

6.6 Future scope

The performance of direct ethanol fuel cell using synthesized anode electrocatalyst shows that it hold a promising future for applications in portable electronic and electrical vehicles. The other considerable advantages are simplicity, low operation temperatures, high energy conversion efficiency, and renewable in nature. The developed DEFC using the synthesized best tri-metallic electrocatalyst i.e., Pt-Ru-Re(1:1:0.5)/f-MWCNT working under optimized conditions could be used as roadmap for further improvement and development of direct ethanol fuel cell (DEFC) in terms of higher current density and power density.

However, several critical issues need to be resolved for the successful commercialization of DEFC. The costs of DEFC are determined by the materials cost associated to fabricate the cells like electrocatalyst and electrolyte mainly. Till now, platinum (Pt) based metal alloy electrocatalysts are recommended and extensively used for ethanol electrooxidation. However, the limited supply of noble metal Pt in nature and extensive use of costly metal Pt are making this technology difficult to reach the common people for their use as a power source. As various studies shows that the anodic electrode, the pure Pt electrocatalysts are highly susceptible to poisoning by adsorbed intermediates such as CO_{ad} and $\text{CH}_{\text{x,ad}}$ generated during the ethanol electrooxidation process. Additional factors that impede the development of DEFC include slow reaction kinetics, a complex reaction mechanism, and an ethanol crossover from the anode to the cathode. In this context, the urgent matter to address is to develop advanced, cost-effective, durable, and catalytically active or even non-precious metal anode electrocatalysts for ethanol electrooxidation that could contribute to lowering the cost and improve the catalytic activity and durability. So far, tremendous research efforts have been concentrated to reduce the above problems by

alloying Pt with 3d transition metal such as Ru, Sn, Rh, Ce, Ir, Ni, Mo, or W to form Pt-based bi-metallic and tri-metallic electrocatalysts with improved electrocatalytic activity due to their better capability of modulating structure, geometric as well as electronic effects. On the other hand, effective multi-metallic electrocatalysts should have the ability to activate the C-C bond cleavage of the ethanol molecule to achieve complete oxidation product (CO_2) at a low overpotential at low temperatures and lower loading of electrocatalysts. The carbon-supported Pt-based bi-metallic and tri-metallic electrocatalysts developed in this work exhibit well under low operating temperature conditions. Thus the future work could focus on developing highly active pluri-metallic electrocatalysts with low Pt content supported on novel support materials for ethanol electrooxidation at high operating temperatures. Single cell performance study of pluri-metallic electrocatalysts as anode materials for other aliphatic alcohols and mixtures of alcohol could be studied in the future research work. To operate the DEFC at high temperature, the polymer membrane electrolyte like Nafion[®] must be modified, so that the membrane conducting for ion transport does not damage at high temperature due to membrane degradation. Thus, the membrane synthesis and modification of the present membrane electrolyte also could be taken as a future work. Although single cell DEFC shows promising results, the stack development using optimized conditions obtained from the single cell study and testing is required to obtain useful and workable voltage and current, making the direct ethanol fuel cell commercially viable.

REFERENCES

Akhairi M.A., and Kamarudin S.K., "Catalysts in direct ethanol fuel cell (DEFC): An overview," *International Journal of Hydrogen Energy*, 2016 , v. 41, pp. 4214-4228.

Almeida C.V., Ferreira D.S., Huang H., Gaiotti A.C., Camara G.A., Russell A.E., Eguiluz K.I., and Salazar-Banda G.R., "Highly active Pt₃Rh/C nanoparticles towards ethanol electrooxidation. Influence of the catalyst structure," *Applied Catalysis B: Environmental*, 2019, v. 254, pp. 113-127.

Almeida T.S., Palma L.M., Leonello P.H., Morais C., Kokoh K.B., and De Andrade A.R., "An optimization study of PtSn/C catalysts applied to direct ethanol fuel cell: Effect of the preparation method on the electrocatalytic activity of the catalysts," *Journal of Power Sources*, 2012, v. 215, pp. 53-62.

Álvarez G., Alcaide F., Miguel O., Calvillo L., Lázaro M.J., Quintana J.J., Calderón J.C., and Pastor E., "Technical electrodes catalyzed with PtRu on mesoporous ordered carbons for liquid direct methanol fuel cells," *Journal of Solid State Electrochemistry*, 2010, v. 14, pp. 1027-1034.

Alzate V., Fatih K., and Wang H., "Effect of operating parameters and anode diffusion layer on the direct ethanol fuel cell performance," *Journal of Power Sources*, 2011, v. 196, pp. 10625-10631.

Ammam M., and Easton E.B., "PtCu/C and Pt (Cu)/C catalysts: synthesis, characterization and catalytic activity towards ethanol electrooxidation," *Journal of Power Sources*, 2013, v. 222, pp. 79-87.

Antolini E., "Carbon supports for low-temperature fuel cell catalysts," *Applied Catalysis B: Environmental*, 2009, v. 88, pp. 1-24.

Antolini E., "Catalysts for direct ethanol fuel cells," *Journal of Power Sources*, 2007a, v. 170, pp. 1-12.

Antolini E., "Effect of the structural characteristics of binary Pt-Ru and ternary Pt-Ru-M fuel cell catalysts on the activity of ethanol electrooxidation in acid medium," *ChemSusChem*, 2013, v. 6, pp. 966-973.

Antolini E., "Platinum-based ternary catalysts for low temperature fuel cells: Part I. Preparation methods and structural characteristics," *Applied Catalysis B: Environmental*, 2007b, v. 74, pp. 324-336.

Antolini E., and Cardellini F., "Formation of carbon supported PtRu alloys: an XRD analysis," *Journal of Alloys and Compounds*, 2001, v. 315, pp. 118-122.

Antolini E., Colmati F., and Gonzalez E.R., "Effect of Ru addition on the structural characteristics and the electrochemical activity for ethanol oxidation of carbon supported Pt-Sn alloy catalysts," *Electrochemistry Communications*, 2007, v. 9, pp. 398-404.

- Antolini E., Colmati F., and Gonzalez E.R., "Ethanol oxidation on carbon supported (PtSn) alloy/SnO₂ and (PtSnPd) alloy/SnO₂ catalysts with a fixed Pt/SnO₂ atomic ratio: effect of the alloy phase characteristics," *Journal of Power Sources*, 2009, v. 193, pp. 555-561.
- Antolini E., Giorgi L., Cardellini F., and Passalacqua E., "Physical and morphological characteristics and electrochemical behaviour in PEM fuel cells of PtRu/C catalysts," *Journal of Solid State Electrochemistry*, 2001, v. 5, pp. 131-140.
- Aricò A.S., Baglio V., Di Blasi A., Modica E., Antonucci P.L., and Antonucci V., "Analysis of the high-temperature methanol oxidation behaviour at carbon-supported Pt-Ru catalysts," *Journal of Electroanalytical Chemistry*, 2003, v. 557, pp. 167-176.
- Asgardi J., Calderón J.C., Alcaide F., Querejeta A., Calvillo L., Lázaro M.J., García G., and Pastor E., "Carbon monoxide and ethanol oxidation on PtSn supported catalysts: Effect of the nature of the carbon support and Pt: Sn composition," *Applied Catalysis B: Environmental*, 2015, v. 168, pp. 33-41.
- Azam A.M., Lee S.H., Masdar M.S., Zainoodin A.M., and Kamarudin S.K., "Parametric study on direct ethanol fuel cell (DEFC) performance and fuel crossover," *International Journal of Hydrogen Energy*, 2019, v. 44, pp. 8566-8574.
- Baghbmidi S.E., Beitollahi H., Mohammadi S.Z., Tajik S., Soltani-Nejad S., and Soltani-Nejad V., "Nanostructure-based electrochemical sensor for the voltammetric determination of benzerazide, uric acid, and folic acid," *Chinese Journal of Catalysis*, 2013, v. 34, pp. 1869-1875.
- Barati S., Ghazi M.M., and Khoshandam B., "Study of effective parameters for the polarization characterization of PEMFCs sensitivity analysis and numerical simulation," *Korean Journal of Chemical Engineering*, 2019, v. 36, pp. 146-156.
- Beard B.C., and Ross Jr P.N., "The structure and activity of Pt-Co alloys as oxygen reduction electrocatalysts," *Journal of the Electrochemical Society*, 1990, v. 137, pp. 3368-3373.
- Beyhan S., Léger J.M., and Kadırgan F., "Pronounced synergetic effect of the nano-sized PtSnNi/C catalyst for ethanol oxidation in direct ethanol fuel cell," *Applied Catalysis B: Environmental*, 2013, v. 130, pp. 305-313.
- Beyhan S., Léger J.M., and Kadırgan F., "Understanding the influence of Ni, Co, Rh and Pd addition to PtSn/C catalyst for the oxidation of ethanol by in situ Fourier transform infrared spectroscopy," *Applied Catalysis B: Environmental*, 2014, v. 144, pp. 66-74.
- Beyhan S., Şahin N.E., Pronier S., Léger J.M., and Kadırgan F., "Comparison of oxygen reduction reaction on Pt/C, Pt-Sn/C, Pt-Ni/C, and Pt-Sn-Ni/C catalysts prepared by Bönemann method: A rotating ring disk electrode study," *Electrochimica Acta*, 2015, v. 151, pp. 565-573.

Bezerra M.A., Santelli R.E., Oliveira E.P., Villar L.S., and Escalera L.A., "Response surface methodology (RSM) as a tool for optimization in analytical chemistry," *Talanta*, 2008, v. 76, pp. 965-977.

Bock C., Paquet C., Couillard M., Botton G.A., and MacDougall B.R., "Size-selected synthesis of PtRu nano-catalysts: reaction and size control mechanism," *Journal of the American Chemical Society*, 2004, v. 126, pp. 8028-8037.

Bonesi A.R., Moreno M.S., Triaca W.E., and Luna A.C., "Modified catalytic materials for ethanol oxidation," *International Journal of Hydrogen Energy*, 2010, v. 35, pp. 5999-6004.

Caglar A., and Kivrak H., "Highly active carbon nanotube supported PdAu alloy catalysts for ethanol electrooxidation in alkaline environment," *International Journal of Hydrogen Energy*, 2019, v. 44, pp. 11734-11743.

