Characterization of 0.02 μm to 1.0 μm Particle Losses in Perma Pure Dryers: Dependence on Size, Charge, and Relative Humidity

by

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Introduction

This report summarizes a study of particle losses in Perma Pure Dryers (Perma Pure Products, Inc., Toms River, NJ). The experimental study was prompted by concerns related to their use in an atmospheric visibility study to be conducted in the Eastern U.S. during the summer of 1995. The dryers will be used in to remove water vapor from humid ambient aerosols in order to prevent condensation within sampling instrumentation installed in air-conditioned stations. Previously measured particle losses in one dryer model for particle size ranging from 0.01 to 0.45 μm were as high as 24%.[1] In this work, we examine losses over a wider size range (D_p=0.02 to 1.0 μm) for two different dryer types.

The Perma Pure Dryer employs a "hygroscopic, ion exchange membrane in a continuous drying process to selectively remove water vapor from mixed gas streams."[2] Aerosol flows through the tubular membrane which is sealed by O-rings into an impermeable shell, as shown in Fig. 1. Water vapor passes through the membrane into a countercurrent flow of dry purge air in the annular region between the membrane and the shell.

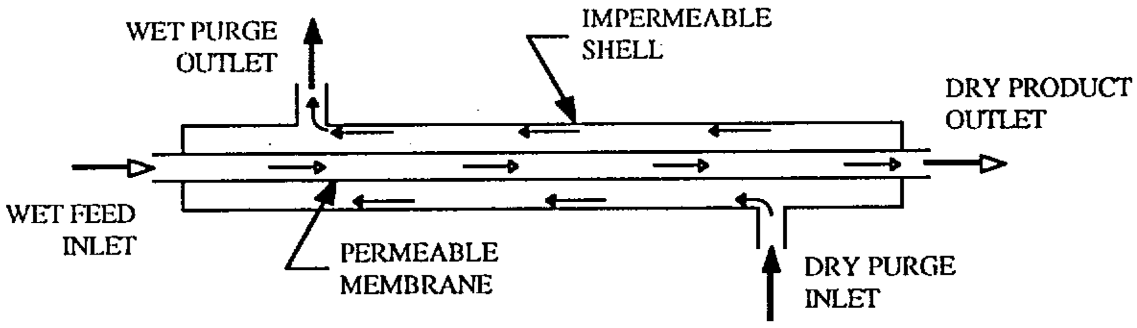

Figure 1. Principle of Perma Pure Dryer operation. (Reproduced from product literature.[2])

Transport efficiencies of monodisperse dioctyl sebacate (DOS) aerosols were measured for two different dryer models. One model (# MD-250-12P) consisted of a 12" long membrane housed in a polypropylene shell with fittings also made of polypropylene. The other model (# MD-110-24CS) consisted of a 24" long membrane housed in a stainless steel shell with stainless steel fittings. Transport (or penetration) efficiencies were measured for both dryers for four combinations of aerosol charge and humidity conditions: aerosols were either unipolarly-charged or neutralized (Boltzmann charge distribution) and humidity was either high or low. In the following section, we describe the apparatus used to make these measurements. In the results section, we compare penetration efficiencies among cases to show the effects of both charging and humidity.

Experiment

The apparatus used to measure size-dependent particle losses for the two Perma Pure Dryers is shown in Fig. 2. A solution of DOS in isopropyl alcohol (0.025% by volume) was atomized to produce a polydispersion of droplets which was diluted with dry air and drawn through a diffusion dryer to remove residual alcohol. Charge-neutralized pure DOS droplets were electrostatically classified using a differential mobility analyzer(3) to produce uniform droplets with mean mobility diameter ranging from 0.02 to 1.0 μm. Aerosol flow into and out of the DMA was 0.20 lpm and sheath air flow was 2.0 lpm. We were able to span the indicated size range using these flows and potential ranging from 15 to 7930 V. A filter diluter, shown to the right of the DMA in Fig. 2, was used to keep the aerosol number concentration as constant as possible across the size range.

Particles exiting the DMA were either neutralized, or left charged as shown in Fig. 2 with a dashed line indicating a bypass. We assume that a Boltzmann charge distribution was produced with a neutralizer, and that particles of unipolar and primarily single elementary charge were produced without it. Measurements were not made to determine the extent of multiple charging which corresponds to classification of particles much larger than the assumed single-charging mobility diameters.

The aerosols were either humidified, with the three saturators shown in series, or left dry as indicated with a dashed line. Maximum humidification was achieved by using 2.0 lpm of humidified air for the sheath flow in the DMA and by diluting the 0.2 lpm of DMA-classified aerosol with 0.8 lpm of humidified air. The dilution was necessary to obtain a recommended 1.0 lpm aerosol flow through the dryer. The relative humidity (RH) of each aerosol was determined from measurements of the dew point temperature made with an EG&G Model 880 dew point hygrometer[1] and ambient temperature made with a type K thermocouple (indicated by a circled T in Fig. 2). The RH of the humidified or "wet" aerosols ranged from 75.8 to 82.8%, while the RH of the "dry" aerosols ranged only

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[1] The performance of the EG&G hygrometer was compared to that of a General Eastern Model 1100DP hygrometer which is installed in the University of Minnesota TDMA system. Dew points measured with the EG&G were an average of 1.5°C higher than those measured with the General Eastern for four humidity levels ranging roughly from 13% to 85% RH. Since RH values derived from the General Eastern hygrometer agreed well with measurements from a Visala RH meter, which was also installed in the TDMA, we decided to subtract 1.5°C from all dew point readings from the EG&G hygrometer.

