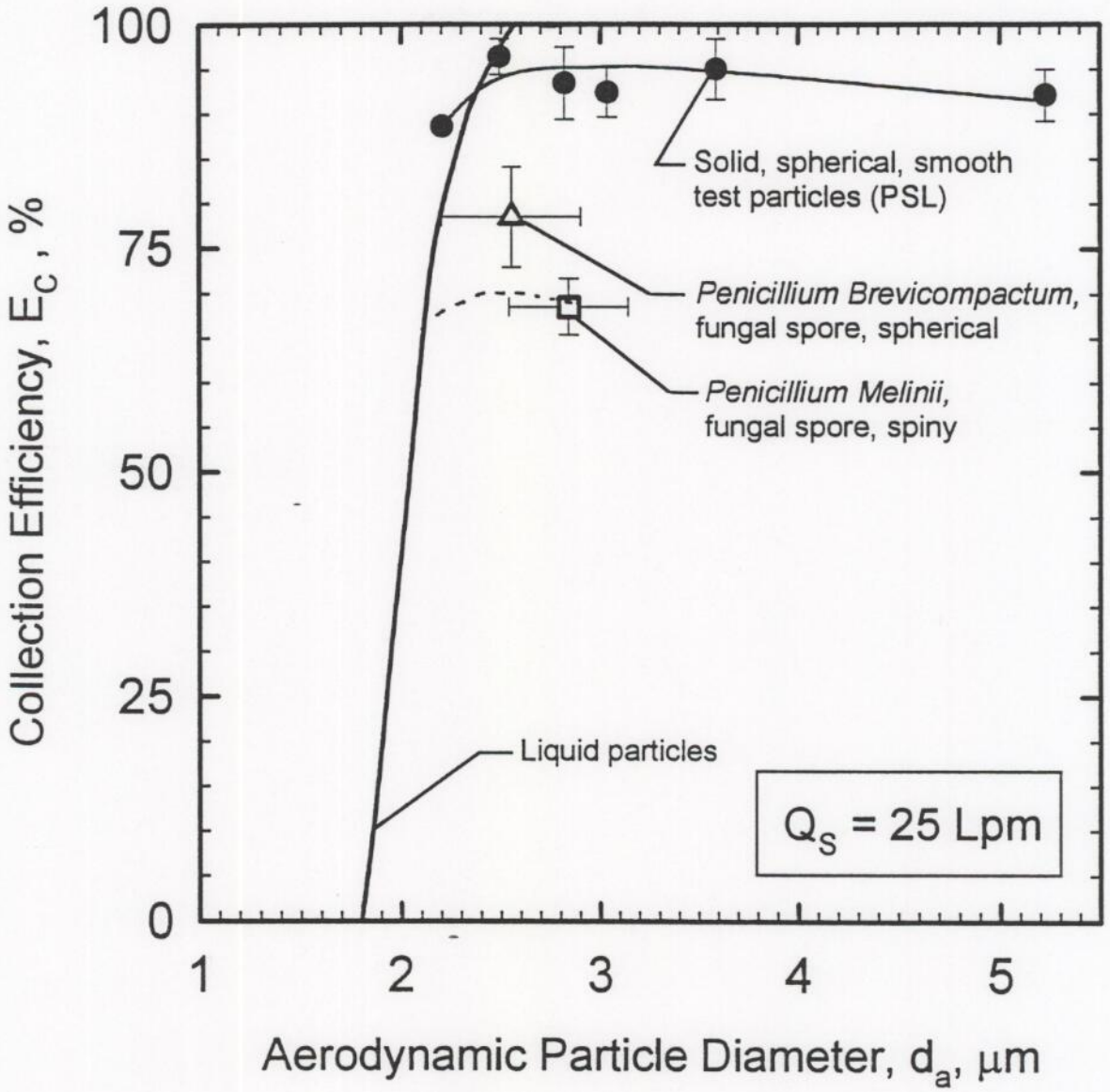

Fig. 6d. Collection efficiency of the Zefon Air-O-Cell for liquid and solid particles at Q_S=25 Lpm, (T=73 F, RH=15 %).

