Investigation of Electret and Filtering Properties of Polypropylene-Based Nonwoven Fabrics and Its Composites with 2 vol% of Silicon Dioxide Inclusions

Anna A. Guliakova
Herzen State Pedagogical University
48 Moika River Embankment
St. Petersburg, 191186, Russia

Mansur F. Galikhanov, Laysan R. Galeeva and Svetlana V. Gilfanova
Kazan National Research Technological University
68 Karl Marx Street
Kazan, 420015, Russia

Peng Fang
CAS Key Laboratory of Human-Machine Intelligence-Synergy Systems
Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences
1068 Xueyuan Avenue
Shenzhen, 518055, China

ABSTRACT

The electret characteristics of polypropylene (PP) nonwoven fabrics processed by melt-blowing and its composites with 2 vol% of silicon dioxide (SiO$_2$) are studied in this work. The surface potential $V_s$, effective surface charge density $\sigma_{ef}$ and electric field strengths $E$ as well as their filtration efficiency are reported. Improvement of electret properties of PP filled with SiO$_2$ in comparison with the samples without filler is observed. It is seen that PP samples poled in a corona discharge show lower filtration rate than the non-poled ones. The electret nonwoven fabrics with improved filtration characteristics are obtained on the basis of PP with SiO$_2$ inclusions.

Index Terms — electret, nonwoven fabrics, polypropylene, composite films

1 INTRODUCTION

NEW potential applications of electret materials appear presently even in the traditional fields of their use. Electret air filter elements used for gas-solid separation (dust particles) are now frequently employed for air purification from nanoparticles, liquid (aerosol) particles and even bio-contamination [1–4]. Electret filters have already gained significant importance in purifying liquids from mechanical impurities [5]. Moreover, membranes being in the electret state allow to intensify the separation of heterogeneous mixtures comprised of different liquids [6, 7]. Most commonly, efficiency directly depends on the value and electret characteristic stability of materials employed.

Polypropylene (PP) nonwovens obtained by means of melt-blown technique with the subsequent electretizing are frequently used for electret filters fabrication [5, 8–10]. Such materials possess unique structure and complex of properties which can be adjusted during fabrication process. Thus, improvement of temperature and thermal stability of their electret properties is required.

The use of different chemical additives including fine hard particles as polymer fillers is one of the simplest and effective ways to improve electret properties of polymers [11–16]. It was shown in [15, 16, 21] that in particular small (2-4 vol%) concentrations of additives could improve the charge stability in polymers. A higher filler concentration could have negative impact on the electret properties values of composite materials.

The aim of the present study is the preparation of polypropylene-based nonwoven fabrics with different composition as well as investigation of electret and filtering properties.
2 EXPERIMENTAL

2.1 PREPARATION OF PP COMPOSITES AND NONWOVEN FABRICS

In this study, nonwoven fabrics based on polypropylene (PP-YX37F, TT (Technical Terms) 20.16.51-136-05766801-2015, with a density of 0.9 g/cm³) as well as PP composites with 2 vol% of silicone dioxide (SiO₂, A-300 (Aerosil)) with a density of 2.6 g/cm³ and mean primary particles diameter of 10 nm used as a filler were investigated.

The preparation of Aerosil concentrate by means of PP mixing with 20 vol% of a filler was performed using single screw extruder SJ-25/25 (with a screw diameter of 25 mm and extruder lengths to diameter ratio of 25) at 190 °C.

The preparation of PP nonwoven fabrics with a density of 25 g/m² was performed by extrusion using melt-blown technique. During fabrication process, PP mixed in the barrel of extruder with aerosil concentrate in the ratio of 10 to 1 was heated up to 265 °C (close to the polymer breaking temperature in order to minimize its viscosity). Then, PP was forced through the small holes in the distribution die spinneret. Hot air convergent flows catch the PP flows and form fibers with a small diameter. These fibers move to the metal drive where they are thermally bonded in the overlapping places in a non-systematic order forming finally the nonwoven material.

The nonwoven PP fabrics were rolled up and stored at room temperature and humidity in paper bags.