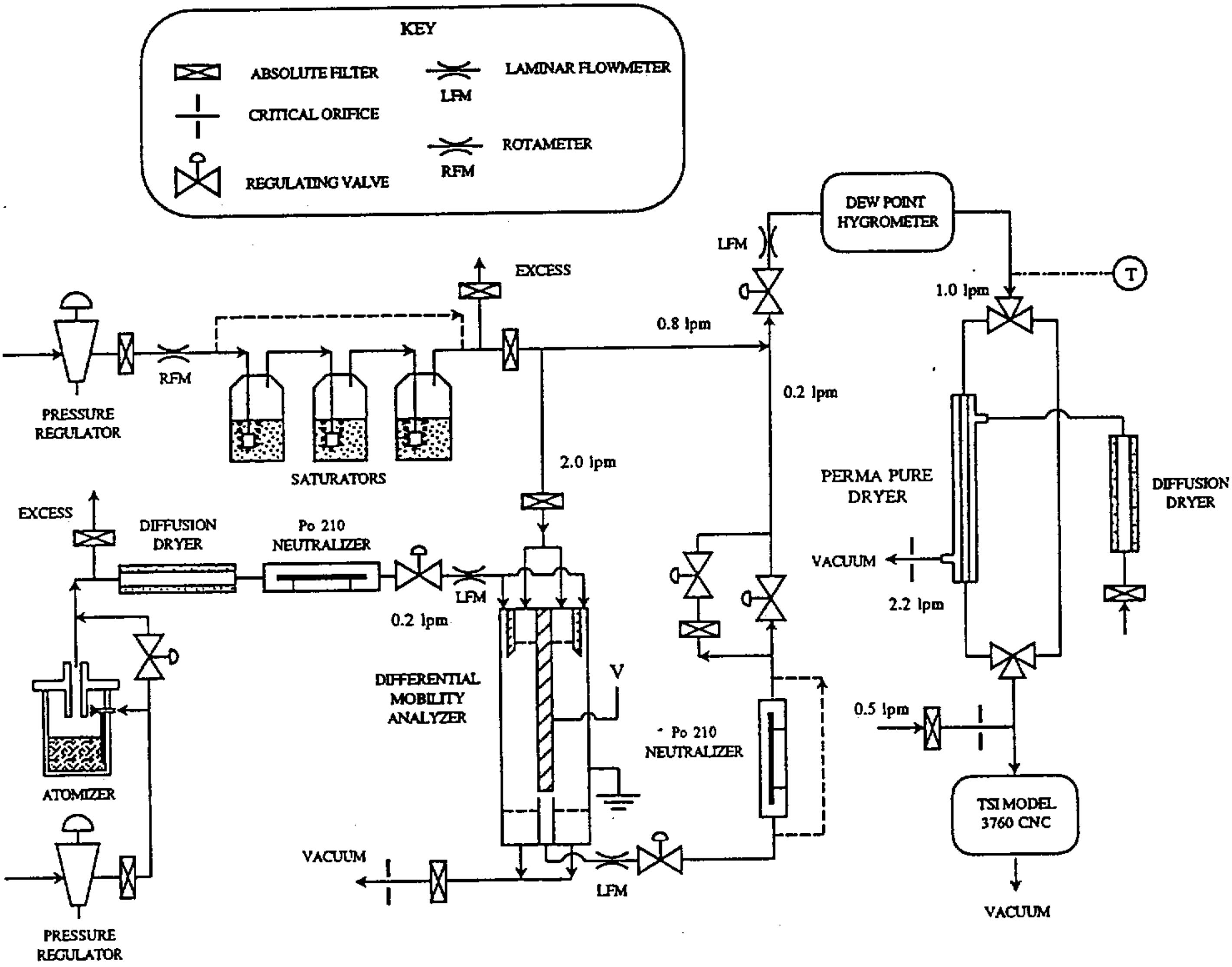


Figure 2. Schematic of the apparatus used for measuring size-dependent penetrations through Perma Pure Dryers.

from 5.3 to 5.6%.

Each aerosol of known RH and charge was then drawn through the testing manifold shown on the right-hand side of Fig. 2. The manifold was constructed so that particle concentration measurements both upstream and downstream of the dryer could be made with one CNC. Aerosol was diverted to either a line containing the test dryer or a straight "reference" line by switching two adjoining 3-way valves in concert. The reference line consisted of a U-shaped piece of 1/4 in. stainless steel tubing (I.D.=0.175 in.) 33.25 in. long from leg-to-leg. Each of the two dryer lines had a U-shape of the same linear dimensions and was constructed by sandwiching the dryer between two right-angled 1/4 in. stainless steel tubes.