Caglar A., Sahan T., Cogenli M.S., Yurtcan A.B., Aktas N., and Kivrak H., "A novel Central Composite Design based response surface methodology optimization study for the synthesis of Pd/CNT direct formic acid fuel cell anode catalyst," *International Journal of Hydrogen Energy*, 2018, v. 43, pp. 11002-11011.

Calvillo L., Celorrio V., Moliner R., and Lázaro M.J., "Influence of the support on the physicochemical properties of Pt electrocatalysts: Comparison of catalysts supported on different carbon materials," *Materials Chemistry and Physics*, 2011, v. 127, pp. 335-341.

Calvillo L., Gangeri M., Perathoner S., Centi G., Moliner R., and Lázaro M.J., "Effect of the support properties on the preparation and performance of platinum catalysts supported on carbon nanofibers," *Journal of Power Sources*, 2009, v. 192, pp. 144-150.

Calvillo L., Lázaro M.J., García-Bordejé E., Moliner R., Cabot P.L., Esparbé I., Pastor E., and Quintana J.J., "Platinum supported on functionalized ordered mesoporous carbon as electrocatalyst for direct methanol fuel cells," *Journal of Power Sources*, 2007, v. 169, pp. 59-64.

Candiotti L.V., De Zan M.M., Cámara M.S., and Goicoechea H.C., "Experimental design and multiple response optimization. Using the desirability function in analytical methods development," *Talanta*, 2014, v. 124, pp. 123-138.

Cao L., Sun G., Li H., and Xin Q., "Carbon-supported IrSn catalysts for direct ethanol fuel cell," *Fuel Cells Bulletin*, 2007, v. 2007, pp. 12-16.

Carrette L., Friedrich K.A., and Stimming U., "Fuel cells-fundamentals and applications," *Fuel Cells*, 2001, v. 1, pp. 5-39.

Charoen K., Prapainainar C., Sureeyatanapas P., Suwannaphisit T., Wongamornpitak K., Kongkachuichay P., Holmes S.M., and Prapainainar P., "Application of response surface methodology to optimize direct alcohol fuel cell power density for greener energy production," *Journal of Cleaner Production*, 2017, v. 142, pp. 1309-1320.

Chen J., Wang M., Liu B., Fan Z., Cui K., and Kuang Y., "Platinum catalysts prepared with functional carbon nanotube defects and its improved catalytic performance for methanol oxidation," *The Journal of Physical Chemistry B*, 2006, v. 110, pp. 11775-11779.

Chen S., Ye F., and Lin W., "Effect of operating conditions on the performance of a direct methanol fuel cell with PtRuMo/CNTs as anode catalyst," *International Journal of Hydrogen Energy*, 2010, v. 35, pp. 8225-8233.

Cheng Y., Xu C., and Shen P.K., "Effect of nitrogen-containing functionalization on the electrocatalytic activity of PtRu nanoparticles supported on carbon nanotubes for direct methanol fuel cells," *Applied Catalysis B: Environmental*, 2014, v. 158, pp. 140-149.

Chetty R., Kundu S., Xia W., Bron M., Schuhmann W., Chirila V., Brandl W., Reinecke T., and Muhler M., "PtRu nanoparticles supported on nitrogen-doped multiwalled carbon nanotubes as catalyst for methanol electrooxidation," *Electrochimica Acta*, 2009, 54, pp. 4208-4215.

Choudhary A.K., and Pramanik H., "Addition of rhenium (Re) to Pt-Ru/f-MWCNT anode electrocatalysts for enhancement of ethanol electrooxidation in half cell and single direct ethanol fuel cell," *International Journal of Hydrogen Energy*, 2020b, v. 45, pp. 13300-13321.

Choudhary A.K., and Pramanik H., "Enhancement of ethanol electrooxidation in half cell and single direct ethanol fuel cell (DEFC) using post-treated polyol synthesized Pt-Ru nano electrocatalysts supported on HNO₃-functionalized acetylene black carbon," *International Journal of Hydrogen Energy*, 2020a, v. 45, pp. 574-594.

Choudhary A.K., and Pramanik H., "Synthesis of low-cost HNO₃-functionalized acetylene black carbon supported Pt-Ru/C_{AB} nano electrocatalysts for the application in direct ethanol fuel cell (DEFC)," *Korean Journal of Chemical Engineering*, 2019, v. 36, pp. 1688-1707.

Chu D., and Gilman S., "Methanol electro-oxidation on unsupported Pt-Ru alloys at different temperatures," *Journal of the Electrochemical Society*, 1996, v. 143, pp. 1685-1689.

Chu Y.H., and Shul Y.G., "Combinatorial investigation of Pt-Ru-Sn alloys as an anode electrocatalysts for direct alcohol fuel cells," *International Journal of Hydrogen Energy*, 2010a, v. 35, pp. 11261-11270.

Chu Y.Y., Wang Z.B., Jiang Z.Z., Gu D.M., and Yin G.P., "Effect of pH Value on Performance of PtRu/C Catalyst Prepared by Microwave-Assisted Polyol Process for Methanol Electrooxidation," *Fuel Cells*, 2010b, v. 10, pp. 914-919.

Ciftci A., Ligthart D.M., Sen A.O., Van Hoof A.J., Friedrich H., and Hensen E.J., "Pt-Re synergy in aqueous-phase reforming of glycerol and the water-gas shift reaction," *Journal of Catalysis*, 2014, v. 311, pp. 88-101.

- Colmati F., Antolini E., and Gonzalez E.R., "Ethanol oxidation on carbon supported Pt-Sn electrocatalysts prepared by reduction with formic acid," *Journal of the Electrochemical Society*, 2007, v. 154, B39-B47.
- Colmati F., Antolini E., and Gonzalez E.R., "Effect of temperature on the mechanism of ethanol oxidation on carbon supported Pt, PtRu and Pt₃Sn electrocatalysts," *Journal of Power Sources*, 2006, v. 157, pp. 98-103.
- Colmenares L., Wang H., Jusys Z., Jiang L., Yan S., Sun G.Q., and Behm R.J., "Ethanol oxidation on novel, carbon supported Pt alloy catalysts—Model studies under defined diffusion conditions," *Electrochimica Acta*, 2006, v. 52, pp. 221-233.
- Corradini P.G., Antolini E., and Perez J., "Activity, short-term stability (poisoning tolerance) and durability of carbon supported Pt–Pr catalysts for ethanol oxidation," *Journal of Power Sources*, 2014, v. 251, pp. 402-410.
- Corradini P.G., Antolini E., and Perez J., "Electro-oxidation of ethanol on ternary non-alloyed Pt–Sn–Pr/C catalysts," *Journal of Power Sources*, 2015, v. 275, pp. 377-383.
- Corradini P.G., Antolini E., and Perez J., "Structural and electrochemical characterization of carbon supported Pt–Pr catalysts for direct ethanol fuel cells prepared using a modified formic acid method in a CO atmosphere," *Physical Chemistry Chemical Physics*, 2013, v. 15, pp. 11730-11739.
- Cunha E.M., Ribeiro J., Kokoh K.B., and De Andrade A.R., "Preparation, characterization and application of Pt–Ru–Sn/C trimetallic electrocatalysts for ethanol oxidation in direct fuel cell," *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 11034-11042.
- Das S., Ray A., and De S., "Optimum combination of renewable resources to meet local power demand in distributed generation: A case study for a remote place of India," *Energy*, 2020, v. 209, pp. 118473-118491.
- Datta J., Singh S., Das S., and Bandyopadhyay N.R., "A comprehensive study on the effect of Ru addition to Pt electrodes for direct ethanol fuel cell," *Bulletin of Materials Science*, 2009, v. 32, pp. 643-652.
- de La Fuente J.G., Martínez-Huerta M.V., and Rojas S., Hernández-Fernández P., Terreros P., Fierro J.L., and Peña M.A., "Tailoring and structure of PtRu nanoparticles supported on functionalized carbon for DMFC applications: New evidence of the hydrous ruthenium oxide phase," *Applied Catalysis B: Environmental*, 2009, v. 88, pp. 505-514.
- De Souza R.F., Parreira L.S., Silva J.C., Simões F.C., Calegari M.L., Giz M.J., Camara G.A., Neto A.O., and Santos M.C., "PtSnCe/C electrocatalysts for ethanol oxidation: DEFC and FTIR "in-situ" studies," *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 11519-11527.

- Deluca N.W., and Elabd Y.A., "Polymer electrolyte membranes for the direct methanol fuel cell: a review," *Journal of Polymer Science Part B: Polymer Physics*, 2006, v. 44, pp. 2201-2225.
- Di Noto V., Zawodzinski T.A., Herring A.M., Giffin G.A., Negro E., and Lavina S, "Polymer electrolytes for a hydrogen economy," *International Journal of Hydrogen Energy*, 2012, v. 7, pp. 6120-6131.
- Dicks A.L., "The role of carbon in fuel cells," *Journal of Power Sources*, 2006, v. 156, pp. 128-141.
- Dong L., Gari R.R.S., Li Z., Craig M.M., and Hou S., "Graphene-supported platinum and platinum–ruthenium nanoparticles with high electrocatalytic activity for methanol and ethanol oxidation," *Carbon*, 2010, v. 48, pp. 781–787.
- Dos Anjos D.M., Kokoh K.B., Léger J.M., Andrade A.D., Olivi P., and Tremiliosi-Filho G., "Electrocatalytic oxidation of ethanol on Pt–Mo bimetallic electrodes in acid medium," *Journal of applied electrochemistry*, 2006, v. 36, pp. 1391-1397.
- dos Santos L., Colmati F., and Gonzalez E.R., "Preparation and characterization of supported Pt–Ru catalysts with a high Ru content," *Journal of Power Sources*, 2006, v. 159, pp. 869-877.
- Drzymala E., Gruzela G., Depciuch J., Pawlyta M., Donten M., and Parlinska-Wojtan M., "Ternary Pt/Re/SnO₂/C catalyst for EOR: Electrocatalytic activity and durability enhancement," *Nano Research*, 2020, v. 13, pp. 832-842.
- Drzymala E., Gruzela G., Pajor-Świerzy A., Depciuch J., Socha R., Kowal A., Warszyński P., and Parlinska-Wojtan M., "Design and assembly of ternary Pt/Re/SnO₂ NPs by controlling the zeta potential of individual Pt, Re, and SnO₂ NPs," *Journal of Nanoparticle Research*, 2018, v. 20, pp. 1-13.
- Duke A.S., Galhenage R.P., Tenney S.A., Sutter P., and Chen D.A., "In situ studies of carbon monoxide oxidation on platinum and platinum–rhenium alloy surfaces," *The Journal of Physical Chemistry C*, 2015, v. 119, pp. 381-391.
- Duke A.S., Xie K., Monnier J.R., and Chen D.A., "Superior long-term activity for a Pt-Re alloy compared to Pt in methanol oxidation reactions," *Surface Science*, 2017, v. 657, pp. 35-43.
- Dutta A., Mondal A., Broekmann P., and Datta J., "Optimal level of Au nanoparticles on Pd nanostructures providing remarkable electro-catalysis in direct ethanol fuel cell," *Journal of Power Sources*, 2017, v. 361, pp. 276-284.
- Esmailifar A., Rowshanzamir S., Eikani M.H., and Ghazanfari E., "Synthesis methods of low-Pt-loading electrocatalysts for proton exchange membrane fuel cell systems," *Energy*, 2010, v. 35, pp. 3941-3957.