2.2 CORONA CHARGING AND ELECTRET PROPERTIES MEASUREMENT

PP fabrics were poled in a negative corona discharge (15 kV) by means of corona point mounted above the extruder pick-up drive in ambient atmosphere. The poled samples were stored in paper envelopes at room temperature and humidity. For IR-spectroscopy measurements as well as for the electret properties investigations, corona electrets were prepared in the laboratory conditions. The samples with the size of 80x80 mm were cut from the non-poled fabrics which were preliminary annealed in a heating chamber at 90 °C during 600 s and subsequently poled in a negative corona discharge (15 kV, poling time 30 s) (Figure 1).

The surface potential \( V_s \) the effective surface charge density \( \sigma_{ef} \) and the electric field strengths \( E \) were measured by means of periodic shielding of measuring probe method using electrostatic field tester (model IPEP-1, the Republic of Belarus).

For thermally stimulated surface-potential decay (TSSPD) measurements a Kelvin probe (electrostatic voltmeter, model 341, TREK Inc., NY, USA) and a temperature-controlled heating plate were used, the temperature was measured with a platinum resistor inserted into the plate.

2.3 STRUCTURE AND PROPERTIES OF PP COMPOSITES AND NONWOVEN FABRICS

A Bruker Alpha-P® FTIR spectrometer operated in ATR mode at room temperature was used to study the IR spectra of PP melt-blown fabrics.

Initial pressure drop \( \Delta P \) was measured using clean filter under nominal air volume flow rate of 1.0 m³/s measured according to GOST (Russian State Standard) REN 779-2014. Method involves pressure measurements in the two chambers of a testing set (before and after filter) downstream with the gas flow with the subsequent subtraction of obtained values.

Sodium chloride aerosol \( D_{NaCl} \) and oil spray \( D_{oil} \) permeability was determined with equation (1):

\[
D = \left( \frac{C_l}{C_b} \right) \cdot 100 \%
\]

where \( C_l \) – NaCl or oil spray content in the canal section placed after filter and \( C_b \) - NaCl or oil spray content in the canal section placed before filter.

Materials filtering capacity was determined as the liquid filtration time through the samples under investigation. Experiment includes the following steps: putting of the samples in the dry state inside Buchner filter (filter crucible) with subsequent wetting with distilled water and drying within several minutes in the presence of working vacuum pump. Then, filter was half-filled with 50 ml of trolley oil (1 %), the pump was turned on so that the liquid started flowing to the Bunsen receiving flask. As the solvent passed through the filter, the rest of liquid was added to the crucible. When all liquid passed through the filtering material, the vacuum pump was disconnected.

Prepared nonwoven fabrics could be applicable both for gaseous and liquid media. It was of interest to measure using this technique also the filtering capacity for paper filters.

3 RESULTS

3.1 ELECTRET PROPERTIES OF PP NONWOVEN FABRICS

First, nonwoven fabrics based on polypropylene and its composites with 2 vol% of SiO₂ were prepared. It was found that an introduction of a filler does not change the melt-blown technological conditions: the extruder temperature, the differential pressure in extruder die and the fabric cooling rate could remain the same.
Second, electret properties of PP nonwoven fabrics were investigated. The charge injection (ions, electrons) with its subsequent trapping occurs during corona discharge poling of polymer materials [17, 18]. Impurities, structural anomalies, phase boundaries between crystalline and amorphous regions as well as air-polymer and polymer-filler interfaces could serve as traps. The values of electret characteristics and their stability depend on the injected charges quantity, their capability to polarize fragments of polymer macromolecules as well as on traps depths and charge relaxation rate.

Polypropylene films possess sufficiently high electret properties [19, 20]. The traps of injected charges in PP are structural (intermolecular), their energy depth is equivalent to the lifetime determined by the molecular chains mobility. It is believed that the deepest charge traps are created as a result of an oxidative degradation of PP crystalline phase.