Penetration efficiencies through the dryers were determined from CNC measurements of upstream concentration from the reference line, N_r, and downstream concentration form the dryer line, N_d. Each value of N_d or N_r was taken as an average of approximately 100 one-second CNC sample readings. Upstream measurements were generally made before downstream measurements, with roughly 20 sec. between measurements. In order to determine absolute losses (penetrations) through each dryer, a correction was made based on the calculated penetration through a section of the reference line of length roughly equal to the length of each membrane. The reference penetration, P_r, was calculated using semi-empirical expressions for losses due to diffusion and gravitational settling through circular tubes. The dryer penetration efficiency, P_d, is given by:

$$P_d = P_r \frac{N_d}{N_r} \qquad (1)$$

The standard deviations in number concentration over the sampling periods were used as the uncertainties ΔN_d and ΔN_r in a root-sum-of square analysis of the dryer penetration efficiency. The penetration uncertainty also included uncertainties in dryer and reference aerosol flow rates, which were based on the resolution of the two flowmeters downstream of the DMA chamber.

The Perma Pure dryers were operated in accordance with information obtained from the manufacturer and researchers with operational experience. Aerosol flow rate through the dryer was maintained at a recommended 1.0 lpm.[4] Room air was drawn a filter and a diffusion dryer at 2.2 lpm for use as purge or sheath air. The recommended purge air flow rate is 1.5 to 2 times the aerosol flow rate.[5] To validate operation of the dryers, measurements of upstream and downstream RH were made. With the polypropylene dryer, RH of wet 0.15 μm DOS aerosol was reduced from 73.7% to 44.6%, or by a factor of 1.65, which is in good agreement with a predicted reduction of 1.5 from the product literature.[1] With the stainless steel dryer, RH was reduced from 72.9% to 28.6%, or by a factor of 2.55, which also agrees well with the predicted reduction of 2.5.

Results of the penetration efficiency measurements are presented in the next section. Size-dependent penetration efficiency values are compared to determine the effects of both charging and humidity.

Results

Four comparisons of penetration efficiencies are made for both polypropylene and stainless steel dryers in Figs. 3-6. In all of the figures, penetration efficiency, in percent, is plotted against particle diameter in microns. In general, penetration efficiencies are greater for the stainless steel dryer than they are for the polypropylene dryer. Since the membranes are identical in composition and geometry (save the length), we attribute this difference to greater losses to the polypropylene fittings than to the stainless steel fittings. Penetration efficiency generally increases with particle diameter due to diffusional losses, approaching 100%, but often it is observed to dip at 0.8 and 1.0 μm. Speculation of loss due to gravitational settling for these large diameters are not supported by the calculations made. Impaction of larger particles when going from 1/4 in. tubing (I.D.=0.175in.) to the membrane (I.D.=0.10 in.) is suspected.

The effects of particle charge on losses in the dryers are shown in Figs. 3 and 4. Penetrations of charged and neutralized aerosols are compared in Fig 3 for high RH and in Fig. 4 for aerosols of low RH. The effect of charge on penetration was very significant for the polypropylene dryer. For "wet" aerosols flowing through the polypropylene dryer (Fig. 3a), penetration at 0.02 μm was 83.0% for neutralized particles and only 14.7% for charged particles. The substantial reduction in penetration was also observed for dry aerosols (Fig. 4a), with 0.02 μm values of 90.2% and 18.4% for neutralized and charged particles, respectively. The effect of charge was less pronounced with the stainless steel dryer, as expected. For both wet and dry aerosols (Figs. 3b and 4b) of small diameter, however, charged particles had slightly greater penetration than their neutralized counterparts. This was the opposite effect of that observed for smaller particles flowing through the polypropylene dryer.

The effects of humidity on penetration can be observed in Fig. 5 (charged aerosols) and Fig. 6 (neutralized aerosols). Overall, it appears that small particles ($Dp \leq 0.1$ µm) in dry air have somewhat higher penetration than small particles in wet air. Above 0.1 µm, there doesn't appear to be any particular trend.

Data from the penetration measurements are presented in Tables A1-A8 in Appendix A. Tables A1-A4 list data for the polypropylene dryer (# MD-250-12P) and Tables A5-A8 list data for the stainless steel dryer (# MD-110-24CS). Size-correlated data include RH values, reference and dryer number concentrations (N_d and N_r), calculated values of diffusional and gravitational settling penetrations (P_{diff} and P_{grav}), and corrected dryer penetration efficiencies and their uncertainties (P_d and ΔP_d).