- Farsadrooh M., Torrero J., Pascual L., Peña M.A., Retuerto M., and Rojas S., "Two-dimensional Pd-nanosheets as efficient electrocatalysts for ethanol electrooxidation. Evidences of the CC scission at low potentials," *Applied Catalysis B: Environmental*, 2018, v. 237, pp. 866-875.
- Fievet F., Lagier J.P., Blin B., Beaudoin B., and Figlarz M., "Homogeneous and heterogeneous nucleations in the polyol process for the preparation of micron and submicron size metal particles," *Solid State Ionics*, 1989, v. 32, pp. 198-205.
- Fujiwara N., Friedrich K.A., and Stimming U., "Ethanol oxidation on PtRu electrodes studied by differential electrochemical mass spectrometry," *Journal of Electroanalytical Chemistry*, 1999, v. 472, pp. 120-125.
- Gálvez M.E., Calvillo L., Alegre C., Sebastián D., Suelves I., Pérez-Rodríguez S., Celorrio V., Pastor E., Pardo J.I., Moliner R., and Lázaro M.J., "Nanostructured carbon materials as supports in the preparation of direct methanol fuel cell electrocatalysts," *Catalysts*, 2013, v. 3, pp. 671-682.
- García G., Tsiouvaras N., Pastor E., Pena M.A., Fierro J.L., and Martíñez-Huerta M.V., "Ethanol oxidation on PtRuMo/C catalysts: in situ FTIR spectroscopy and DEMS studies," *International Journal of Hydrogen Energy*, 2012, v. 37, pp. 7131-7140.
- Ghumman A., Vink C., Yopez O., and Pickup P.G., "Continuous monitoring of CO₂ yields from electrochemical oxidation of ethanol: Catalyst, current density and temperature effects," *Journal of Power Sources*, 2008, v. 177, pp. 71-76.
- Godoi D.R., Perez J., and Villullas H.M., "Alloys and oxides on carbon-supported Pt-Sn electrocatalysts for ethanol oxidation," *Journal of Power Sources*, 2010, v. 195, pp. 3394-3401.
- Goel J., and Basu S., "Effect of support materials on the performance of direct ethanol fuel cell anode catalyst," *International Journal of Hydrogen Energy*, 2014, v. 39, pp. 15956-15966.
- Goel J., and Basu S., "Mathematical modeling and experimental validation of direct ethanol fuel cell," *International Journal of Hydrogen Energy*, 2015, v. 40, pp. 14405-14415.
- Goel J., and Basu S., "Pt-Re-Sn as metal catalysts for electro-oxidation of ethanol in direct ethanol fuel cell," *Energy Procedia*, 2012, v. 28, pp. 66-77.
- Gu Z., Li S., Xiong Z., Xu H., Gao F., and Du Y., "Rapid synthesis of platinum-ruthenium bimetallic nanoparticles dispersed on carbon support as improved electrocatalysts for ethanol oxidation," *Journal of Colloid and Interface Science*, 2018, v. 521, pp. 111-118.
- Guo J., Sun G., Shiguo S., Shiyu Y., Weiqian Y., Jing Q., Yushan Y., and Qin X., "Polyol-synthesized PtRu/C and PtRu black for direct methanol fuel cells," *Journal of Power Sources*, 2007, v. 168, pp. 299-306.

Guo J.W., Zhao T.S., Prabhuram J., Wong C.W., "Preparation and the physical/electrochemical properties of a Pt/C nanocatalyst stabilized by citric acid for polymer electrolyte fuel cells," *Electrochimica Acta*, 2005, v. 50, pp. 1973-1983.

Gupta U.K., and Pramanik H., "Electrooxidation study of pure ethanol/methanol and their mixture for the application in direct alcohol alkaline fuel cells (DAAFCs)," *International Journal of Hydrogen Energy*, 2019, v. 44, pp. 421-435.

Han K., Lee J., and Kim H., "Preparation and characterization of high metal content Pt-Ru alloy catalysts on various carbon blacks for DMFCs," *Electrochimica Acta*, 2006, v. 52, pp. 1697-1702.

Her S.C., and Lai C.Y., "Dynamic behavior of nanocomposites reinforced with multi-walled carbon nanotubes (MWCNTs)," *Materials*, 2013, v. 6, pp. 2274-2284.

Herrera-Méndez H.D., Roquero P., Smit M.A., and Ordóñez L.C., "Carbon-supported platinum molybdenum electro-catalysts and their electro-activity toward ethanol oxidation," *International Journal of Electrochemical Science*, 2011, v. 6, pp. 4454-4469.

Heysiattalab S., Shakeri M., Safari M., and Keikha M.M., "Investigation of key parameters influence on performance of direct ethanol fuel cell (DEFC)," *Journal of Industrial and Engineering Chemistry* 2011, v. 17, pp. 727-729.

Hickner M.A., Ghassemi H., Kim Y.S., Einsla B.R., and McGrath J.E., "Alternative polymer systems for proton exchange membranes (PEMs)," *Chemical Reviews*, 2004, v. 104, pp. 4587-4612.

Higa M., Hatemura K., Sugita M., Maesowa S.I., Nishimura M., and Endo N., "Performance of passive direct methanol fuel cell with poly (vinyl alcohol)-based polymer electrolyte membranes," *International Journal of Hydrogen Energy*, 2012, v. 37, pp. 6292-6301.

Hitmi H., Belgsir E.M., Léger J.M., Lamy C., and Lezna R.O., "A kinetic analysis of the electro-oxidation of ethanol at a platinum electrode in acid medium," *Electrochimica Acta*, 1994, v. 39, pp. 407-415.

Hsu N.Y., Chien C.C., and Jeng K.T., "Characterization and enhancement of carbon nanotube-supported PtRu electrocatalyst for direct methanol fuel cell applications," *Applied Catalysis B: Environmental*, 2008, v. 84, pp. 196-203.

Hu Y., Zhu A., Zhang Q., and Liu Q., "Preparation of PtRu/C core-shell catalyst with polyol method for alcohol oxidation," *International Journal of Hydrogen Energy*, 2016, v. 41, pp. 11359-11368.

Huang K.J., Zhang J.Z., Jia Y.L., Xing K., and Liu Y.M., "Acetylene black incorporated layered copper sulfide nanosheets for high-performance supercapacitor," *Journal of Alloys and Compounds*, 2015, v. 641, pp. 119-126.

-
- International Energy Outlook, "U.S. Energy Information Administration" 24 Sept. (2019), <https://www.eia.gov/ieo>.
- Iwasita T., and Pastor E., "A DEMS and FTIR spectroscopic investigation of adsorbed ethanol on polycrystalline platinum," *Electrochimica Acta*, 1994, 39, 531-537.
- Jacob J.M., Corradini P.G., Antolini E., Santos N.A., Perez J., "Electro-oxidation of ethanol on ternary Pt-Sn-Ce/C catalysts," *Applied Catalysis B: Environmental*, 2015, v. 165, pp. 176-184.
- Jha N., Jafri R.I., Rajalakshmi N., and Ramaprabhu S., "Graphene-multi walled carbon nanotube hybrid electrocatalyst support material for direct methanol fuel cell," *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 7284-7290.
- Jiang L., Hsu A., Chu D., and Chen R., "Ethanol electro-oxidation on Pt/C and PtSn/C catalysts in alkaline and acid solutions," *International Journal of Hydrogen Energy*, 2010, v. 35, pp. 365-372.
- Jiang L., Sun G., Wang S., Wang G., Xin Q., Zhou Z., and Zhou B., "Electrode catalysts behavior during direct ethanol fuel cell life-time test," *Electrochemistry Communications*, 2005, v. 7, pp. 663-668.
- Jin G., Mingang Z., Shijian Y., Xiaoyan Y., and Shiwei W., "Electrochemical properties of modified acetylene black/sulfur composite cathode material for lithium/sulfur batteries," *Ionics*, 2018, 24, pp. 2219-2225.
- Kadirgan F., Beyhan S., and Atilan T., "Preparation and characterization of nano-sized Pt-Pd/C catalysts and comparison of their electro-activity toward methanol and ethanol oxidation," *International Journal of Hydrogen Energy*, 2009, v. 34, pp. 4312-4320.
- Kamarudin M.Z.F., Kamarudin S.K., Masdar M.S., and Daud W.R.W., "Review: direct ethanol fuel cells," *International Journal of Hydrogen Energy*, 2013, v. 38, pp. 9438-9453.
- Key World Energy Statistics "Analysis IEA", August (2020), <https://www.iea.org/reports/key-world-energy-statistics-August>.
- Komarneni S., Li D., Newalkar B., Katsuki H., and Bhalla A.S., "Microwave- polyol process for Pt and Ag nanoparticles," *Langmuir*, 2002, v. 18, pp. 5959-5962.
- Kutz R.B., Braunschweig B., Mukherjee P., Behrens R.L., Dlott D.D., and Wieckowski A., "Reaction pathways of ethanol electrooxidation on polycrystalline platinum catalysts in acidic electrolytes," *Journal of Catalysis*, 2011, v. 278, pp. 181-188.
- Kuwertz R., Kirstein C., Turek T., and Kunz U., "Influence of acid pretreatment on ionic conductivity of Nafion® membranes," *Journal of Membrane Science*, 2016, v. 500, pp. 225-235.

