

Effect of Air Humidity on Charge Decay and Lifetime of PP Electret Nonwovens

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Abstract

The effects of air humidity on the charge decay and lifetime of polypropylene (PP) electret nonwovens manufactured by the pneumothermic method are presented. The PP fabric samples were corona-charged from a needle electrode under high voltage. The thermally-stimulated equivalent surface voltages were measured at a linear heating rate in a temperature range from 293 K to 395 K. The results of the measurements showed that the equivalent voltage depends on the structural properties of the PP nonwovens as well as the conditions of formation. The selected electret nonwovens were next placed in a chamber whose humidity was controlled within a range of 39% to 94%, and the decay of the electret charge was measured and analysed. The results show that conditioning the samples at a higher humidity influences the changes of the equivalent voltage and the lifetime of the electret fibre.

Keywords: PP filtration fabric, corona charging, electret, electric charge lifetime, relative air humidity.

Introduction

Fibrous air filters are widely used for dust collection and environmental protection. Effective filtration of submicron particles is of great importance, because such particles constitute a health hazard. Electret polymeric filters are commonly used for the filtration of submicron aerosol particles from polluted gases. Fibrous materials used for air filtration provide high filtration efficiency, low air resistance (due to low pressure drop across the filter) and show a high efficiency of collecting dust particles. The fibres in the filter are permanently charged, and electrostatic charges enhance filtration efficiency in comparison with that of mechanical filters. The electret filters have less breathing resistance than mechanical filters with the same efficiency and surface area. Products utilising electret filters can be made lighter in weight and more compact than those which use mechanical filtration elements.

The aerosol or dust capture mechanisms of electret filters depend on a combination of mechanical and electrical components. The conventional mechanical component includes diffusion, which is a prominent mechanism of filtration for small particles ($< 0.3 \mu\text{m}$), and fine fibres are essential for the high collection efficiency of submicron particles [1]. Other mechanisms are important for large particles ($> 1 \mu\text{m}$), including interception, impaction, impingement, sieving, and gravitational settling. The mechanical capture processes are short-range and a grid of dense fibres is needed for an effective filtration process. The electrical component includes Coulombic and dielectrophoretic mechanisms. The Coulombic capture is dominant for small aerosols ($< 0.1 \mu\text{m}$) and particles; the dielectrophoretic capture is dominant for particles larger than $0.3 \mu\text{m}$ [2]. The

electrostatic forces acting on aerosol particles are long-range, which is why the mesh dimensions of nonwoven structure can be larger, and the pressure drop across an electret filter is several times lower in comparison to the mechanical filter.

The collection efficiency of electret filters depends on many parameters, such as fibre charge density, filter packing density, filter thickness and aerosol particle sizes & charges. The collection efficiency decreases exponentially with the operation time due to the decrease in the electrical component [3]. Solid aerosol particles clog the pores of the electret filter, and the deposited aerosol reduces the surface charge [4]. The liquid aerosol coats over the surface of the charged fibres, which results in a decrease in the surface charge and collection efficiency. Increasing the relative humidity may reduce the collection efficiency of electret filters [5, 6].

Polymers with extremely low electrical conductivity as polypropylene, polycarbonate, polyurethane and polyethylene oxide are usually used as filter materials. Various processes such as splitting of corona-charged film, electrostatic spinning, tribocharging and meltblown are now applied in the production of nonwovens. Electrospinning can produce very fine electret fibers in the one-step process, but its efficiency is rather low [7]. Tribocharging is only appropriate for charging fibres with dissimilar electronegativity. The corona method is one of the best charging method for non-polar materials, and for this reason it was applied for electrifying PP electret nonwovens. In this work, the properties of two kinds of PP nonwovens are described, and in particular the effect of relative air humidity (RH) on the charge decay and lifetime of PP filtration nonwovens.