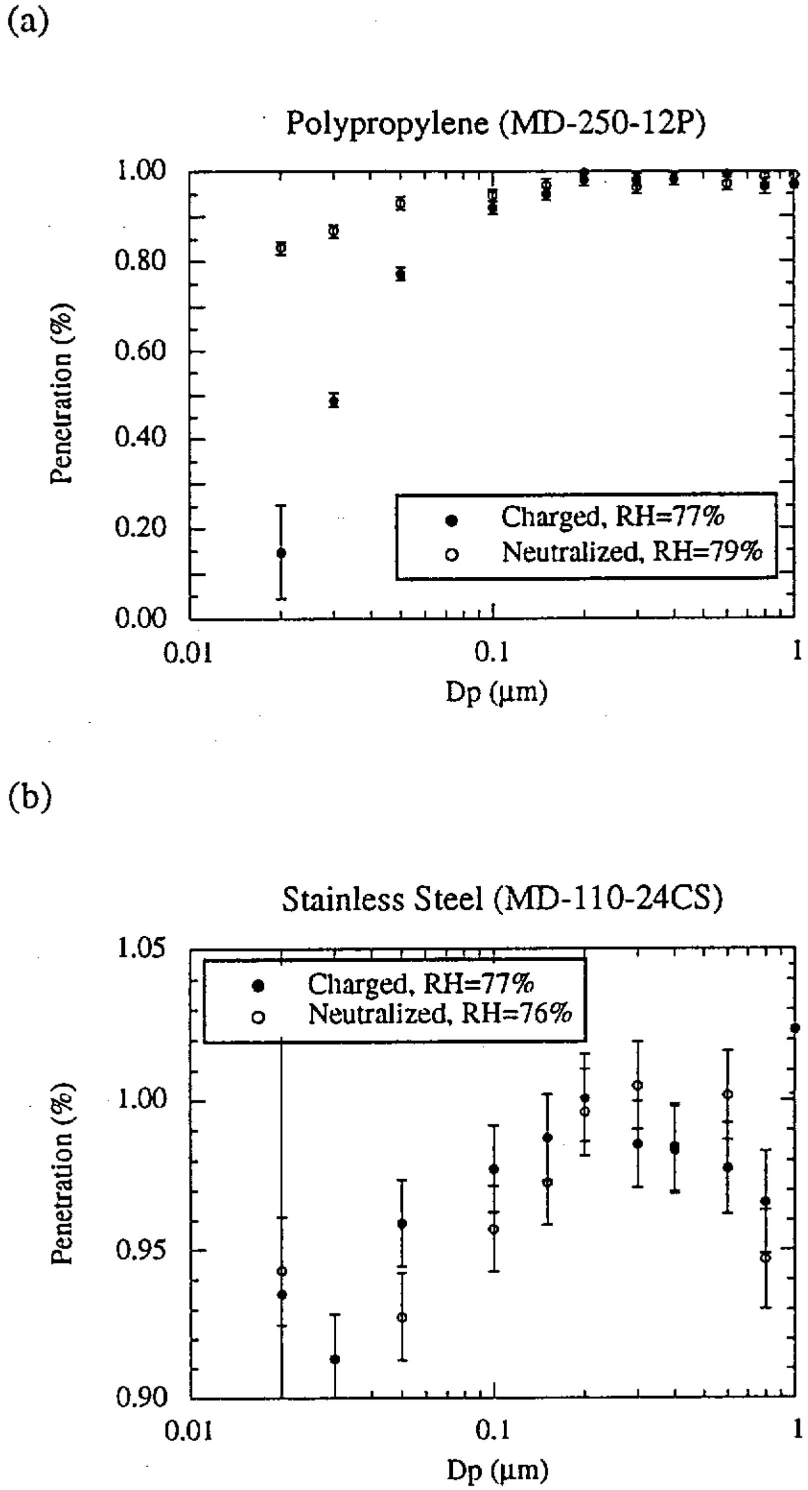


Figure 3. Comparison of penetration efficiencies of charged and neutralized aerosols of high RH for the polypropylene dryer (a) and the stainless steel dryer (b).