Kwok Y.H., Wang Y., Wu M., Li F., Zhang Y., Zhang H., and Leung D.Y., "A dual fuel microfluidic fuel cell utilizing solar energy and methanol," *Journal of Power Sources*, 2019, v. 409, pp. 58-65.

Lakshmi N., Rajalakshmi N., and Dhathathreyan K.S., "Functionalization of various carbons for proton exchange membrane fuel cell electrodes: analysis and characterization," *Journal of Physics D: Applied Physics*, 2006, v. 39, pp. 2785-2790.

Lamy C., Belgsir E.M., and Leger J-M., "Electrocatalytic oxidation of aliphatic alcohols: application to the direct alcohol fuel cell (DAFC)," *Journal of Applied Electrochemistry*, 2001, v.31, pp.799-809.

Lamy C., Lima A., LeRhun V., Delime F., Coutanceau C., and Léger J.M., "Recent advances in the development of direct alcohol fuel cells (DAFC)," *Journal of Power Sources*, 2002, v. 105, pp. 283-296.

Lamy C., Rousseau S., Belgsir E.M., Coutanceau C., and Leger J.M., "Recent progress in the direct ethanol fuel cell: Development of new platinum-tin electrocatalysts," *Electrochimica Acta*, 2004, v. 49, pp. 3901-3909.

Larminie J., and Dicks A., *Fuel Cell Systems Explained*, 2nd edition, John Wiley & Sons, 2003.

Lázaro M.J., Celorrio V., Calvillo L., Pastor E., and Moliner R., "Influence of the synthesis method on the properties of Pt catalysts supported on carbon nanocoils for ethanol oxidation," *Journal of Power Sources*, 2011, v. 196, pp. 4236-4241.

Lee E., Murthy A., and Manthiram A., "Effect of Mo addition on the electrocatalytic activity of Pt–Sn–Mo/C for direct ethanol fuel cells," *Electrochimica Acta*, 2011, v. 56, pp. 1611-1618.

Lee K.S., Park H.Y., Cho Y.H., Park I.S., Yoo S.J., and Sung Y.E., "Modified polyol synthesis of PtRu/C for high metal loading and effect of post-treatment," *Journal of Power Sources*, 2010, v. 195, pp. 1031-1037.

Lee W.D., Lim D.H., Chun H.J., and Lee H.I., "Preparation of Pt nanoparticles on carbon support using modified polyol reduction for low-temperature fuel cells," *International Journal of Hydrogen Energy*, 2012, v. 37, pp. 12629-12638.

Leng Y., *Materials characterization: introduction to microscopic and spectroscopic methods*, John Wiley & Sons, 2009.

Li G., and Pickup P.G., "Analysis of performance losses of direct ethanol fuel cells with the aid of a reference electrode," *Journal of Power Sources*, 2006, v. 161, pp. 256-263.

Li H., Sun G., Cao L., Jiang L., and Xin Q., "Comparison of different promotion effect of PtRu/C and PtSn/C electrocatalysts for ethanol electro-oxidation," *Electrochimica Acta*, 2007, v. 52, pp. 6622-6629.

- Li L., Huang M., Liu J., and Guo Y., "Pt_xSn/C electrocatalysts synthesized by improved microemulsion method and their catalytic activity for ethanol oxidation," *Journal of Power Sources*, 2011, v. 196, pp. 1090-1096.
- Li W., Liang C., Zhou W., Qiu J., Zhou Z., Sun G., and Xin Q., "Preparation and characterization of multiwalled carbon nanotube-supported platinum for cathode catalysts of direct methanol fuel cells," *The Journal of Physical Chemistry B*, 2003, v. 107, pp. 6292-6299.
- Li Z., Fan L., Zhang T., and Li K., "Facile synthesis of Ag nanoparticles supported on MWCNTs with favorable stability and their bactericidal properties," *Journal of Hazardous Materials*, 2011, v. 187, pp. 466-472.
- Liu B., Chia Z.W., Cheng C.H., and Lee J.Y., "Promotional effects of Ir addition in carbon-supported Pt₅Rh electrocatalysts for the electrooxidation of ethanol at room temperature," *Energy & fuels*, 2011, v. 25, pp. 3135-3141.
- Liu H., Song C., Zhang L., Zhang J., Wang H., and Wilkinson D.P., "A review of anode catalysis in the direct methanol fuel cell," *Journal of Power Sources*, 2006, v. 155, pp. 95-110.
- Liu Z., Ling X.Y., Su X., Lee J.Y., and Gan L.M., "Preparation and characterization of Pt/C and PtRu/C electrocatalysts for direct ethanol fuel cells," *Journal of Power Sources*, 2005, v. 149, pp. 1-7.
- Long N.V., Ohtaki M., Hien T.D., Randy J., and Nogami M., "A comparative study of Pt and Pt-Pd core-shell nanocatalysts," *Electrochimica Acta*, 2011, v. 56, pp. 9133-9143.
- Lopes T., Antolini E., and Gonzalez E.R., "Carbon supported Pt-Pd alloy as an ethanol tolerant oxygen reduction electrocatalyst for direct ethanol fuel cells," *International Journal of Hydrogen Energy*, 2008, v. 33, pp. 5563-5570.
- Lopes T., Antolini E., Colmati F., and Gonzalez E.R., "Carbon supported Pt-Co (3: 1) alloy as improved cathode electrocatalyst for direct ethanol fuel cells," *Journal of Power Sources*, 2007, v. 164, pp. 111-114.
- López-Suárez F.E., Carvalho-Filho C.T., Bueno-López A., Arboleda J., Echavarría A., Eguiluz K.I., and Salazar-Banda G.R., "Platinum-tin/carbon catalysts for ethanol oxidation: Influence of Sn content on the electroactivity and structural characteristics," *International Journal of Hydrogen Energy*, 2015, v. 40, pp. 12674-12686.
- Mann J., Yao N., and Bocarsly A.B., "Characterization and analysis of new catalysts for a direct ethanol fuel cell," *Langmuir*, 2006, v. 22, pp. 10432-10436.
- Martínez-Huerta M.V., and Lázaro M.J., "Electrocatalysts for low temperature fuel cells," *Catalysis Today*, 2017, v. 285, pp. 3-12.

- Mathe N.R., Scriba M.R., and Coville N.J., Methanol oxidation reaction activity of microwave-irradiated and heat-treated Pt/Co and Pt/Ni nano-electrocatalysts,” *International Journal of Hydrogen Energy*, 2014, v. 39, pp. 18871-18881.
- Meenakshi S., Nishanth K.G., Sridhar P., and Pitchumani S., “Spillover effect induced Pt-TiO₂/C as ethanol tolerant oxygen reduction reaction catalyst for direct ethanol fuel cells,” *Electrochimica Acta*, 2014, v. 135, pp. 52-59.
- Mekhilef S., Saidur R., and Safari A., “Comparative study of different fuel cell technologies,” *Renewable and Sustainable Energy Reviews*, 2012, v. 16, pp. 981-989.
- Miao L.X., Wang W.K., Wang A.B., Yuan K.G., and Yang Y.S., “A high sulfur content composite with core-shell structure as cathode material for Li-S batteries,” *Journal of Materials Chemistry A*, 2013, v. 1, pp. 11659-11664.
- Montanheiro T.L., Cristóvan F.H., Machado J.P., Tada D.B., Durán N., and Lemes A.P., “Effect of MWCNT functionalization on thermal and electrical properties of PHBV/MWCNT nanocomposites,” *Journal of Materials Research*, 2015, v. 30, pp. 55-65.
- Motupally S., Becker A.J., and Weidner J.W., “Diffusion of water in Nafion 115 membranes,” *Journal of the Electrochemical Society*, 2000, v. 147, pp. 3171-3177.
- Munawer M.E., “Human health and environmental impacts of coal combustion and post-combustion wastes” *Journal of Sustainable Mining*, 2018, v. 17, pp. 87-96.
- Murthi V.S., Urian R.C., and Mukerjee S., “Oxygen reduction kinetics in low and medium temperature acid environment: correlation of water activation and surface properties in supported Pt and Pt alloy electrocatalysts,” *The Journal of Physical Chemistry B*, 2004, v. 108, pp. 11011-11023.
- Muthuswamy N., de la Fuente J.L., Tran D.T., Walmsley J., Tsytkin M., Raaen S., Sunde S., Rønning M., and Chen D., “Ru@ Pt core-shell nanoparticles for methanol fuel cell catalyst: Control and effects of shell composition,” *International Journal of Hydrogen Energy*, 2013, 38, pp. 16631-16641.
- Nakagawa N., Kaneda Y., Wagatsuma M., and Tsujiguchi T., “Product distribution and the reaction kinetics at the anode of direct ethanol fuel cell with Pt/C, PtRu/C and PtRuRh/C,” *Journal of Power Sources*, 2012, v. 199, pp. 103-109.
- Neburchilov V., Martin J., Wang H., and Zhang J., “A review of polymer electrolyte membranes for direct methanol fuel cells,” *Journal of Power Sources*, 2007, v. 169, pp. 221-238.
- Nikolić V.M., Žugić D.L., Maksić A.D., Šaponjić D.P., and Kaninski M.P., “Performance comparison of modified poly (vinyl alcohol) based membranes in alkaline fuel cells,” *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 11004-11010.

Oh H.S., Oh J.G., Hong Y.G., and Kim H., "Investigation of carbon-supported Pt nanocatalyst preparation by the polyol process for fuel cell applications," *Electrochimica Acta*, 2007, v. 52, pp. 7278-7285.

Oliveira R.T., Santos M.C., Marcussi B.G., Tanimoto S.T., Bulhões L.O., and Pereira E.C., "Ethanol oxidation using a metallic bilayer Rh/Pt deposited over Pt as electrocatalyst," *Journal of Power Sources*, 2006, v. 157, pp. 212-216.

Olu P.Y., Job N., and Chatenet M., "Evaluation of anode (electro) catalytic materials for the direct borohydride fuel cell: methods and benchmarks," *Journal of Power Sources*, 2016, v. 327, pp. 235-257.

Ong BC, Kamarudin SK, and Basri S., "Direct liquid fuel cells: A review," *International Journal of Hydrogen Energy*, 2017, v. 42, pp. 10142-10157.

