Unprecedented SPEEK-trimetal oxide composites: physicochemical and electrochemical performance in fuel cell

Gandhimathi Sivasubramanian, Senthil Andavan Gurusamy Thangavelu, Berlina Maria Mahimai, Krishnan Hariharasubramanian, Paradesi Deivanayagam

1Department of Physics, SRM Valliammai Engineering College, Kattankulathur, Chengalpattu District, Tamilnadu, India, 603203
2Department of Chemistry, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu District, Tamilnadu, India, 603203

ORCID: 0000-0003-2894-0478

*Corresponding author Email: paradesi77@yahoo.com or krishveni63@gmail.com

Abstract

Advanced polymer composite membranes were prepared from a linear sulfonated poly(ether ether ketone) (SPEEK) with bismuth cobalt zinc oxide [BCZO, (Bi2O3)0.07(CoO)0.03(ZnO)0.90] nanopowder as an inorganic additive for the application of H2-O2 fuel cell. Morphology data tend to provide evidences for the incorporation of BCZO into SPEEK polymer. Indeed, composite membrane loaded with 7.5 wt.% of BCZO was identified to uptake maximum water, while the pristine SPEEK membrane occurred to retain only 24.0 %. As such SPEEK matrix loaded with 7.5 wt.% of BCZO was found to exhibit the maximum proton conductivity of 0.030 S cm⁻¹, whereas the pristine membrane was restricted to 0.021 S cm⁻¹. Evidently, TGA profile of the composite membrane was measured to exhibit sufficient thermal stability to employ as electrolyte in fuel cell. The membrane electrode assembly of pristine SPEEK and SP-BCZO-7.5 wt.% membranes were fabricated and studied for their electrochemical performance. Indeed, the characteristics of newly developed composite membranes led to possess incredible feature towards fuel cell applications.

Keywords
Poly (ether ether ketone), composite, fuel cell, electrolyte membrane, proton conductivity
1. **Introduction**

Global energy consumption for the next century as well as the depletion of fossil fuel insists the need for other alternative sources of energy [1-3]. Fossil fuel consumption also leads to global pollution, which is considered as a major threat for the developing countries. Burning of fossil fuel for the generation of energy tends to release more amount of noxious carbon dioxide and greenhouse gases, which causes changes in climatic conditions [4-8]. Hence, the world is prompting to move towards the clean energy technology. Fuel cell is one of the pollution free energy conversion devices, which can be competent with conventional devices [9-12]. The major advantage of fuel cells exists in their ability to reduce the power loses upon exclusion of the intermediate steps essential with similar diesel powered engine. In accordance with the literature reports, Nafion® membrane is the standard material for fuel cell applications [13-17]. However, the technology has to resolve the issues associated with Nafion based membranes such as expensive and complex synthesis, low proton conduction at high temperatures and environmental concern [18-20]. Arylene hydrocarbon based polymer electrolyte membrane is identified as one of the suitable alternative to Nafion towards electrolysis and fuel cell applications. Moreover, perfluorinated membranes are expensive and difficult to process, whereas the choice to use hydrocarbon based polymers in different physical forms would be an imperative option [21-24].

In the current perspective, sulfonated poly ether ether ketone (SPEEK) has been chosen as an alternative for Nafion, since it possesses excellent oxidative stability, mechanical properties, thermal stability, exceptional tensile strength, viable cost and strong chemical resistance. Thus, our present effort emphasizes on synthesis and characterization of polymer nanocomposite membranes based on SPEEK. Indeed, the development of organic-inorganic composite membrane is an intriguing strategy for the enhancement of excellent thermal behaviour and intrinsic conductivity [25-28]. The approach towards the fabrication of a robust hybrid membrane by the incorporation of nanomaterials into polymer matrix was executed to improve the characteristics of the membrane. The inorganic additives in nanodimension such as SiO₂, TiO₂, ZrO₂, P₂O₅ etc., have been chosen often for the preparation of such composite. The fundamental properties of the polymers can be remarkably tuned upon incorporation of inorganic nanoparticles which influences to improve the physical and structural properties of the membranes. The interfacial interaction among the nanoparticles and polymer matrix enhance the membrane performance [29,30].