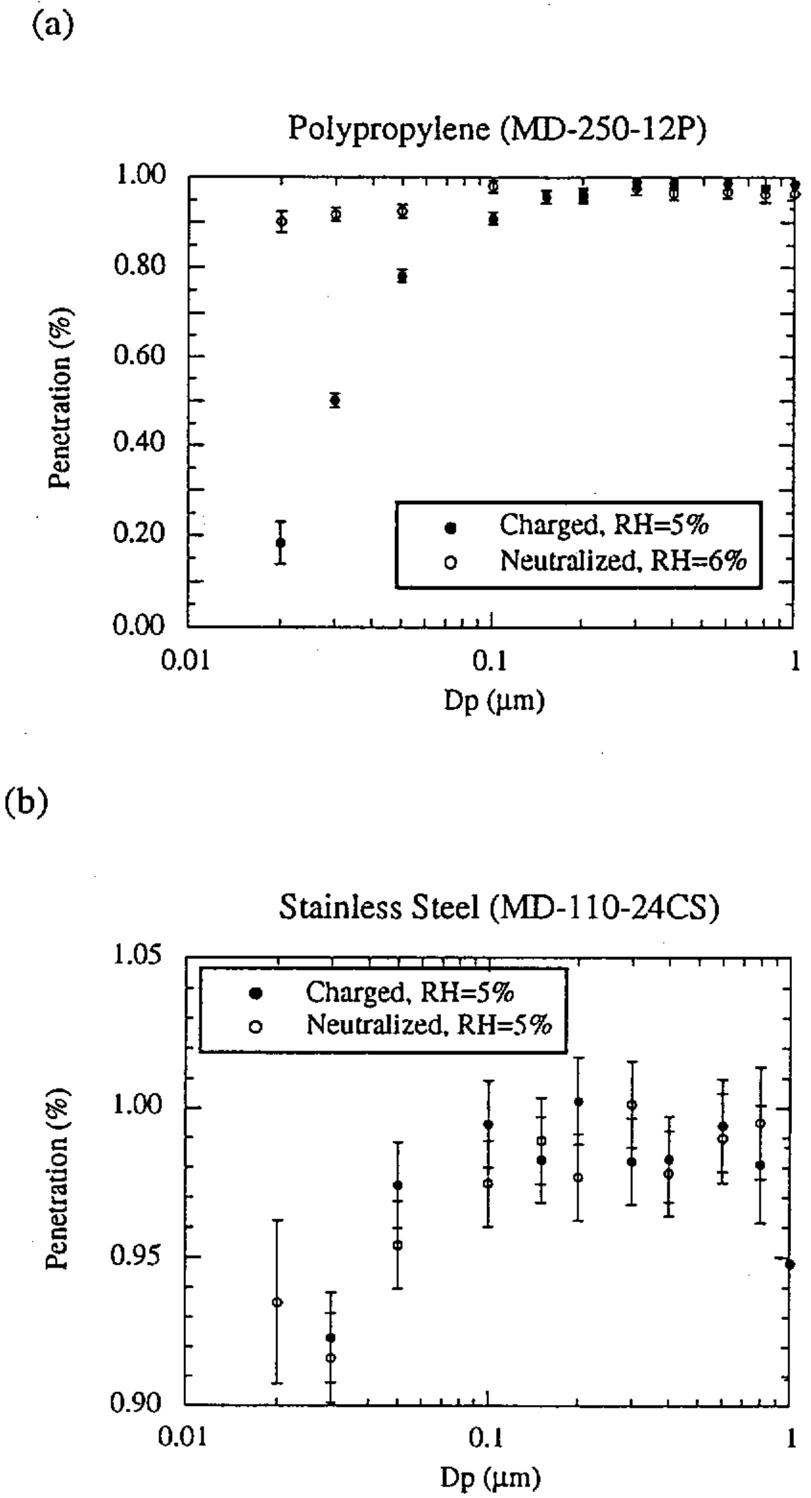


Figure 4. Comparison of penetration efficiencies of charged and neutralized aerosols of low RH for the polypropylene dryer (a) and the stainless steel dryer (b).