Panjiara D., and Pramanik H., "Electrooxidation study of glycerol on synthesized anode electrocatalysts Pd/C and Pd-Pt/C in a Y-shaped membraneless air-breathing microfluidic fuel cell for power generation," *Ionics*, 2020a, v. 26, pp. 2435-2452.

Panjiara D., and Pramanik H., "Optimization of process parameters using response surface methodology (RSM) for power generation via electrooxidation of glycerol in T-Shaped air breathing microfluidic fuel cell (MFC)," *International Journal of Hydrogen Energy*, 2020b, v. 45, pp. 33968-33979.

Park K.C., Jang I.Y., Wongwiriyan W., Morimoto S., Kim Y.J., Jung Y.C., Toya T., and Endo M., "Carbon-supported Pt–Ru nanoparticles prepared in glyoxylate-reduction system promoting precursor–support interaction," *Journal of Materials Chemistry*, 2010, v. 20, pp. 5345-5354.

Parlinska-Wojtan M., Drzymala E., Gruzal G., Depciuch J., Donten M. and Kowal A., "Ternary Pt/Re/SnO₂ nanoparticles for ethanol oxidation reaction: Understanding the correlation between the synthesis route and the obtained material," *Applied Catalysis A: General*, 2019, v. 570, pp. 319-328.

Pech-Rodríguez W.J., Gonzalez-Quijano D., Vargas-Gutierrez G., Morais C., Napporn T.W., and Rodríguez-Varela F.J., "Electrochemical and in situ FTIR study of the ethanol oxidation reaction on PtMo/C nanomaterials in alkaline media," *Applied Catalysis B: Environmental*, 2017, v. 203, pp. 654-662.

Peighambardoust S.J., Rowshanzamir S., and Amjadi M., "Review of the proton exchange membranes for fuel cell applications," *International Journal of Hydrogen Energy*, 2010, v. 35, pp. 9349-9384.

Perez J.M., Beden B., Hahn F., Aldaz A., and Lamy C., "In situ infrared reflectance spectroscopic study of the early stages of ethanol adsorption at a platinum electrode in acid medium," *Journal of Electroanalytical Chemistry and Interfacial Electrochemistry*, 1989, v. 262, pp. 251-261.

- Peron J., Mani A., Zhao X., Edwards D., Adachi M., Soboleva T., Shi Z., Xie Z., Navessin T., and Holdcroft S., "Properties of Nafion[®] NR-211 membranes for PEMFCs," *Journal of Membrane Science*, 2010, v. 356, pp. 44-51.
- Pires F.I., Corradini P.G., Paganin V.A., Antolini E., and Perez J., "Effect of the degree of alloying of PtRu/C (1:1) catalysts on ethanol oxidation," *Ionics*, 2013, v. 19, pp. 1037-1045.
- Pramanik H., and Basu S., "A study on process parameters of direct ethanol fuel cell," *The Canadian Journal of Chemical Engineering*, 2007, v. 85, pp. 781-785.
- Pramanik H., and Basu S., "Cyclic voltammetry of oxygen reduction reaction using Pt-based electrocatalysts on a Nafion-bonded carbon electrode for direct ethanol fuel cell," *Indian Chemical Engineer*, 2011, v. 53, pp. 124-135.
- Pramanik H., and Basu S., "Modeling and experimental validation of overpotentials of a direct ethanol fuel cell," *Chemical Engineering and Processing: Process Intensification*, 2010, 49, pp. 635-642.
- Pramanik H., and Rathoure A.K., "Electrooxidation study of NaBH₄ in a membraneless microfluidic fuel cell with air breathing cathode for portable power application," *International Journal of Hydrogen Energy*, 2017, v. 42, pp. 5340-5350.
- Pramanik H., Wragg A.A., and Basu S., "Studies of some operating parameters and cyclic voltammetry for a direct ethanol fuel cell," *Journal of Applied Electrochemistry*, 2008, v. 38, pp. 1321-1328.
- Qian Y., Wen W., Adcock P.A., Jiang Z., Hakim N., Saha M.S., and Mukerjee S., "PtM/C catalyst prepared using reverse micelle method for oxygen reduction reaction in PEM fuel cells," *The Journal of Physical Chemistry C*, 2008, v. 112, pp. 1146-1157.
- Qin H., Miao X., Song D., Li Y., Shen Y., Tang J., Qu Y., Cao Y., Wang L., and Wang B., "Simple synthesis of N-doped catalysts with controllable Pt-Ni nanoparticles for high-efficiency ethanol oxidation," *Ionics*, 2019, v. 25, pp. 3179-3188.
- Qu Y., Wang L., Li C., Gao Y., Sik J.K., Rao J., and Yin G., "Quantitative pinhole on-line electrochemical mass spectrometry study on ethanol electro-oxidation at carbon-supported Pt and Ir-containing catalysts," *International Journal of Hydrogen Energy*, 2017, v. 42, pp. 228-235.
- Raman R.K., Shukla A.K., Gayen A., Hegde M.S., Priolkar K.R., Sarode P.R., and Emura S., "Tailoring a Pt-Ru catalyst for enhanced methanol electro-oxidation," *Journal of Power Sources*, 2006, v. 157, pp. 45-55.
- Ramos S.G., Calafiore A., Bonesi A.R., Triaca W.E., Luna A.C., Moreno M.S., Zampieri G., and Bengio S., "Supported catalysts for alcohol oxidation synthesis and analysis of their catalytic activity," *International Journal of Hydrogen Energy*, 2012, v. 37, pp. 14849-14853.

Rao C.V., and Viswanathan B., "Carbon supported Pd–Co–Mo alloy as an alternative to Pt for oxygen reduction in direct ethanol fuel cells," *Electrochimica Acta*, 2010, v. 55, pp. 3002-3007.

Rao L., Jiang Y.X., Zhang B.W., Cai Y.R., and Sun S.G., "High activity of cubic PtRh alloys supported on graphene towards ethanol electrooxidation," *Physical Chemistry Chemical Physics*, 2014, v. 16, pp. 13662-13671.

Ribadeneira E., and Hoyos B.A., "Evaluation of Pt–Ru–Ni and Pt–Sn–Ni catalysts as anodes in direct ethanol fuel cells," *Journal of Power Sources*, 2008, v. 180, pp. 238-242.

Ribeiro J., Dos Anjos D.M., Kokoh K.B., Coutanceau C., Léger J.M., Olivi P., De Andrade A.R., and Tremiliosi-Filho G., "Carbon-supported ternary PtSnIr catalysts for direct ethanol fuel cell," *Electrochimica Acta*, 2007, v. 52, pp. 6997-7006.

Ribeiro J., Dos Anjos D.M., Léger J.M., Hahn F., Olivi P., De Andrade A.R., Tremiliosi-Filho G., and Kokoh K.B., "Effect of W on PtSn/C catalysts for ethanol electrooxidation," *Journal of Applied Electrochemistry*, 2008, v. 38, pp. 653-662.

Rikukawa M., and Sanui K., "Proton-conducting polymer electrolyte membranes based on hydrocarbon polymers," *Progress in Polymer Science*, 2000, v. 25, pp. 1463-1502.

Rizo R., Sebastián D., Lázaro M.J., and Pastor E., "On the design of Pt–Sn efficient catalyst for carbon monoxide and ethanol oxidation in acid and alkaline media," *Applied Catalysis B: Environmental*, 2017b, v. 200, pp. 246-254.

Rizo R., Sebastián D., Rodríguez J.L., Lázaro M.J., and Pastor E., "Influence of the nature of the carbon support on the activity of Pt/C catalysts for ethanol and carbon monoxide oxidation," *Journal of Catalysis*, 2017a, v. 348, pp. 22-28.

Roca-Ayats M., García G., Soler-Vicedo M., Pastor E., Lázaro M.J., and Martínez-Huerta M.V., "The role of Sn, Ru and Ir on the ethanol electrooxidation on Pt₃M/TiCN electrocatalysts," *International Journal of Hydrogen Energy*, 2015, v. 40, pp. 14519-14528.

Rolison D.R., Hagans P.L., Swider K.E., and Long J.W., "Role of hydrous ruthenium oxide in Pt–Ru direct methanol fuel cell anode electrocatalysts: the importance of mixed electron/proton conductivity," *Langmuir*, 1999, v. 15, pp. 774-779.

Romero-Cano L.A., Rosado-Ortiz G., Valenzuela-Muñiz A.M., Ordóñez L.C., Gauvin R., and Gómez Y.V., "Solvent effect in the synthesis of nanostructured Pt–Sn/CNT as electrocatalysts for the electrooxidation of ethanol," *International Journal of Hydrogen Energy*, 2019, v. 44, pp. 12430-12438.

Rousseau S., Coutanceau C., Lamy C., and Léger J.M., "Direct ethanol fuel cell (DEFC): electrical performances and reaction products distribution under operating conditions with different platinum-based anodes," *Journal of Power Sources*, 2006, v. 158, pp. 18-24.