Inorganic nanoparticles reveal high-k value, which occur to enhance the effective dielectric properties of the polymer nanocomposite without compromising the high intrinsic dielectric strength of the polymers matrix [31]. The enhancement of dielectric constant of the polymer composites can be attributed to free oscillation of polymer chain and side chains at elevated temperatures. This induces the dissociation of ion pairs, which causes increase in ionic conductivity [32]. To the best of our knowledge, this is the first example to explore with investigation of influence due to incorporation of a trimetal oxide, BCZO into the SPEEK polymer. The above strategy prompts us to explore with studies of physicochemical, thermal and electrochemical properties of the newly developed nanocomposite membranes.
2. Experimental procedures

2.1 Materials

Poly(ether ether ketone) was gifted by Gharda chemicals limited, Mumbai, India under the trade name of GATONE 1100. Bismuth cobalt zinc oxide \([\text{Bi}_2\text{O}_3]_{0.07}\text{CoO}_{0.03}\text{ZnO}_{0.90}\) nanopowder (<100 nm particle size based on BET) and concentrated sulfuric acid (99.9 %) were procured from Sigma Aldrich. N, N-dimethyl formamide (DMF) was supplied by sisco research laboratories, Mumbai, India.

2.2 Preparation of SPEEK/BCZO polymer nanocomposites

The SPEEK polymer has been synthesized with reference to the previous report [33]. FT-IR data of SPEEK sample was collected to support the sulfonation over PEEK. A known quantity of SPEEK polymer was dissolved in DMF at 50 °C for 30 min. to obtain a solution of homogeneous medium. An appropriate quantity of BCZO nanopowder (2.5 to 10.0 wt.%) was slowly added to the pristine SPEEK solution. The temperature of the reaction mixture was raised up to 60 °C and maintained at same condition for 60 min. The resultant viscous polymer composite was treated for 15 min. under probe sonicator in ice bath and directly transferred uniformly on the surface of flat glass plate to cast as film upon incubation at closed chamber for 24 h. Further, the polymer nanocomposite membrane casted in those glass plates were subjected to stepwise heating at 80 °C for 8 h, 100 °C for 6 h and 120 °C for 3 h in preheated hot air oven. Later, those glass plates coated with composite were dipped in deionized water to recover the membrane samples. Further, the resultant polymer nanocomposite membrane samples were dried at 100 °C under vacuum for 8 h prior to investigate the structural and physicochemical characterizations. Fig. 1 illustrates the schematic representation for the fabrication of SP/BCZO nanocomposites.

2.3 Method of characterization

Fourier transform infrared (FT-IR) instrument (Shimadzu IRTracer-100) equipped with attenuated total reflectance has been accessed to collect the vibrational spectroscopy data. The spectral data of control SPEEK and composite membranes were recorded over a wave number range between 4000 cm\(^{-1}\) and 500 cm\(^{-1}\). The existence of possible interaction among the functional groups (-SO\(_3\)H) along the SPEEK with BCZO in the polymer composites was detected by FT-IR data. The membrane surface morphology was examined using the field emission scanning electron microscope (FE-SEM) FEI, Quanta FEG200, USA. X-ray diffraction pattern of the polymeric membranes was acquired using PANalytical, X’Pert 3 diffractometer and those peaks confirm the loading of BCZO over the composite membrane. Contact angle measurement of all membrane samples was performed by sessile drop technique using Holmarc contact angle meter. The ion exchange capacity (IEC) of the samples was performed through back titration method. After drying the membrane sample, its protonic form was treated with 1.0 M brine solution at room temperature for a day. During this period, protons (H\(^+\) ions) exist in PEM material occurred to exchange with sodium ions (Na\(^+\)). Further, the solution was titrated against 0.01 M NaOH solution in the presence of phenolphthalein indicator. The IEC of the membrane samples was calculated using the following equation

\[
\text{IEC} = \frac{[\text{NaOH}] \times \text{T.V}}{\text{W}_{\text{dry}}}
\]
Where, \( N_{\text{NaOH}} \) and T.V are referred to concentration (mol/L) of sodium hydroxide solution and titre value (ml) respectively. The dry weight of PEM sample is denoted as \( W_{\text{dry}} \). Swelling ratio and water uptake measurements of the electrolyte membrane were carried out by quantifying the respective variation of length and weight of the samples before and after hydration step. The PEM samples were tested after immersion into deionized water at room temperature for a day. All these wet membrane samples have been taken apart and wiped its surface water using a neat tissue paper and membranes were dried further in a hot air oven at 105 °C overnight, subsequently measured for its length (\( L_{\text{dry}} \)) and weight (\( W_{\text{dry}} \)). The difference in length and weight prior and later to the hydration followed by drying membrane samples have been measured and estimated the values of swelling ratio and extend of water uptake (%) using the following equations (2) and (3) respectively.