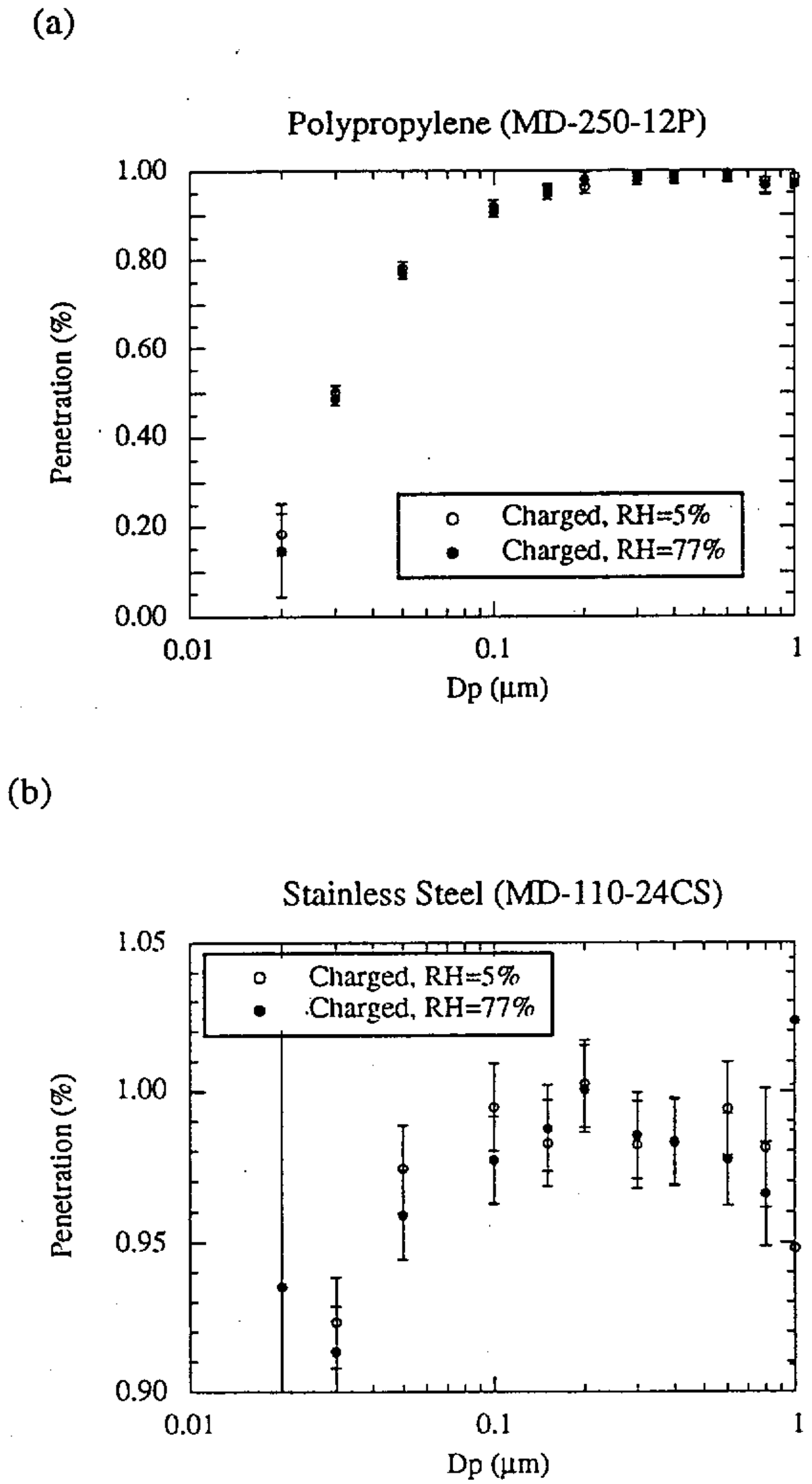
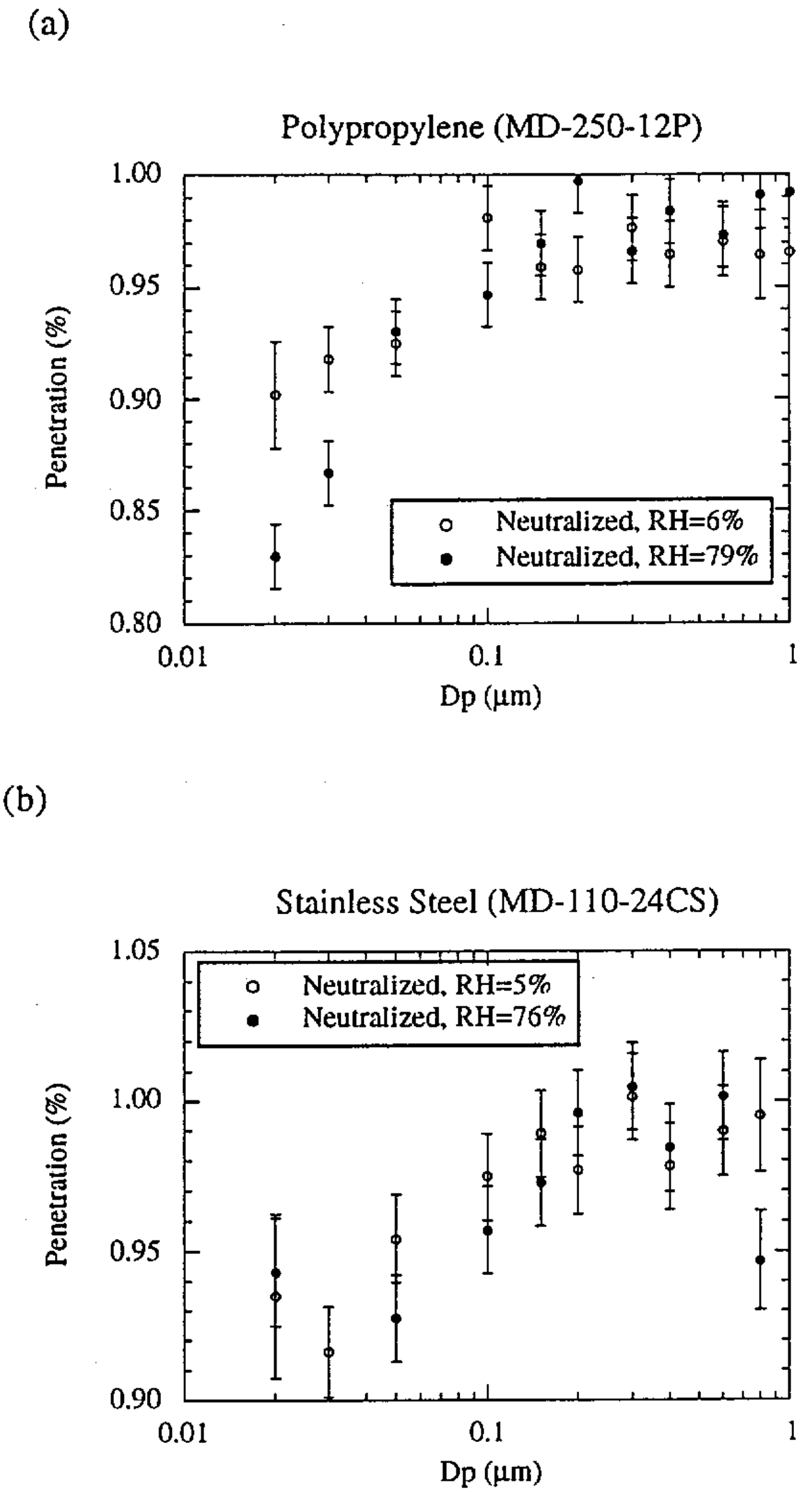


Figure 5. Comparison of penetration efficiencies of charged high RH and low RH aerosols for the polypropylene dryer (a) and the stainless steel dryer (b).