PP melt-blown fabrics are prepared by extrusion process when the polymer melt being approximately at its breaking temperature is forced through extruder spinneret in the form of thin continuous threads. This process is accompanied by an intense progress of oxidation. The analysis of the IR spectra of PP-based nonwoven fabrics showed that along with the bands assigned to the fluctuations of –CH₂ (~2880 cm⁻¹, ~1350 cm⁻¹, etc.) and –CH₃ groups (~2960 cm⁻¹, ~1460 cm⁻¹, etc.) sufficiently strong bands appear in the region of 1700-1750 cm⁻¹ indicating the presence of defects (carbonyl groups and unsaturated fragments). Figure 2 shows IR spectra of melt-blown fabrics based on polypropylene.

![Figure 2. IR spectra of melt-blown nonwoven fabrics based on polypropylene: 1 – PP, 2 – PP with 2 vol% of SiO₂.](image)

Absorption bands between 1060-1090 cm⁻¹ correspond to the Si-O stretching modes. A small amount of SiO₂ in the composite material (2 vol%) manifests in insignificant differences in IR-spectra for PP samples and PP with SiO₂ within the mentioned region.

However, PP nonwoven fabrics possess lower electret characteristics values in comparison with polymer films. This could be explained by the presence of an interfibrillary spaces (transverse pores) in the samples (Figure 3). During sample poling in corona discharge, such spaces favour to the majority of the charge carriers to reach the lower electrode thus flying over the polymer fibers.

![Figure 3. Photograph of PP melt-blown nonwoven fabric obtained by means of Bresser Junior 40-1024x microscope with integrated camera.](image)

The investigation showed that the presence of 2 vol% of SiO₂ inclusions in PP fibers has no significant influence on the initial characteristic values for nonwoven fabrics. However, after some storage time the values of the surface potential $V_e$, the effective surface charge density $\sigma_{ef}$, as well as the electric field strengths $E$ for fabrics based on PP with SiO₂ inclusions become higher than corresponding values for the samples without filler (Table 1).

**Table 1. Electret properties of PP nonwoven fabrics.**

| Nonwoven fabric material | $V_e$, kV | $\sigma_{ef}$, $\mu$C/m² | $E$, kV/m |
|-------------------------|-----------|--------------------------|-----------|
| initial values (immediately after charging) | | | |
| PP | 1.17 | 26.65 | 0.20 |
| PP + 2 vol% of SiO₂ | 1.08 | 24.75 | 0.18 |
| values after 30 days of storage | | | |
| PP | 0.14 | 9.10 | 0.08 |
| PP + 2 vol% of SiO₂ | 0.29 | 12.40 | 0.10 |

Several factors could be responsible for improvement of the electret properties for PP filled with SiO₂ in comparison with the samples without filler:

- the difference in electrical and dielectric properties of PP and its composites with aerosil;
- the presence of oxygen-containing groups in the PP macromolecules as a result of mechanochemical degradation during mixing process of the components in composite;
- the presence of traps for injected charges at the polymer-filler interface.

An introduction of a filler in the samples does not lead to a significant change in PP volume and specific surface resistivity. It can be concluded that changes of electret characteristics of PP nonwoven fabrics with the filler are not connected with the change in conductivity.
An IR spectra analysis helps to investigate changes in PP surface chemical structure after filler introduction (Figure 2). The intensity of bands associated with the fluctuations of oxygen-containing groups (1700-1750 cm⁻¹) was not significantly changed indicating an insignificant macromolecular oxidation process in PP during the composite material fabrication. Thus, this is not the main reason for the change of electret properties with filler introduction.

The surface potential decay method (TSSPD) was employed for the investigation of electret properties of PP and its composites (Figure 4).

The filler introduction has practically no influence on the stability of electret properties of the polymers under investigation during thermal treatment.

### 3.2 FILTERING PROPERTIES OF PP NONWOVEN FABRICS

The influence of electret state on materials filtering capability can be determined using the electret characteristics values of PP nonwoven fabrics. Thus, it is important to determine the barrier properties of materials and electrets based on them.