\[
\text{Swelling ratio} = \left( \frac{L_{\text{wet}} - L_{\text{dry}}}{L_{\text{dry}}} \right) \times 100
\]

\[
\text{Water uptake} (\%) = \left( \frac{W_{\text{wet}} - W_{\text{dry}}}{W_{\text{dry}}} \right) \times 100
\]

The thermal properties of control and composite membranes have been studied by thermogravimetric analysis (Netzsch-STA-2500 REGULUS). Weight loss of these samples were recorded between the temperature range of 25 and 600 °C under nitrogen atmosphere at the heating rate of 15 °C/min. Electrochemical impedance study was conducted on each composite and bare SPEEK membranes using Biologic SP-300. Impedance value was collected over the variation of frequency range, 1 MHZ and 10 HZ at the amplitude of 10 mV. The resistance (R) value of each PEM sample was noted and respective conductivity (\( \sigma \)) value of membranes use to be estimated using membrane thickness (L), membrane area (A) and resistance (R) by the following equation 4.

\[
\sigma \text{ (S. cm}^{-1}) = \frac{L}{RA}
\]

3. Results and discussion

3.1 FT-IR spectral data

FT-IR spectral data of all samples use to be investigated to identify the functional group analysis of the control and nanocomposite membranes. Fig. 2 depicts the FT-IR spectra of SPEEK and composite membranes. The execution of sulfonation process on the PEEK polymer was confirmed by the vibrational spectral data, which depicted the characteristic stretching vibrations for O=S=O at 1078 cm\(^{-1}\) (asymmetric) and 1020 cm\(^{-1}\) (symmetric). A broad band was identified at 3445 cm\(^{-1}\) in the spectrum of SPEEK, which infer the existence of O–H group vibrations of water molecules absorbed as moisture. The presence of aromatic ether (R–O–R) linkage in polymers network was identified as sharp peak at 1220 cm\(^{-1}\). Also, the pair of intense signals at 1595 cm\(^{-1}\) and 1476 cm\(^{-1}\) found to be noticed to detect the vibrations of aromatic ring skeleton. The Bi–O–Bi vibration corresponds to bismuth oxide was observed in the composite membrane at 844 cm\(^{-1}\), which supported the incorporation of BCZO into SPEEK polymer [34].

3.2 XRD analysis

The X-ray diffraction pattern for the SPEEK and composite membranes are compared in Fig. 3. In the peak profile of composite, it evidently displays the incorporated peaks arisen due to the nanoparticles of BCZO. In general, SPEEK polymer exhibit broad peak with respect to its amorphous nature as compared to PEEK, since the sulfonation step strongly reduces the crystallinity. The pristine BCZO is used to show a sharp and
intense peak at 2θ value of 28° which found to be faded while it was incorporated to the control polymer, SPEEK. Hence, the low intense peaks of BCZO noticed in the composite membranes inferred that it occurs to reveal the interface or combination of both the crystalline and amorphous nature of those samples.

3.3 Morphology

The morphological feature of control SPEEK, BCZO nanoparticles and polymer composite membrane were depicted in Fig. 4. As such the control SPEEK sample has been noted to exist as nonporous as shown in Fig. 4a [35]. In Fig. 4d, the encapsulation of SPEEK with BCZO was manifested with respect to uniform distribution of nanoparticles over SPEEK matrix due to interface of both components on its composite morphology. In Fig. 4b and 4c, uniform size (~ 100 nm) of spherical shape mixed metal oxide nanoparticles with high surface area found to show prospective of potential functional chemical interactions with the polymers matrix. In practice, the incorporation of inorganic filler tends to create minor pores on the membranes, which enhanced to support on accommodating excess water molecules. Fig. S1 depicts the energy dispersive X-ray (EDX) spectra of SP-BCZO-5.0 and SP-BCZO-10 composite membranes and corroborates the presence of elements such as sulfur, bismuth, cobalt and zinc.