Polypropylene (MD-250-12P)

Stainless Steel (MD-110-24CS)

Figure 6. Comparison of penetration efficiencies of neutralized high RH and low RH aerosols for the polypropylene dryer (a) and the stainless steel dryer (b).

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Table A1 Perma Pure Dyer Type : Polypropylene (MD-250-12P)
Ambient Temperature : 25.2 °C
Aerosol Charge Condition : Neutralized

Dp (µm)	RH (%)	Nr (#/cc)	Nd (#/cc)	Penetration			Uncert. ΔPd
				Pdif	Pgrav	Pd	
0.02	81.21	2.838	2.405	0.979	1.000	0.830	0.016
0.03	82.79	86.849	76.237	0.987	1.000	0.867	0.016
0.05	81.34	150.247	140.698	0.993	1.000	0.930	0.016
0.10	80.41	159.447	151.398	0.997	1.000	0.947	0.016
0.15	79.45	178.107	173.058	0.998	1.000	0.970	0.016
0.20	78.53	108.747	108.658	0.999	1.000	0.998	0.016
0.30	78.06	148.657	143.788	0.999	1.000	0.966	0.016
0.40	77.60	117.717	115.948	0.999	0.999	0.984	0.016
0.60	77.14	58.134	56.663	0.999	0.999	0.973	0.016
0.80	76.68	21.069	20.923	1.000	0.998	0.991	0.017
1.00	76.68	7.706	7.668	1.000	0.997	0.992	0.018

Table A2 Perma Pure Dyer Type : Polypropylene (MD-250-12P)
Ambient Temperature : 26.0 °C
Aerosol Charge Condition : Unipolar-charged

Dp (µm)	RH (%)	Nr (#/cc)	Nd (#/cc)	Penetration			Uncert. ΔPd
				Pdif	Pgrav	Pd	
0.02	76.29	0.588	0.089	0.979	1.000	0.147	0.105
0.03	76.29	52.436	25.846	0.987	1.000	0.487	0.017
0.05	76.29	136.465	106.047	0.993	1.000	0.772	0.016
0.10	76.75	128.725	118.657	0.997	1.000	0.919	0.016
0.15	76.75	184.665	175.787	0.998	1.000	0.950	0.016
0.20	76.73	136.765	134.727	0.999	1.000	0.984	0.016
0.30	76.75	177.675	174.777	0.999	1.000	0.982	0.016
0.40	76.75	109.715	108.087	0.999	0.999	0.984	0.016
0.60	76.76	51.406	51.236	0.999	0.999	0.995	0.017
0.80	76.76	14.447	14.019	1.000	0.998	0.968	0.019
1.00	76.76	6.131	5.976	1.000	0.997	0.972	0.023

Table A3 Perma Pure Dyer Type : Polypropylene (MD-250-12P)
Ambient Temperature : 26.6 °C
Aerosol Charge Condition : Unipolar-charged

Dp	RH	Nr	Nd	Penetration			Uncert.
(µm)	(%)	(#/cc)	(#/cc)	Pdif	Pgrav	Pd	ΔPd
0.02	5.32	1.068	0.200	0.979	1.000	0.183	0.046
0.03	5.36	53.222	26.992	0.987	1.000	0.501	0.017
0.05	5.33	187.720	147.749	0.993	1.000	0.782	0.016
0.10	5.25	172.180	157.089	0.997	1.000	0.910	0.016
0.15	5.30	159.140	152.619	0.998	1.000	0.957	0.016
0.20	5.27	163.040	157.339	0.999	1.000	0.964	0.016
0.30	5.28	130.110	128.999	0.999	1.000	0.990	0.016
0.40	5.29	121.650	120.519	0.999	0.999	0.989	0.016
0.60	5.29	49.277	48.824	0.999	0.999	0.989	0.017
0.80	5.29	10.075	9.864	1.000	0.998	0.977	0.032
1.00	5.29	2.167	2.143	1.000	0.997	0.986	0.028

Table A4 Perma Pure Dyer Type : Polypropylene (MD-250-12P)
Ambient Temperature : 27.5 °C
Aerosol Charge Condition : Neutralized

Dp	RH	Nr	Nd	Penetration			Uncert.
(µm)	(%)	(#/cc)	(#/cc)	Pdif	Pgrav	Pd	ΔPd
0.02	5.45	2.764	2.547	0.979	1.000	0.902	0.025
0.03	5.41	99.500	92.494	0.987	1.000	0.918	0.016
0.05	5.37	135.550	126.226	0.993	1.000	0.925	0.016
0.10	5.51	171.100	168.326	0.997	1.000	0.981	0.016
0.15	5.51	171.600	164.876	0.998	1.000	0.959	0.016
0.20	5.48	154.460	148.186	0.999	1.000	0.958	0.016
0.30	5.53	165.990	162.286	0.999	1.000	0.976	0.016
0.40	5.50	171.530	165.646	0.999	0.999	0.964	0.016
0.60	5.51	32.844	31.919	0.999	0.999	0.970	0.017
0.80	5.51	6.516	6.297	1.000	0.998	0.964	0.021
1.00	5.63	1.287	1.246	1.000	0.997	0.965	0.035