Materials and methods

Materials

Polypropylene (PP) nonwovens were manufactured by the melt-blown, pneumothermic method. The nonwovens were produced by extruding molten PP through a multi-orifice die, in order to form fibres cast onto a collector with high pressure air. Polypropylene (Malen PF-401) is a non-polar material which has a very low electrical conductivity. Two types of nonwovens, P1 and P2 of basis weights 78 and 104 g/m^2 were investigated. The thickness of P1 nonwoven is about 1 mm, and consists of fibres with diameters between $3 \mu\text{m}$ and $20 \mu\text{m}$. The fibre diameters of P2 nonwovens are between $0.5 \mu\text{m}$ and $10 \mu\text{m}$. The thickness of P2 nonwoven is about 1.6 mm. Microscopic images of nonwoven surfaces are shown in Figure 1. The fibres

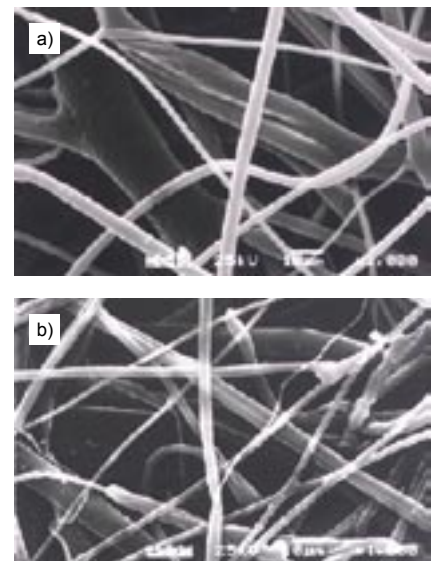


Figure 1. SEM photomicrographs of P1 (a) and P2 (b) fabric samples, enlargement $\times 1000$.

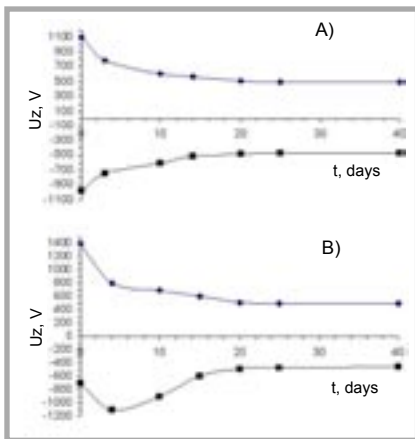


Figure 2. Decay of equivalent surface voltages for fabrics: A) P1, B) P2. The potential of side a of a sample directed to corona electrode during charging is positive. Negative voltages concern the opposite side b. (Measurement conducted after reversing the same sample).

are randomly distributed in nonwoven samples. The P2 nonwovens are nappier in comparison to P1.

Square samples (8 cm × 8 cm) were cut from randomly selected places in the nonwovens P1 and P2. Next, they were corona-charged from a high-voltage needle electrode under a +10 kV potential for 60 s at normal atmospheric conditions. The distance between the corona electrode and the nonwoven sample was 10 cm. During this process, the charges settled on the fibres' surfaces are trapped in surface traps or structural defects of the PP [8]. Semi-crystalline PP contains plenty of small crystallites, which create very effective sites for persistent charge storage. The trapping sites are centred near the crystallites. The crystallites form very effective barriers that restrain the charge transport, and thus charge neutralisation. The number of traps available in PP is therefore more than sufficient [9]. The stored charge is stable because several traps are deep, and the escape of charges to the conduction band of the polymer is negligible.

Electrostatic methods

Next, the samples were discharged in open-circuit conditions, and the equivalent surface voltage U_z was measured using Reedyk and Perlman compensation method [10]. The voltage U_z is related to the equivalent surface charge q_s :

$$q_s = \epsilon_0 \epsilon_r \frac{U_z}{d}, \quad (1)$$

where ϵ_0 is the vacuum permittivity, ϵ_r is the relative permittivity and d is the

thickness of the fabric. Measurements of U_{za} and U_{zb} for both sides of a sample (side a was directed to the corona electrode during charging) allow us to estimate the equivalent surface charges q_{sa} and q_{sb} and the parameters p_z and q_z , which are related to the electrical state of the charged sample. The electrical momentum p_z and equivalent charge q_z of a charged sample equal the following:

$$p_z = \frac{1}{2}(q_{sa} - q_{sb}) \quad q_z = q_{sa} + q_{sb}. \quad (2)$$

The parameters p_z and q_z were introduced by Croitorou [11] in order to characterise the space charge distribution in a dielectric sample. The equivalent momentum of charged sample p_z – (calculated respectively to the sample centre $d/2$) depends on the space distributions of charge density $q_v(z)$ and the slow relaxational polarisation $P_r(z)$ according to the following relation:

$$p_z = \int_{-d/2}^{d/2} q_v(z) \left(\frac{z}{d} - \frac{1}{2} \right) dz + \frac{1}{d} \int_{-d/2}^{d/2} P_r(z) dz, \quad (3)$$

where z is co-ordinate along the sample thickness. A one-dimensional case of space distributions is assumed. The equivalent charge q_z is a sum of the charges stored in the fabric sample:

$$q_z = \int_{-d/2}^{d/2} q_v(z) dz \quad (4)$$

In order to estimate the activation energy and lifetime of the electret charges, the discharging process was thermally stimulated and the samples were heated at a constant rate $b = 3$ K/min. The stability of the electret filter fabrics was estimated from thermograms of $U_z(T)$ using the method described in [12].