3.4 Contact angle measurement studies

The conventional approach was used to determine the wettability or hydrophilic nature of the membranes for the study of contact angle measurements. In case of minimum affinity observed to exist among the solid and liquid, the contact angle values measured with the liquid droplet deposited on the smooth surface are supposed to show values above 90°. In general, the contact angle values of polymers use to be less than 90° with respect to their hydrophilic nature due to the presence of polar groups such as hydroxyl, sulfonic acid and carboxylic acid [36]. In Fig. 5, the contact angle measurements of pristine SPEEK and composite membranes are depicted in detail. The findings of contact angle studies infer that SP-BCZO-7.5 membrane was noted to be more hydrophilic than that of neat SPEEK and SP-BCZO-10. It is perceived that the contact angle of SP-BCZO-10 was noted to be higher than SP-BCZO-7.5 due to the fact of agglomeration amidst BCZO in SP-BCZO-10.

3.5 Water uptake and IEC studies

The essential characteristic of PEM material use to be their capability to retain water molecules, since it is associated with dimensional stability and mechanical strength of the polymer backbone. In fact, water uptake capacity of any polymeric membranes can be directly related to the number of exchangeable ionic groups as well as the selectivity of fillers while it was used for the transformation into composite materials. The extent of water uptake values (%) of the pristine and polymer composite membranes are entered in Table 1. These values suggested that the incorporation of trimetal oxide occurred to influence over control polymer matrix to enhance the water uptake capacity of membranes. Exceptionally, the composite membrane loaded with 10.0 wt.% of BCZO found to be observed with reduced water uptake. The above declined water uptake capacity can be justified by the following two points, (i) increase in loading of di- or trimetal oxide use to reduce the membrane free volume and swelling activity. (ii) agglomeration of BCZO use to be progressive at higher loading concentration, led to drop in water uptake capacity. The comparison of water uptake and IEC of SPEEK and composite membranes are shown in Fig. 6.
Table 1 Physicochemical properties of SPEEK and polymer nanocomposite membranes

| Polymer code | Composition\(^a\) (g) | Thickness (µm) | IEC (meq.g\(^{-1}\)) | Water uptake (%) | Swelling ratio (%) |
|--------------|------------------------|----------------|-----------------------|------------------|-------------------|
| SPEEK        | 1.000                  | 33             | 1.62                  | 24.0             | 5.7               |
| SP-BCZO-2.5  | 0.975                  | 34             | 1.69                  | 27.3             | 6.1               |
| SP-BCZO-5.0  | 0.950                  | 32             | 1.76                  | 29.8             | 6.4               |
| SP-BCZO-7.5  | 0.925                  | 33             | 1.81                  | 33.3             | 6.8               |
| SP-BCZO-10.0 | 0.900                  | 35             | 1.73                  | 28.6             | 6.2               |

\(^a\) The concentration of SPEEK and BCZO in 20 mL of DMF.

3.6 Proton conductivity

The proton conductivity values of the pristine SPEEK and polymeric composite membranes use to vary according to temperature as depicted in Fig. 7. In case of solid polymer electrolytes, the conductivity values are supposed to vary with respect to increase of temperature, which use to be stimulated due to segmental motion and subsequent expansion of free volume of the sample under study. The segmental motions tend to be prompted by ions use to hop from one site to another or induced for the mobility of additional path of protons readily [37]. Obviously, the proton transfer pathways tend to be intensified due to interaction among the BCZO nanoparticles in composite membranes, which enhanced the good ionic conduction of the polymer composites. Among the prepared composite membranes, SP-BCZO-7.5 sample exhibited the maximum proton conductivity of 0.030 S cm\(^{-1}\) at 90 °C. Though, polymer nanocomposite membranes loaded with 10.0 wt.% of BCZO found to exhibit a minor reduction in ionic conductivity due to its lower IEC and water uptake capacities.