Table A5 Perma Pure Dyer Type : Stainless Steel (MD-110-24CS)
Ambient Temperature : 25.9 °C
Aerosol Charge Condition : Neutralized

Dp	RH	Nr	Nd	Penetration			Uncert.
(μm)	(%)	(#/cc)	(#/cc)	Pdif	Pgrav	Pd	ΔPd
0.02	76.68	1.388	1.356	0.979	1.000	0.943	0.019
0.03	0.00			0.987	1.000		
0.05	75.78	112.758	105.753	0.993	1.000	0.927	0.016
0.10	76.25	112.608	108.313	0.997	1.000	0.957	0.016
0.15	76.25	124.128	121.143	0.998	1.000	0.973	0.016
0.20	75.80	137.388	137.223	0.999	1.000	0.996	0.016
0.30	75.81	123.758	124.633	0.999	1.000	1.005	0.016
0.40	75.81	113.678	112.163	0.999	0.999	0.984	0.016
0.60	76.29	85.835	86.247	0.999	0.999	1.002	0.016
0.80	76.76	26.084	24.808	1.000	0.998	0.947	0.018
1.00	0.00			1.000	0.997		

Table A6 Perma Pure Dyer Type : Stainless Steel (MD-110-24CS)
Ambient Temperature : 26.0 °C
Aerosol Charge Condition : Unipolar-charged

Dp	RH	Nr	Nd	Penetration			Uncert.
(μm)	(%)	(#/cc)	(#/cc)	Pdif	Pgrav	Pd	ΔPd
0.02	76.76	0.098	0.095	0.979	1.000	0.935	0.123
0.03	76.76	44.746	41.742	0.987	1.000	0.913	0.017
0.05	76.76	125.994	122.192	0.993	1.000	0.959	0.016
0.10	76.78	177.734	174.562	0.997	1.000	0.977	0.016
0.15	77.66	211.904	210.012	0.998	1.000	0.988	0.016
0.20	77.67	168.574	169.172	0.999	1.000	1.001	0.016
0.30	77.22	169.234	167.142	0.999	1.000	0.985	0.016
0.40	77.22	87.738	86.492	0.999	0.999	0.983	0.016
0.60	77.22	34.406	33.734	0.999	0.999	0.977	0.017
0.80	77.67	10.254	9.950	1.000	0.998	0.966	0.019
1.00	77.20	4.535	4.670	1.000	0.997	1.023	0.023

Table A7 Perma Pure Dyer Type : Stainless Steel (MD-110-24CS)
Ambient Temperature : 27.3 °C
Aerosol Charge Condition : Unipolar-charged

Dp	RH	Nr	Nd	Penetration			Uncert.
(µm)	(%)	(#/cc)	(#/cc)	Pdif	Pgrav	Pd	ΔPd
0.02	5.41	0.071	0.079	0.979	1.000	1.078	0.133
0.03	5.36	52.427	49.437	0.987	1.000	0.923	0.017
0.05	5.36	162.977	160.578	0.993	1.000	0.974	0.016
0.10	5.37	114.477	114.448	0.997	1.000	0.995	0.016
0.15	5.37	150.817	148.718	0.998	1.000	0.983	0.016
0.20	5.34	187.367	188.348	0.999	1.000	1.003	0.016
0.30	5.35	128.697	126.698	0.999	1.000	0.982	0.016
0.40	5.34	124.307	122.468	0.999	0.999	0.983	0.016
0.60	5.34	22.774	22.715	0.999	0.999	0.994	0.017
0.80	5.38	4.142	4.082	1.000	0.998	0.981	0.021
1.00	5.38	0.829	0.791	1.000	0.997	0.948	0.040

Table A8 Perma Pure Dyer Type : Stainless Steel (MD-110-24CS)
Ambient Temperature : 27.6 °C
Aerosol Charge Condition : Neutralized

Dp	RH	Nr	Nd	Penetration			Uncert.
(µm)	(%)	(#/cc)	(#/cc)	Pdif	Pgrav	Pd	ΔPd
0.02	5.39	2.135	2.068	0.979	1.000	0.935	0.028
0.03	5.39	93.559	87.554	0.987	1.000	0.916	0.017
0.05	5.39	153.137	147.765	0.993	1.000	0.954	0.016
0.10	5.35	150.827	147.745	0.997	1.000	0.975	0.016
0.15	5.38	148.757	147.635	0.998	1.000	0.989	0.016
0.20	5.35	190.217	186.325	0.999	1.000	0.977	0.016
0.30	5.35	139.357	139.875	0.999	1.000	1.001	0.016
0.40	5.44	180.797	177.265	0.999	0.999	0.978	0.016
0.60	5.44	34.455	34.218	0.999	0.999	0.990	0.017
0.80	5.41	7.129	7.126	1.000	0.998	0.995	0.020
1.00	5.42	1.731	1.839	1.000	0.997	1.056	0.029