The results of filterability investigations show that electret PP fabrics have significantly lower sodium chloride aerosol $D_{NaCl}$ and oil spray $D_{oil}$ permeability at the same air resistance index (Table 2).

| Non-woven fabric material | $\Delta P_{air}$, Pa | $D_{NaCl}$, % | $D_{oil}$, % |
|---------------------------|----------------------|--------------|--------------|
| PP                        | 69                   | 7.66         | 11.07        |
| PP + 2 vol% SiO₂          | 67                   | 7.89         | 11.01        |
| PP (electret)             | 65                   | 0.73         | 1.50         |
| PP + 2 vol% SiO₂ (electret)| 68                   | 0.70         | 1.53         |

This result be explained by the working peculiarity of electret filters: the capability to attract neutral particles by means of electric forces of charged fibers [5, 8-10]. This allows to improve the working efficiency of the filtering material.

High filtration capacity values mean that the rate with which the filterable medium passes through a filter becomes lower. During the filtering capacity evaluation, it was determined that PP samples poled in a corona discharge obtain lower filtration rate than the non-poled ones (Table 3).

| Nonwoven fabric material | Filtering capacity, s |
|-------------------------|----------------------|
| PP                      | 2.4                  |
| PP + 2 vol% SiO₂        | 2.5                  |
| PP (electret)           | 4.5                  |
| PP + 2 vol% SiO₂ (electret) | 4.6               |

Such different could be due to the fact, that materials unipolar corona charging leads to the energy barrier formation. In order to overcome it, the driving force of the liquid flow through the fiber material is spent. The polarization charge has influence on wetting, absorbability and diffusion processes [22, 23] which always occur during filtration process through PP nonwoven fabrics. The displacement of the polar fluid molecules in the fibers volume (over the fibers surface) becomes difficult because of the electrostatic interaction with electric field of PP fiber electrets. This, in turn, leads to an increase of work that liquid molecules have to perform against surface tension on the solid-liquid interphases where the electric potential jump occurs.

The dependence of diffusion processes on the presence of electric field is known in the literature [18]. The investigation of influence of metal-polymer electrets based on polyvinylbutyral and pentaplast charge on the electrolyte diffusion into the polymer coating showed that diffusate liquid mass decreased by 3-5 times with the increase of charge [18]. This could be due to the fact that dielectric liquid diffusivity is inversely proportional to the dynamical viscosity which, in turn, increases in the electric field. Thus, the field action should cause the decrease of diffusivity.

### 4 CONCLUSIONS

Filling of PP nonwoven fabrics with 2 vol% of SiO₂ (Aerosil) has no influence on the melt-blown technological conditions.

The presence of a filler does not show significant influence on the surface potential, effective surface charge density and electric field strengths initial values for nonwoven PP fabrics. However, these characteristics become higher for fabrics based on PP with SiO₂ inclusions than for the samples without filler after storage time.

Improvement of the electret properties of PP filled with SiO₂ in comparison with the samples without filler could be explained by several factors: the presence of traps for injected charges at the polymer-filler interface; the presence of oxygen-containing groups in the PP macromolecules (as a
result of mechanical-chemical degradation during mixing process in composite); the difference in electrical and dielectric properties of PP and its compositions with SiO₂ inclusions.

The introduction of a filler has no significant influence on the stability of electret properties of the polymers during thermal treatment.

Electret PP fabrics have significantly lower sodium chloride aerosol \( D_{NaCl} \) and oil spray \( D_{up} \) permeability at the same air resistance index. It was determined that the samples poled in a corona discharge obtain lower filtration rate than the non-poled ones.

**ACKNOWLEDGMENTS**

A. A. G. is indebted to the Chinese Academy of Sciences (CAS) President’s International Fellowship Initiative (project number 2019VMB0004) for granting a research fellowship.

P. F. acknowledges financial support within the National Key Research & Development Program of China (2017YFA0701103), the CAS Youth Innovation Promotion Association (2018395), the Shenzhen Basic Research Program (JCYJ20170818163724754), and the Shenzhen Engineering Laboratory of Neural Rehabilitation Technology.

**REFERENCES**

[1] M. Goel, “Electret sensors, filters and MEMS devices: New challenges in materials research,” Current science, vol. 85, no. 4, pp. 443–453, 2005.