3.7 Thermal Analysis

TGA profile of the pristine polymer and the nanocomposite membranes are depicted in Fig. 8. In Fig. 8a, the first step of weight loss at 110 °C was assigned to the evaporation of residual solvent and excess moisture absorbed or bounded with sulfonic acid groups in SPEEK. The second step of weight loss was observed around 350 °C with respect to the degradation of sulfonic acid groups and third step of break-down inferred the decomposition of polymer backbone. In Fig. 8b and Fig. 8c, TGA curves of both samples of SP/BCZO nanocomposite membranes were observed to decompose at higher temperature range as compared to SPEEK matrix. Indeed, the enhancement of thermal stability as well as the increase of residual mass for the composite membranes as compared to the control SPEEK matrix occurred due to the effective reinforcement of BCZO into the pristine polymer matrix.
3.8 Fuel cell performance

The PEMFC single cell was fabricated to demonstrate the function of both the control SPEEK and SP-BCZO-7.5 membranes in terms of their performances as plotted in Fig. 9. Herein, the prospective of single cell performances of the fabricated electrolyte membranes was depicted at 60 °C under 100 % RH. In specific, SP-BCZO-7.5 membrane found to be generated a maximum peak power density value of 574 mW cm$^{-2}$. Obviously, the ultimate performance was noticed under above operating conditions for the composite membrane sample, while the control SPEEK occurred to generate value only to the extent of 450 mW cm$^{-2}$. Certainly, the high proton conductivity of SP-BCZO-7.5 membrane is shown to be involved effectively to achieve the efficient performance in electrochemical devices while venturing with such composite membrane in H$_2$-O$_2$ fuel cell.

4. Conclusion

Herein, new series of hybrid polymer electrolyte membranes have been formulated from sulfonated poly (ether ether ketone) as a linear constituent with bismuth cobalt zinc oxide as an inorganic additive for the application of H$_2$-O$_2$ fuel cell. These composite membranes were characterized to venture their ion-exchange capacity, water uptake, thermal stability and proton conductivity. In terms of the strong hydrophilic nature of BCZO nanoparticles, composite membranes reveal the adequate water uptake ability and proton conductivity as compared to that of pristine SPEEK material. Since BCZO tends to be highly stable metal oxide, the developed composites use to exhibit excellent thermal stability as compared to the neat SPEEK. Indeed, the electrochemical studies exhibit that SPEEK polymer loaded with 7.5 wt.% of BCZO found to show the maximum peak power density of 574 mW cm$^{-2}$. Evidently, the battery of data measured from the newly developed organic-inorganic PEM materials found to be demonstrated as a feasible membrane for fuel cell applications.