- Saleem F., Zhang Z., Xu B., Xu X., He P., and Wang X., "Ultrathin Pt–Cu nanosheets and nanocones," *Journal of the American Chemical Society*, 2013, v. 135, pp. 18304-18307.
- Salgado J.R., Alcaide F., Álvarez G., Calvillo L., Lázaro M.J., and Pastor E., "Pt–Ru electrocatalysts supported on ordered mesoporous carbon for direct methanol fuel cell," *Journal of Power Sources*, 2010, v. 195, pp. 4022-4029.
- Samad S., Loh K.S., Wong W.Y., Lee T.K., Sunarso J., Chong S.T., and Daud W.R., "Carbon and non-carbon support materials for platinum-based catalysts in fuel cells," *International Journal of Hydrogen Energy*, 2018, v. 43, pp. 7823-7854.
- Schmidt V.M., Ianniello R., Pastor E., and González S., "Electrochemical reactivity of ethanol on porous Pt and PtRu: Oxidation/reduction reactions in 1 M HClO₄," *The Journal of Physical Chemistry*, 1996, v. 100, pp. 17901-17908.
- Şen S., Şen F., and Gökağaç G., "Preparation and characterization of nano-sized Pt–Ru/C catalysts and their superior catalytic activities for methanol and ethanol oxidation," *Physical Chemistry Chemical Physics*, 2011, v. 13, pp. 6784-6792.
- Seweryn J., and Lewera A., "Electrooxidation of ethanol on carbon-supported Pt–Pd nanoparticles," *Journal of Power Sources*, 2012, v. 205, pp. 264-271.
- Shah A.A., Ralph T.R., and Walsh F.C., "Modeling and simulation of the degradation of perfluorinated ion-exchange membranes in PEM fuel cells," *Journal of the Electrochemical Society*, 2009, v. 156, pp. B465- B484.
- Sharaf O.Z., and Orhan M.F., "An overview of fuel cell technology: Fundamentals and applications," *Renewable and Sustainable Energy Reviews*, 2014, v. 32, pp. 810-853.
- Sharifi S., Rahimi R., Mohebbi-Kalhor D., and Colpan C.O., "Coupled computational fluid dynamics-response surface methodology to optimize direct methanol fuel cell performance for greener energy generation," *Energy*, 2020, v. 198, pp. 117293-117302.
- Sharma R., Bisen D.P., Shukla U., and Sharma B.G., "X-ray diffraction: a powerful method of characterizing nanomaterials," *Recent Research in Science and Technology*, 2012, v. 4, pp. 77-79.
- Shen S.Y., Zhao T.S., and Xu J.B., "Carbon supported PtRh catalysts for ethanol oxidation in alkaline direct ethanol fuel cell," *International Journal of Hydrogen Energy*, 2010, v. 35, pp. 12911-12917.
- Shen Y., Xiao K., Xi J., and Qiu X., "Comparison study of few-layered graphene supported platinum and platinum alloys for methanol and ethanol electro-oxidation," *Journal of Power Sources*, 2015, v. 278, pp. 235-244.

- Siahroudi M.G., Daryakenari A.A., Cao Q., Daryakenari M.A., Delaunay J.J., Siavoshi H., and Molaei F., "Ethylene glycol assisted solvo-hydrothermal synthesis of NGr-Co₃O₄ nanostructures for ethanol electrooxidation," *International Journal of Hydrogen Energy*, 2020, v. 45, pp. 30357-30366.
- Sieben J.M., and Duarte M.M., "Methanol, ethanol and ethylene glycol electro-oxidation at Pt and Pt–Ru catalysts electrodeposited over oxidized carbon nanotubes," *International Journal of Hydrogen Energy*, 2012, v. 37, pp. 9941-9947.
- Silva-Junior L.C., Maia G., Passos R.R., de Souza E.A., Camara G.A., and Giz M.J., "Analysis of the selectivity of PtRh/C and PtRhSn/C to the formation of CO₂ during ethanol electrooxidation," *Electrochimica Acta*, 2013, v. 112, pp. 612-619.
- Simões F.C., Dos Anjos D.M., Vigier F., Léger J.M., Hahn F., Coutanceau C., Gonzalez E.R., Tremiliosi-Filho G., De Andrade A.R., Olivi P., and Kokoh K.B., "Electroactivity of tin modified platinum electrodes for ethanol electrooxidation," *Journal of Power Sources*, 2007, v. 167, pp. 1-10.
- Simonetti D.A., Kunkes E.L., and Dumesic J.A., "Gas-phase conversion of glycerol to synthesis gas over carbon-supported platinum and platinum–rhenium catalysts," *Journal of Catalysis*, 2007, v. 247, pp. 298-306.
- Singh S., and Datta J., "Kinetic investigations and product analysis for optimizing platinum loading in direct ethanol fuel cell (DEFC) electrodes," *Ionics*, 2011, v. 17, pp. 785-798.
- Song S., Zhou W., Tian J., Cai R., Sun G., Xin Q., Kontou S., and Tsiakaras P., "Ethanol crossover phenomena and its influence on the performance of DEFC," *Journal of Power Sources*, 2005, v. 145, pp. 266-271.
- Soundararajan D., Park J.H., Kim K.H., and Ko J.M., "Pt–Ni alloy nanoparticles supported on CNF as catalyst for direct ethanol fuel cells," *Current Applied Physics*, 2012, v. 12, pp. 854-859.
- Spinacé E.V., Neto A.O., Vasconcelos T.R., and Linardi M., "Electro-oxidation of ethanol using PtRu/C electrocatalysts prepared by alcohol-reduction process," *Journal of Power Sources*, 2004, v. 137, pp. 17-23.
- Stobinski L., Lesiak B., Kövér L., Tóth J., Biniak S., Trykowski G., and Judek J., "Multiwall carbon nanotubes purification and oxidation by nitric acid studied by the FTIR and electron spectroscopy methods," *Journal of Alloys and Compounds*, 2010, v. 501, pp. 77-84.
- Sudachom N., Warakulwit C., Prapainainar C., Witoon T., and Prapainainar P., "One step NaBH₄ reduction of Pt-Ru-Ni catalysts on different types of carbon supports for direct ethanol fuel cells: Synthesis and characterization," *Journal of Fuel Chemistry and Technology*, 2017, v. 45, pp. 596-607.

- Tang J., Yang J., Zhou X., Xie J., and Chen G., "Oxidation of acetylene black by nitric acid in hermetically sealed condition," *Microporous and Mesoporous Materials*, 2014, v. 193, pp. 54-60.
- Tayal J., Rawat B., and Basu S., "Bi-metallic and tri-metallic Pt–Sn/C, Pt–Ir/C, Pt–Ir–Sn/C catalysts for electro-oxidation of ethanol in direct ethanol fuel cell," *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 14884-14897.
- Tayal J., Rawat B., and Basu S., "Effect of addition of rhenium to Pt-based anode catalysts in electro-oxidation of ethanol in direct ethanol PEM fuel cell," *International Journal of Hydrogen Energy*, 2012, v. 37, pp. 4597-4605.
- Teixeira F.C., de Sá A.I., Teixeira A.P., and Rangel C.M., "Nafion phosphonic acid composite membranes for proton exchange membranes fuel cells," *Applied Surface Science*, 2019, v. 487, pp. 889-897.
- Themsirimongkon S., Sarakonsri T., Lapanantnoppakhun S., Jakmunee J., and Saipanya S., "Carbon nanotube-supported Pt-Alloyed metal anode catalysts for methanol and ethanol oxidation," *International Journal of Hydrogen Energy*, 2019, v. 44, pp. 30719-30731.
- Theodore M., Hosur M., Thomas J., and Jeelani S., "Influence of functionalization on properties of MWCNT–epoxy nanocomposites," *Materials Science and Engineering: A*, 2011, v. 528, pp. 1192-1200.
- Tian X.K., Zhao X.Y., Yang C., Pi Z.B., and Zhang S.X., "Performance of ethanol electro-oxidation on Ni–Cu alloy nanowires through composition modulation," *Nanotechnology*, 2008, v. 19, pp. 215711-215716.
- Toda T., Igarashi H., Uchida H., and Watanabe M., "Enhancement of the electroreduction of oxygen on Pt alloys with Fe, Ni, and Co.," *Journal of the Electrochemical Society*, 1999, v. 146, pp. 3750-3756.
- Torrero J., Pérez-Alonso F.J., Peña M.A., Domínguez C., Al-Youbi A.O., Al-Thabaiti S.A., Basahel S.N., Alshehri A.A., and Rojas S., "In situ infrared study of the electrooxidation of ethanol and acetaldehyde in acid electrolyte," *ChemElectroChem*, 2016, v. 3, pp. 1072-1083.
- Tóth M., Varga E., Oszkó A., Baán K., Kiss J., and Erdőhelyi A., "Partial oxidation of ethanol on supported Rh catalysts: Effect of the oxide support," *Journal of Molecular Catalysis A: Chemical*, 2016, v. 411, pp. 377-387.
- Uchida M., Fukuoka Y., Sugawara Y., Eda N., and Ohta A., "Effects of microstructure of carbon support in the catalyst layer on the performance of polymer-electrolyte fuel cells," *Journal of the Electrochemical Society*, 1996, 143, pp. 2245-2252.

- Velazquez-Palenzuela A., Centellas F., Garrido J.A., Arias C., Maria Rodriguez R., Brillas E., and Cabot P.L., "Structural properties of unsupported Pt– Ru nanoparticles as anodic catalyst for proton exchange membrane fuel cells," *The Journal of Physical Chemistry C*, 2010, v. 114, pp. 4399-4407.
- Vigier F., Rousseau S., Coutanceau C., Leger J.M., and Lamy C., "Electrocatalysis for the direct alcohol fuel cell," *Topics in Catalysis*, 2006, v. 40, pp. 111-121.
- Vigier F.A., Coutanceau C.H., Hahn F.R., Belgsir E.M., and Lamy C.L., "On the mechanism of ethanol electro-oxidation on Pt and PtSn catalysts: electrochemical and in situ IR reflectance spectroscopy studies," *Journal of Electroanalytical Chemistry*, 2004, v. 563, pp. 81-89.
- Vyas A.N., Desai M.A., Phase D.M., Saratale R.G., Ambekar J.D., Kale B.B., Pathan H.M., and Sartale S.D., "Nickel nanoparticles grown by successive ionic layer adsorption and reaction method for ethanol electrooxidation and electrochemical quartz crystal microbalance study," *New Journal of Chemistry*, 2019, v. 43, pp. 2955-2965.
- Vyas A.N., Saratale G.D., and Sartale S.D., "Recent developments in nickel based electrocatalysts for ethanol electrooxidation," *International Journal of Hydrogen Energy*, 2020, v. 45, pp. 5928-5947.
- Wang G., Takeguchi T., Muhamad E.N., Yamanaka T., and Ueda W., "Investigation of grain boundary formation in PtRu/C catalyst obtained in a polyol process with post-treatment," *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 3322-3332.
- Wang G., Takeguchi T., Muhamad E.N., Yamanaka T., Sadakane M., and Ueda W., "Preparation of well-alloyed PtRu/C catalyst by sequential mixing of the precursors in a polyol method," *Journal of The Electrochemical Society*, 2009, v. 156, pp. B1348-B1353.
- Wang H., Jusys Z., and Behm R.J., "Ethanol electro-oxidation on carbon-supported Pt, PtRu and Pt₃Sn catalysts: A quantitative DEMS study," *Journal of Power Sources*, 2006, v. 154, pp. 351-359.
- Wang K., Wang F., Zhao Y., and Zhang W., "Surface-tailored PtPdCu ultrathin nanowires as advanced electrocatalysts for ethanol oxidation and oxygen reduction reaction in direct ethanol fuel cell," *Journal of Energy Chemistry*, 2021, v. 52, pp. 251-261.
- Wang L., Li L., Shen J., Gao H., Sun J., Wang H., and Cao Y., "High conductivity and anti-corrosive tantalum surface modified ferritic stainless steel bipolar plate for direct ethanol fuel cell," *Results in Physics*, 2019, v. 14, pp. 102394-102397.
- Wang P., Wen Y., Yin S., Wang N., and Shen P.K., "PtRh alloys on hybrid TiO₂–Carbon support as high efficiency catalyst for ethanol oxidation" *International Journal of Hydrogen Energy*, 2017, v. 42, pp. 24689-24696.
- Wang X., and Economides M., *Advanced natural gas engineering*, Elsevier, 2013.