[2] X. Li et al., “Electreted polyehteramide-silica fibrous membranes for enhanced filtration of fine particles,” J. Colloid and Interface Science, vol. 439, pp. 12–20, 2015.

[3] H. Zhang et al., “Design of electret polypeethylene melt blown air filtration material containing nucleating agent for effective PM2.5 capture,” RSC Adv., vol. 8, pp. 7932–7941, 2018.

[4] N. Mao, *Engineering design of high-performance filter fabrics.* Engineering of High-Performance Textiles. Elsevier, 2018, pp. 435–488.

[5] A. Mellinger, F. C. Gonzalez, and R. Gerhard-Multhaupt, “Ultraviolet-induced discharge currents and reduction of the piezoelectric coefficient in cellular polyeletroneum films,” Appl. Phys. Lett., vol. 82, no. 2, pp. 254–256, 2003.

[6] V. O. Dryakhlov et al., “Effect of parameters of the corona discharge treatment of the surface of polycrystalline membranes on the separation efficiency of oil-in-water emulsions,” Surface Engineering and Applied Electrochemistry, vol. 51, no. 4, pp. 406–411, 2015.

[7] A. Kilic, E. Shim, and B. Pourdeyhimi, “Electrostatic Capture Efficiency Enhancement of Polyeletroneum Electret Filters with Barium Titanate,” Aerosol Science and Technology, vol. 49, no. 8, pp. 666–673, 2015.

[8] A. P. Viroveva, T. A. Yovcheva, and M. F. Galikanov, “Electret properties of PP/ZrO₂ and PP/CuO composite films,” IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 3, pp. 1343–1348, 2015.

[9] M. A. Ramazanov, F. V. Hajiyeva, A. M. Magerramov, and U. A. Gasanova, “Effect of a corona discharge on the morphology and photoluminescence intensity of nanocomposites based on polyeletroneum (PP) and zirconia (ZrO₂) nanoparticles,” Surface Engineering and Applied Electrochemistry, vol. 53, no. 3, pp. 213–217, 2017.

[10] G. Sessler and R. Gerhard-Multhaupt, Electrets, 3rd Ed., Laplacian Press, Morgan Hill, California, USA, 1999.

[11] V. M. Estelman, L. S. Pinchuk, and V. A. Goldade, “Effect of a corona discharge on the morphology and photoluminescence intensity of nanocomposites based on polyeletroneum (PP) and zirconia (ZrO₂) nanoparticles,” Surface Engineering and Applied Electrochemistry, vol. 53, no. 3, pp. 213–217, 2017.

[12] G. Sessler and R. Gerhard-Multhaupt, “Ultraviolet-induced discharge currents and reduction of the piezoelectric coefficient in cellular polyeletroneum films,” Appl. Phys. Lett., vol. 82, no. 2, pp. 254–256, 2003.

[13] A. A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

[14] A. Kilic, E. Shim, and B. Pourdeyhimi, “Electrostatic Capture Efficiency Enhancement of Polyeletroneum Electret Filters with Barium Titanate,” Aerosol Science and Technology, vol. 49, no. 8, pp. 666–673, 2015.

[15] A. P. Viroveva, T. A. Yovcheva, and M. F. Galikanov, “Electret properties of PP/ZrO₂ and PP/CuO composite films,” IEEE Trans. Dielectr. Electr. Insul., vol. 22, no. 3, pp. 1343–1348, 2015.

[16] M. A. Ramazanov, F. V. Hajiyeva, A. M. Magerramov, and U. A. Gasanova, “Effect of a corona discharge on the morphology and photoluminescence intensity of nanocomposites based on polyeletroneum (PP) and zirconia (ZrO₂) nanoparticles,” Surface Engineering and Applied Electrochemistry, vol. 53, no. 3, pp. 213–217, 2017.

[17] G. Sessler and R. Gerhard-Multhaupt, Electrets, 3rd Ed., Laplacian Press, Morgan Hill, California, USA, 1999.