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Declaration

There are no conflicts to declare.
References

[1] T. Xu, D. Wu, L. Wu, Prog. Polym. Sci. 33, 894 (2008).
[2] B. Smitha, S. Sridhar, A.A. Khan, J. Membr. Sci. 259, 10 (2005).
[3] R. Arunkumar, R. Shanker babu, M. Usha rani, J. Mater. Sci.: Mater. Electron. 28, 3309 (2017).
[4] A. K. Sahu, K. Ketpang, S. Shanmugam, O. Kwon, S. Lee, H. Kim, J Phys. Chem. C 120, 15855 (2016).
[5] K. Divya, M. S. Abirami Saraswathi, S. Alwarappan, A. Nagendran, D. Rana, Polymer 155, 42 (2018).
[6] A. R. Kim, M. Vinothkannan, D. J. Yoo, Int. J. Hydrogen Energy 42(7), 4349 (2017).
[7] C. L. Robert, K. Valle F. Pereira and C. Sanchez, Chem. Soc. Rev. 40, 961 (2011).
[8] S. Bose, T. Kuila, T. X. H. Nguyenb, N. H. Kim, K. Lau, J. H. Lee, Prog. Polym. Sci. 36, 813 (2011).
[9] J. Kalaiselvimary, M.R. Prabhu, J. Mater. Sci. 29, 5525 (2018).
[10] D. Paradesi, S. N. Jaisankar, J. Macromol. Sci. Pure Appl. Chem. 49, 1092 (2012).
[11] J. M. Andujar, F. Segura, Renew. Sust. Energy Rev. 13 (9), 2309 (2009).
[12] D. Paradesi, S. Gandhimathi, H. Krishnan, R. Jeyalakshmi, High Perform. Polym. 30 (1), 116 (2018).
[13] M. Vatanparast, M.T. Taghizadeh, J. Mater. Sci.: Mater. Electron. 28, 778 (2017).
[14] A. K. Sahu, S. Pitchumani, P. Sridhar and A. K. Shukla, Bull. Mater. Sci. 32 (3), 285 (2009).
[15] F. Shang, L. Lei, Y. Zhang, H. Li, J. Mater. Sci. 44, 4383 (2009).
[16] G. M. Vinothkannan, A. R. Kim, G. Gnana kumar, D. J. Yoo, RSC Adv. 8, 7494 (2018).
[17] T. Y. Chen and J. Leddy, Langmuir 16, 2866 (2000).
[18] K. Divya, M. S. Saraswathi, D. Rana, S. Alwarappan, A. Nagendran, Polymer 147, 48 (2018).
[19] S. Gandhimathi, H. Krishnan, D. Paradesi, R. Jeyalakshmi, Polym. J. 49, 703 (2017).
[20] K. Selvakumar, M. Ramesh prabhu, J. Mater. Sci.: Mater. Electron. 29, 15163 (2018).
[21] G. Lavanya, D. Paradesi, P. Hemalatha, J. Macromol. Sci. Pure Appl. Chem. 57 (4), 283 (2020).
[22] A. K. Mandal, D. Bera, S. Banerjee, Mat. Chem. Phy. 181, 265 (2016).
[23] H. Zhang, R. J. Stanis, Y. Song, W. Hu, C. J. Cornelius, Q. Shi, B. Liu, M. D. Guiver, J. Power Sources 368, 30 (2017).
[24] W. Jang, S. Sundar, S. Choi,Y.-G Shul, H. S. Han, J. Membr. Sci. 280, 321 (2006).
[25] M. Berлина, K. Poonkuzhali, S. Gandhimathi, D. Paradesi, Polym. Plast. Technol. 59(16), 1791 (2020).
[26] M. Helen, B. Viswanathan, S. S. Murthy, J. Membr. Sci. 292, 98 (2007).
[27] A. R. Kim, C. J. Park, M. Vinothkannan, D. J. Yoo, Compos. B. Eng. 155, 272 (2018).
[28] D. Paradesi, R. A. Ramanujam, S. N. Jaisankar, Polym. J. 45, 166 (2013).
[29] D. J. Kim, M. J. Jo, S. Y. Nam, J. Ind. Eng. Chem. 21, 36 (2015).
[30] A. Muthumeenal, M. S. Saraswathi, D. Rana, A. Nagendran, J. Environ. Chem. Eng. 5, 3828 (2017).
[31] Y. Kobayashi, T. Tanase, T. Tabata, Miwa, M. Konno, J. Eur. Ceram. Soc. 28, 117 (2008).
[32] W. Han, T. Kim, B. Yoo, H. H. Park, Sci. Rep. 8, 4086 (2018).
[33] S. Gandhimathi, H. Krishnan, D. Paradesi, Polym. Polym. Comp. 28 (7), 492 (2020).
[34] Z. Huang, Y. Zhao, Y. Song, Y. Li, G. Wu, H. Tang , J. Zhao, RSC Adv. 6, 80059 (2016).
[35] S. Seetharaman, G. Sozhan, S. Ravichandran, S, Vasudevan, J. Davidson, Int. J. Polym. Mater. 60 (10), 742 (2011).
[36] A. Umadevi, K. Divya, S. A. Saraswathi, A. Nagendran, Mat. Chem. Phys. 212, 533 (2018).

[37] A. M. Attaran, M. Javanbakht, K. Hooshyari, M. Enhessari, Solid State Ionics 269 (1-2), 98 (2015).
Figure captions

Fig.1  Schematic representation for the preparation of SP-BCZO composite membranes.

Fig.2  FT-IR spectra of SPEEK and SP-BCZO-10 composite.

Fig.3  XRD patterns of BCZO, SPEEK and SP-BCZO-5.0 membranes.

Fig.4  SEM images of a) SPEEK, b) and c) BCZO and as well as d) SP-BCZO-5.0 samples.

Fig.5  Contact angle measurements on a) SPEEK, b) SP-BCZO-7.5 and c) SP-BCZO-10 membranes.

Fig.6  Comparison between water uptake and IEC of the pristine and composite membranes.

Fig.7  Proton conductivity measurements on pristine and composite membranes.

Fig.8  TGA profile of a) SPEEK b) SP-BCZO-5.0 and c) SP-BCZO-10.0 composite membranes.

Fig.9  Polarization and power density curves of pristine SPEEK and SP-BCZO-7.5 membranes.