Wang Y., Song S., Andreadis G., Liu H., and Tsiakaras P., "Understanding the electrocatalytic activity of Pt_xSn_y in direct ethanol fuel cells," *Journal of Power Sources*, 2011, v. 196, pp. 4980-4986.

Wang Y., Zhang J., Wang X., Ren J., Zuo B., and Tang Y., "Metal nanoclusters stabilized with simple ions and solvents-promising building blocks for future catalysts," *Topics in Catalysis*, 2005, v. 35, pp. 35-41.

Wang Z.B., Yin G.P., and Lin Y.G., "Synthesis and characterization of PtRuMo/C nanoparticle electrocatalyst for direct ethanol fuel cell," *Journal of Power Sources*, 2007, v. 170, pp. 242-250.

Wang Z.B., Yin G.P., Zhang J., Sun Y.C., and Shi P.F., "Investigation of ethanol electrooxidation on a Pt-Ru-Ni/C catalyst for a direct ethanol fuel cell," *Journal of Power Sources*, 2006, v. 160, pp. 37-43.

Wikander K., Ekström H., Palmqvist A.E., Lundblad A., Holmberg K., and Lindbergh G., "Alternative catalysts and carbon support material for PEMFC," *Fuel Cells*, 2006, v. 6, pp. 21-25.

Wnuk P., and Lewera A., "On-line analysis of ethanol electrochemical oxidation process in a low-temperature direct ethanol fuel cell," *Electrochimica Acta*, 2020, v. 330, pp. 135256-135267.

Xing Y., "Synthesis and electrochemical characterization of uniformly-dispersed high loading Pt nanoparticles on sonochemically-treated carbon nanotubes," *The Journal of Physical Chemistry B*, 2004; v. 108, pp. 19255-19259.

Xu M.W., Su Z., Weng Z.W., Wang Z.C., and Dong B., "An approach for synthesizing PtRu/MWCNT nanocomposite for methanol electro-oxidation," *Materials Chemistry and Physics*, 2010, v. 124, pp. 785-790.

Yang B., Lu Q., Wang Y., Zhuang L., Lu J., Liu P., Wang J., and Wang R., "Simple and low-cost preparation method for highly dispersed PtRu/C catalysts," *Chemistry of Materials*, 2003, v. 15, pp. 3552-3557.

Yang J., Deivaraj T.C., Too H.P., and Lee J.Y., "Acetate stabilization of metal nanoparticles and its role in the preparation of metal nanoparticles in ethylene glycol," *Langmuir*, 2004, v. 20, pp. 4241-4245.

Yang X., Zheng J., Zhen M., Meng X., Jiang F., Wang T., Shu C., Jiang L., and Wang C., "A linear molecule functionalized multi-walled carbon nanotubes with well dispersed PtRu nanoparticles for ethanol electro-oxidation," *Applied Catalysis B: Environmental*, 2012, v. 121, pp. 57-64.

You P.Y., and Kamarudin S.K., "Recent progress of carbonaceous materials in fuel cell applications: An overview," *Chemical Engineering Journal*, 2017, v. 309, pp. 489-502.

Zainoodin A.M., Kamarudin S.K., Masdar M.S., Daud W.R., Mohamad A.B., and Sahari J., "Optimization of a porous carbon nanofiber layer for the membrane electrode assembly in DMFC," *Energy Conversion and Management*, 2015, v. 101, pp. 525-531.

Zakaria Z., Kamarudin S.K., and Timmiati S.N., "Membranes for direct ethanol fuel cells: an overview," *Applied Energy*, 2016, v. 163, pp. 334-342.

Zakil F.A., Kamarudin S.K., and Basri S., "Modified Nafion membranes for direct alcohol fuel cells: An overview," *Renewable and Sustainable Energy Reviews*, 2016, v. 65, pp. 841-852.

Zhang H., and Shen P.K., "Advances in the high performance polymer electrolyte membranes for fuel cells," *Chemical Society Reviews*, 2012, v. 41, pp. 2382-2394.

Zhang L., Chae S.R., Hendren Z., Park J.S., and Wiesner M.R., "Recent advances in proton exchange membranes for fuel cell applications," *Chemical Engineering Journal*, 2012, v. 204, pp. 87-97.

Zhao Y., Yang X., Tian J., Wang F., and Zhan L., "A facile and novel approach toward synthetic polypyrrole oligomers functionalization of multi-walled carbon nanotubes as PtRu catalyst support for methanol electro-oxidation," *Journal of Power Sources*, 2010, v. 195, pp. 4634-4640.

Zhiani M., Gasteiger H.A., Piana M., and Catanorchi S., "Comparative study between platinum supported on carbon and non-noble metal cathode catalyst in alkaline direct ethanol fuel cell (ADEFC)," *International Journal of Hydrogen Energy*, 2011, v. 36, pp. 5110-5116.

Zhiani M., Jalili J., Rezaei B., and Taghiabadi M.M., "Methanol electrooxidation on synthesized PtRu nanocatalyst supported on acetylene black in half cell and in direct methanol fuel cell," *International Journal of Hydrogen Energy*, 2013, v. 38, pp. 5419-5424.

Zhou W., Apkarian R., Wang Z.L., and Joy D., *Fundamentals of scanning electron microscopy (SEM)*. In *Scanning microscopy for nanotechnology*, Springer, New York, NY, 2006.

Zhou W., Zhou Z., Song S., Li W., Sun G., Tsiakaras P., and Xin Q., "Pt based anode catalysts for direct ethanol fuel cells," *Applied Catalysis B: Environmental*, 2003, v. 46, pp. 273-285.

Zhou W.J., Li W.Z., Song S.Q., Zhou Z.H., Jiang L.H., Sun G.Q., Xin Q., Pouliaitis K., Kontou S., and Tsiakaras P., "Bi- and tri-metallic Pt-based anode catalysts for direct ethanol fuel cells," *Journal of Power Sources*, 2004, v. 131, pp. 217-223.

Zhou W.J., Song S.Q., Li W.Z., Zhou Z.H., Sun G.Q., Xin Q., Douvartzides S., and Tsiakaras P., "Direct ethanol fuel cells based on PtSn anodes: the effect of Sn content on the fuel cell performance," *Journal of Power Sources*, 2005, v. 140, pp. 50-58.

Zhu F., Kim J., Tsao K.C., Zhang J., and Yang H., "Recent development in the preparation of nanoparticles as fuel cell catalysts," *Current Opinion in Chemical Engineering*, 2015, v. 8, pp. 89-97.

Zhu Y., Bu L., Shao Q., and Huang X., "Subnanometer PtRh nanowire with alleviated poisoning effect and enhanced C–C bond cleavage for ethanol oxidation electrocatalysis," *ACS Catalysis*, 2019, v. 9, pp. 6607-6612.

Zignani S.C., Gonzalez E.R., Baglio V., Siracusano S., and Aricò A.S., "Investigation of a Pt₃Sn/C electro-catalyst in a direct ethanol fuel cell operating at low temperatures for portable applications," *International Journal of Electrochemical Science*, 2012, v. 7, pp. 3155-3166.

Zu C., Su Y.S., Fu Y., and Manthiram A., "Improved lithium–sulfur cells with a treated carbon paper interlayer," *Physical Chemistry Chemical Physics*, 2013, v. 15, pp. 2291-2297.

APPENDIX A

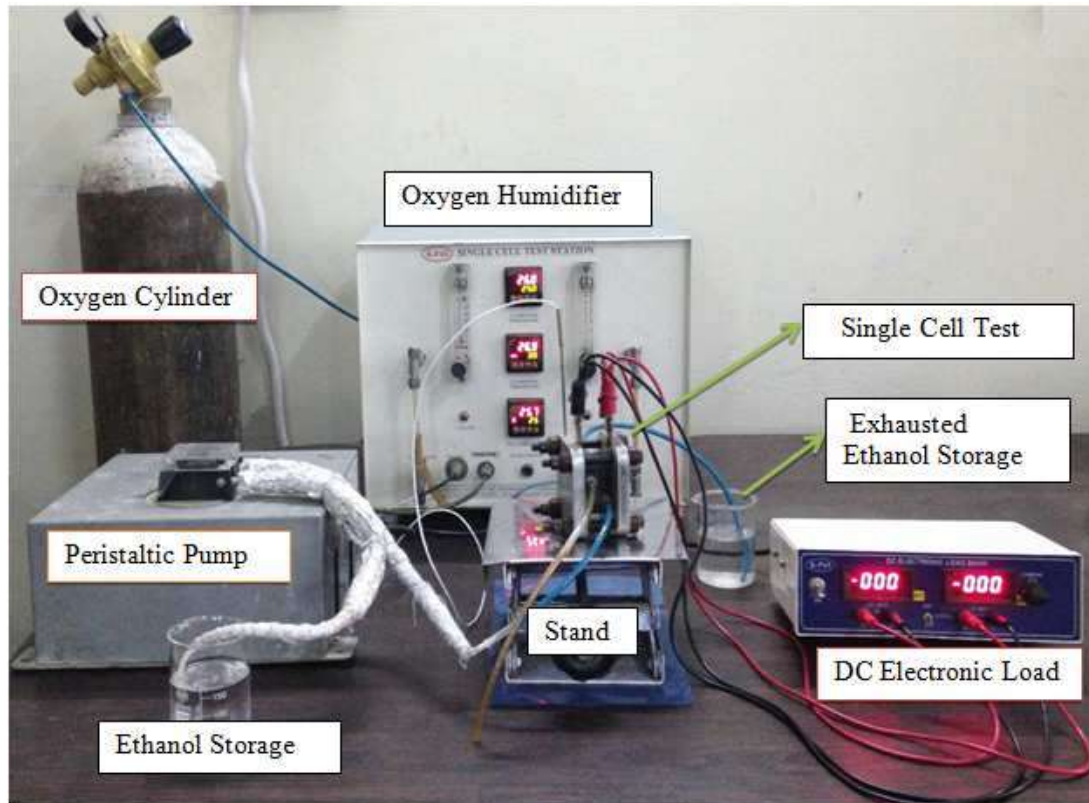


Figure A.1 The pictorial view of single DEFC experimental set-up.