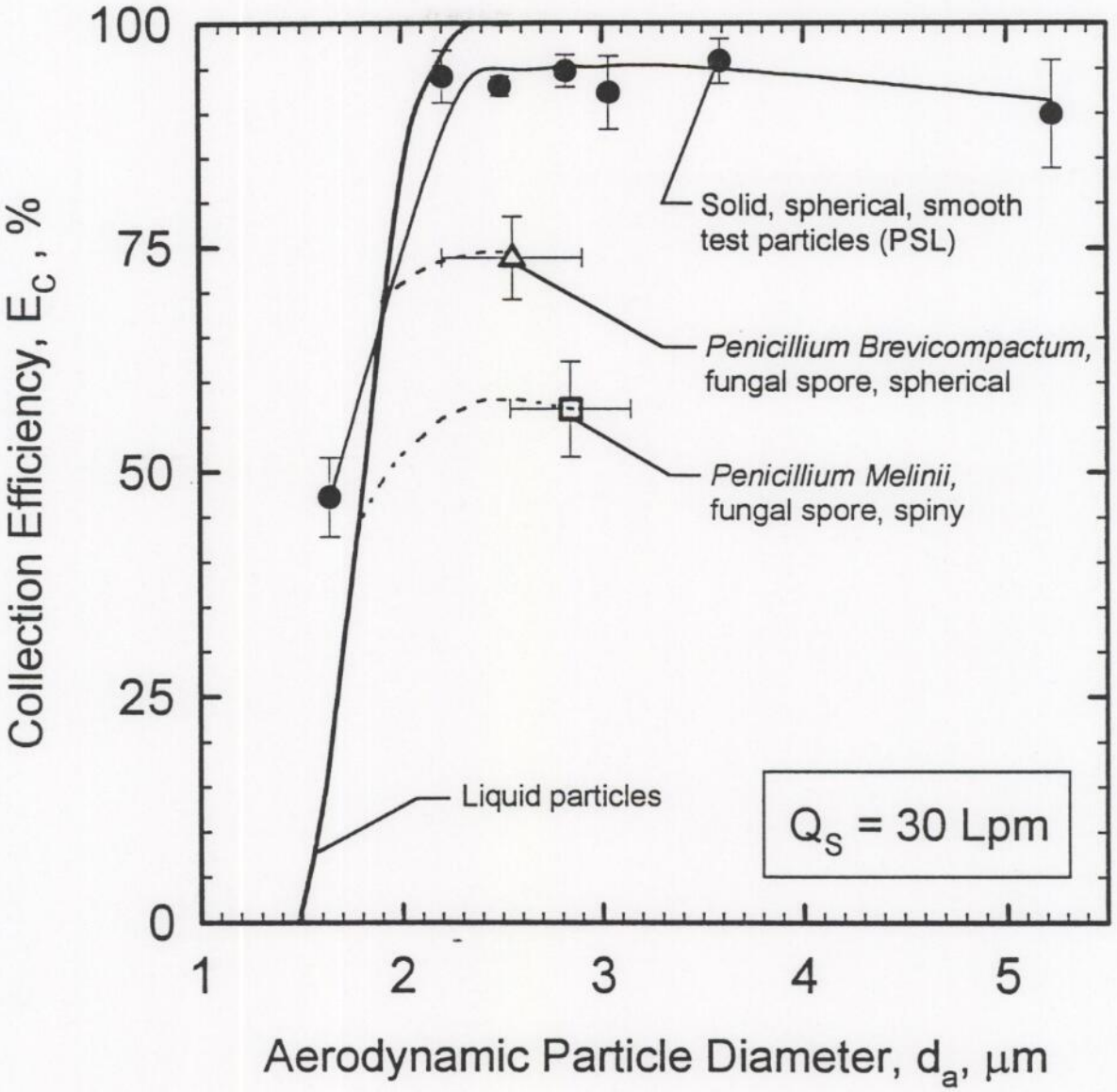

Fig. 6e. Collection efficiency of the Zefon Air-O-Cell for liquid and solid particles at Q_s=30 Lpm, (T=73 F, RH=15 %).