Humidity conditioning

The selected charged samples of P1 and P2 fabrics were next placed in a controlled humidity chamber at the temperature of 24 °C for 18 days at relative humidities of 39%, 78%, and 94%. CaCl₂ solution was used for RH 39%, Na₂S₂O₃ solu-

tion for 78%, and CuSO₄ for 94%. After conditioning, the electrostatic parameters were measured at normal conditions, and the thermally stimulated U_z was also measured and analysed.

Results

Isothermal decay of equivalent surface voltage

The decay of the equivalent surface voltage measured from both sides of the charged samples is shown in Figure 2. Positive voltage U_z concerns the surface directed to the positive corona electrode during charging. Initially the charges from shallow traps are liberated, and a rapid decay of voltage is observed. After 18 days the U_z is stable because the remaining charge cannot escape from the deep traps. The increase in negative voltage observed for P2 fibres results from the decay of the opposite charge. That is why the bipolar charges can be trapped at the same side of the fibre sample.

Croitorou parameters

30 samples were corona-charged from a high-voltage needle electrode under a +10 kV potential for 60 s under normal atmospheric conditions. Next, the equivalent voltages were measured from both sides of every sample, and the Croitorou parameters were calculated. Column 3 in Table 1 shows the average values of p_z and q_z directly after charging. The negative and high value of momentum p_z of both types of nonwovens indicates that homocharges are accumulated on both sides of the nonwovens. The positive charge on side a comes from the positive corona, and the negative charge on side b comes from the bottom electrode, which is grounded during charging. The P2 nonwovens show a greater ability to accumulate charges than P1. The high value of the total charge q_z stored in nonwoven P2 results from positive charge transferred from the area near side b while tearing off the sample from the grounded electrode (back ionisation). The value of

Table 1. The charge stability of P1 and P2 nonwovens under humid conditions. Croitorou parameters after conditioning the electret samples at relative humidity of 39%, 78% and 94% by 18 days at the temperature of 24 °C.

Croitorou parameters	Nonwoven types	Directly after charging	After conditioning at RH		
			39%	78%	94%
p_z pC/cm ²	P1	-790	-440	-330	-300
	P2	-990	-770	-630	-310
q_z pC/cm ²	P1	-50	-70	-20	-40
	P2	+590	-50	+90	+200

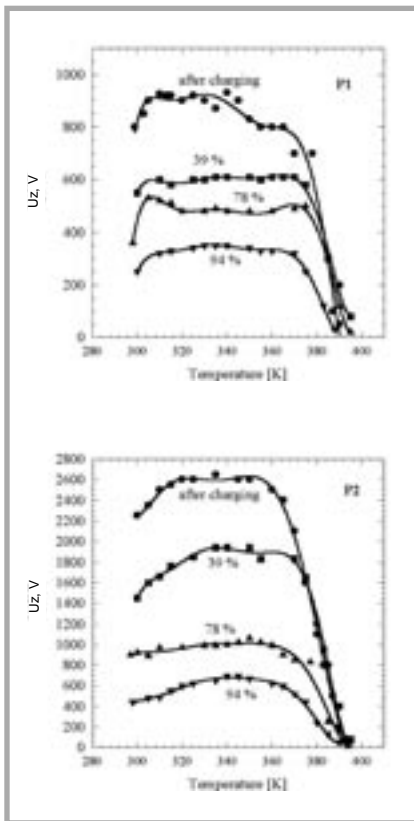


Figure 3. Thermograms of TSESV for selected samples of fabrics: a) P1 and b) P2.

the remaining total charge q_z changes accidentally from sample to sample.

After charging, the electret nonwoven samples were conditioned in a humid atmosphere with RH levels of 39%, 78% and 94% by 18 days. 10 samples for each RH were placed in a controlled humidity chamber. As seen from Table 1, humidity affects the values of the Croitorou parameters. The equivalent charge momentum p_z decreases as humidity increases. This is the result of reducing the ions and electrons, which are poorly bounded to the surface, by water molecules. P2 nonwovens show better water repellence than P1.