[18] V. M. Estelman, L. S. Pinchuk, and V. A. Goldade, Electrets in Engineering: Fundamentals and Applications, Boston-Dordrecht-London, Kluwer Acad. Publ., 2000, 281 p.

[19] A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

[20] A. Mellinger, F. C. Gonzalez, and R. Gerhard-Multhaupt, “Ultraviolet-induced discharge currents and reduction of the piezoelectric coefficient in cellular polyeletroneum films,” Appl. Phys. Lett., vol. 82, no. 2, pp. 254–256, 2003.

[21] A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

[22] A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

[23] A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

[24] A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

[25] A. G. Rozno et al., “Vliyanie radiacionnogo okisleniya na kinetiku eleetrotrazieii polipropylenia pri obluchenii electronami (in Russian),” Himiya Vysokhi Energii, vol. 26, no. 6, pp. 473–477, 1992.

Anna A. Guliakova was born in Saint-Petersburg, Russia, in 1985. She studied physics at the Herzen University of Saint Petersburg (Russia) where she obtained the B.Sc. and M.Sc. degrees in 2006 and 2008, respectively. In 2010 she received the Grant of the President of the Russian Federation to study abroad and joined the Applied condensed-matter physics group at the University of Potsdam (Germany). She received the Ph.D. degree in condensed-matter physics in 2012. Her research activities are focused on the investigation of polymer electrets by means of thermo-activation spectroscopy. Since 2013 she has been a member of the teaching staff at the Herzen University. She is currently an Associate Professor at the Department of General and Experimental Physics. In 2016 and 2018 she has been awarded a scholarship by the DAAD. She is a Member of the IEEE Dielectrics and Electrical Insulation Society.

Mansur F. Galikanov was born in Kazan, Russia in 1972. He received the specialist degree from the Institute of Polymers, Kazan State Technological University, Kazan, Russia in 1995, the Ph.D. degree from the Kazan State Technological University in 1999 and Doctor of Technical Sciences degree (the highest research degree in this country) from the KSTU in 2010. He has been being full professor at the Department of Processing Technology of Polymers and Composite Materials of the Kazan National Research Technological University, Kazan, Russia since 2009. Scientific interests of Prof. Galikanov include properties and structure investigation of electrets based on such polymer compositions as filled polymers, polymer blends, multilayer and sandwiched materials.

Laysan R. Galeeva was born in Kazan in 1987. She graduated from the Polymers Institute of the Kazan State Technological University in 2009. She was awarded the Ph.D. degree in Technical Sciences in 2013. Now she works as an associate professor at the Department of Processing Technology of Polymers and Composite Materials of the Kazan National Research
Technological University. The area of scientific interests is aimed at obtaining and researching the properties of modified materials based on pulp-and-paper and polymer compositions.

Svetlana V. Gilfanova was born in Yelabuga, Russia in 1994. She studied at the Institute of Polymers, Kazan State Technological University, where she obtained the B.Sc. and M.Sc. degrees with honors in 2017 and 2019, respectively. Her research interests include the study of the properties of polymer nonwoven filters and electrets based on them.

Peng Fang received the Bachelor’s degree in applied physics from the University of Science and Technology of China in 2004, the joint Master’s degree in polymer science from the Humboldt University of Berlin and the University of Potsdam in 2006, and the Doctor’s degree in applied physics from the University of Potsdam in 2010. From 2010 to 2012, he worked as a Senior R&D Engineer in a company in Shenzhen, China, to develop piezoelectret-based electro-acoustical transducers like microphones and speakers. Since 2012, he has been with the Shenzhen Institutes of Advanced Technology (SIAT), Chinese Academy of Sciences (CAS), and is currently a Professor at SIAT, CAS. His current research interests include the functional materials and transducer devices, e.g., polymeric electrets and their applications on biomedical engineering, and piezo/ferroelectrets and their transducer applications in human-machine interface. He is an IEEE Senior Member, an International Advisory Committee Member of the IEEE International Symposium on Electrets (ISE), an Academy Committee Member of the Chinese National Conference on Electrets (CNCE) and the Chair of the 3rd CNCE.