Thermally-stimulated equivalent surface voltage

Figures 3a and 3b show the temperature runs of thermally-stimulated equivalent surface voltage (TSESV) for nonwovens just after charging and after conditioning at controlled humidity. TS curves were measured after corona charging from high-voltage needle electrode under +10 kV potential for 60 s under normal atmospheric conditions (top curves), and after conditioning in a controlled humidity chamber at the temperature of 24 °C for 18 days at relative humidity of 39%,

78%, and 94%. Samples were discharged at linear heating rate $b = 3$ K/min.

Very fast voltage decay is observed at temperatures higher than 370 K, and at temperatures higher than 390 K voltage U_z drops to zero. The initial values of equivalent voltage are higher for P2 fibres in comparison to P1. Conditioning at higher humidity decreases these voltages significantly; the higher RH the lower initial voltage.

The TSESV thermograms were used to calculate the activation energy of the discharging process W using the following equation:

$$W = -\frac{kT_n^2}{U_z} \left. \frac{dU_z(T)}{dT} \right|_{T=T_n}, \quad (5)$$

where T_n is the bending point of the thermogram. At this point, the first derivative of the curve reaches its minimum value. The lifetime of the fabric samples at temperature T was estimated from the following equation:

$$\tau = \frac{kT^2}{bW} \exp\left(\frac{W}{k} \left(\frac{1}{T} - \frac{1}{T_e}\right)\right). \quad (6)$$

where T_e is the temperature at which the TSESV equals value U_{zm}/e , U_{zm} is the amplitude of the thermogram and e is the natural logarithm radix.

The T_n values are within the range from 379 K to 384 K, and those of T_e within the range from 380 K to 385 K. The calculated values of the activation energies and lifetimes at 293 K for the two kinds of PP nonwovens, P1 and P2, are shown in Table 2. The activation energy of the discharging process is high, and equals about 1.6 eV. This means that charges are not liable to decay, although they are firmly trapped in the polypropylene structure. Humidity does not have any major effect on the traps' depth. Therefore, the decrease of the nonwoven lifetimes is not caused by the trapping

structure of the polymer, but by reducing the charges by water molecules, resulting in the decrease in the surface charge. The greater the RH, the greater the decrease in the surface charge.

Interpreting the results, it can be concluded that extremely low conductivity and the existence of structural defects or traps are the main material properties affecting the stability of the charge of nonwovens. The charges injected during the corona charging process are accumulated in these traps. These traps are deep, so the escape of the charges into the conduction band of the polymer is negligible, and so the stored charges are not easily lost. The PP electret nonwovens also remains sufficiently stable regarding humidity. The good moisture stability results from the hydrophobic property of PP and its water repellency. The P2 nonwovens show better electret properties than P1, which may result from their different fibrous structure. The fibres in P2 nonwoven are thinner, which results in a higher surface-to-volume ratio. Injected charges are stored in the polymeric surface traps. Their amount at P2 surfaces is significantly higher in comparison to P1 nonwovens. The lower diameter of fibres is also advantageous for the filtering operation. The local electrical field in nonwovens created by an electret fibre can be rather high, which makes the filtration process more efficient.

Conclusions

Two types of PP fibre samples, P1 and P2, have been compared. Both fibres have sufficiently good electret properties to guarantee a lifetime of one year or even more at relatively high humidities. The thicker and nappier P2 nonwovens show higher service lifetimes than P1. The fibres of P2 nonwovens are also thinner compared to those in P1, which results in a higher surface to volume ratio, and this is favourable for dust collection.

Table 2. Activation energies and lifetimes of two kinds of PP nonwovens, P1 and P2. Conditioning by 18 days at various RH decreases the lifetime of nonwovens.

Kind of nonwoven	Sample conditioning at RH	W, eV	τ , years
P1	non-conditioning	1.60	1.8
	39%, 18 days	1.55	1.3
	78%, 18 days	1.52	1.2
	94%, 18 days	1.48	1.0
P2	non-conditioning	1.62	2.3
	39%, 18 days	1.61	2.2
	78%, 18 days	1.61	2.1
	94%, 18 days	1.60	2.0

The effect of the conditioning at higher humidities is lower for the P2 nonwovens in comparison to the P1 samples. The P2 nonwovens lifetime shows practically no dependence on humidity conditions. In summary, the P2 nonwovens are favourable for such applications, because of their better electrostatic, filtration and humidity resistance properties in comparison to the P1 samples.



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