APPENDIX B

The laboratory synthesized Pt-Ru-Re (1:1:0.5)/f-MWCNT and the commercial Pt/C_{HISPEC} were used for the preparation of anode and cathode electrodes for MEA fabrication, respectively. The commercial PEM Nafion[®] 117 was used for MEA fabrication and detail single cell study with various ethanol fuel concentrations, anode electrocatalyst loading and operating cell temperature were performed. The fixed cathode electrocatalyst loading of 1 mg/cm² was taken for all the experiments. The cathode oxidant used was humidified oxygen. The experimental results (current density vs. cell voltage and current density vs. power density characteristics) are given below:

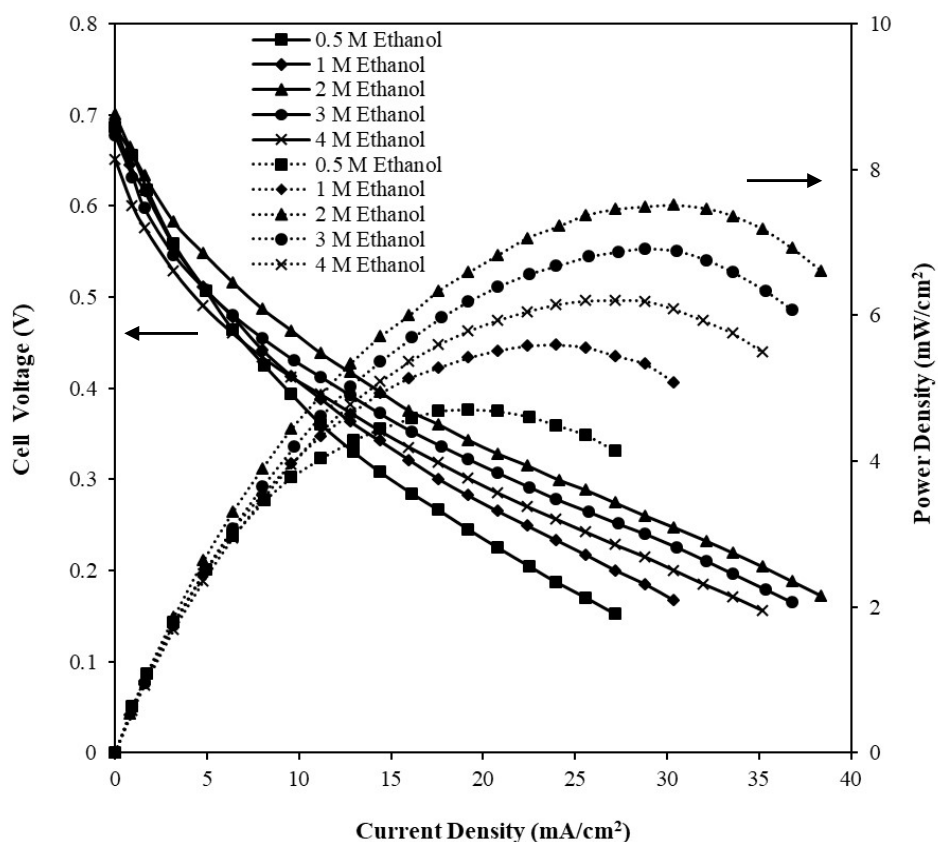


Figure B.1 Current density vs. cell voltage and power density curves for varying ethanol concentration (A), fixed anode electrocatalyst loading (B) of 0.5 mg/cm² and operating cell temperature (C) at 40 °C; Solid line -polarization curves, Dotted line- power density curves.

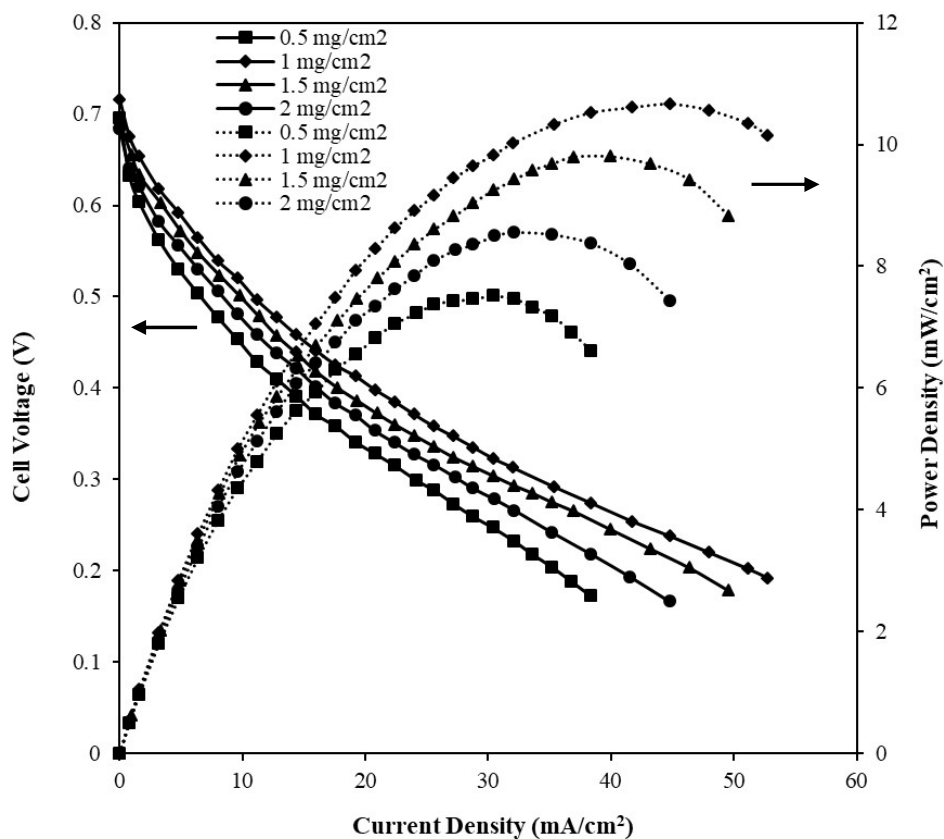


Figure B.2 Current density vs. cell voltage and power density curves for varying anode electrocatalyst loading (B), fixed ethanol concentration (A) of 2 M ethanol, operating cell temperature (C) at 40 °C ; Solid line -polarization curves, Dotted line- power density curves.

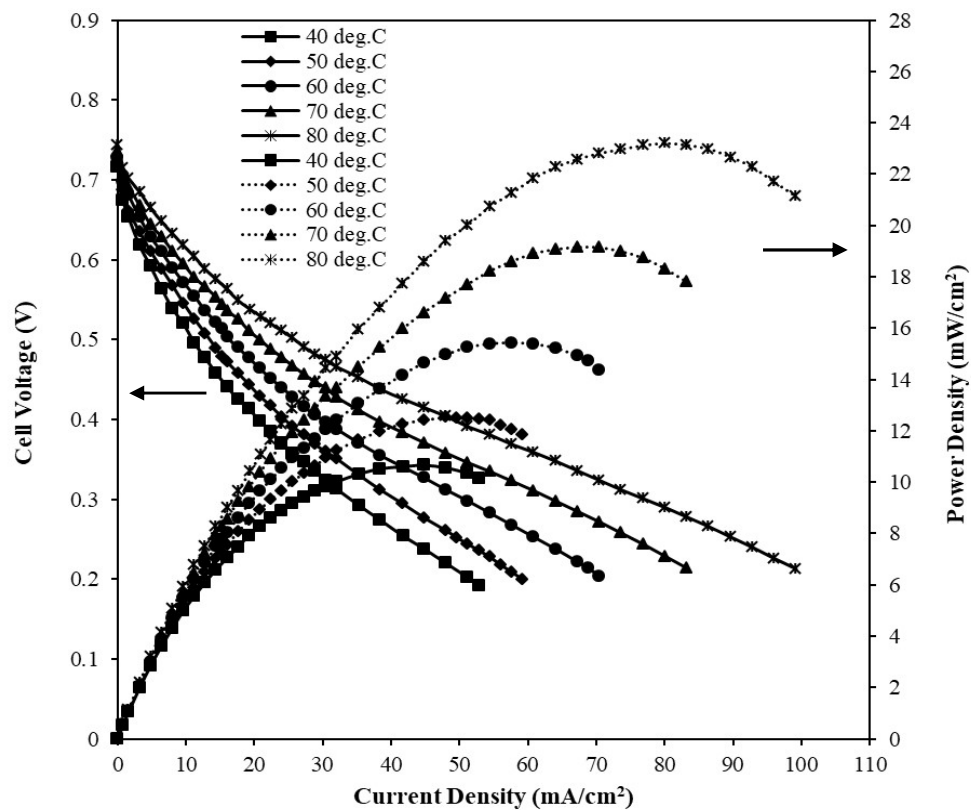


Figure B.3 Current density vs. cell voltage and power density curves for varying operating cell temperature (C), fixed ethanol concentration (A) of 2 M and anode electrocatalyst loading (B) of 1 mg/cm²; Solid line -polarization curves, Dotted line-power density curves.

APPENDIX C

The laboratory synthesized Pt-Ru/C_{AB}-FAM and commercial Pt-Ru/C were used as anode electrocatalyst, while Pt/C_{HiSPEC} was used as cathode electrocatalyst for MEA fabrication, respectively. The commercial PEM Nafion[®] 117 was used for MEA fabrication and detail single cell study with various ethanol fuel concentrations are presented below. The fixed cathode electrocatalyst loading of 1 mg/cm² was taken for all the experiments. The cathode oxidant used was humidified oxygen. The experimental results (current density vs. cell voltage and current density vs. power density characteristics) are given below:

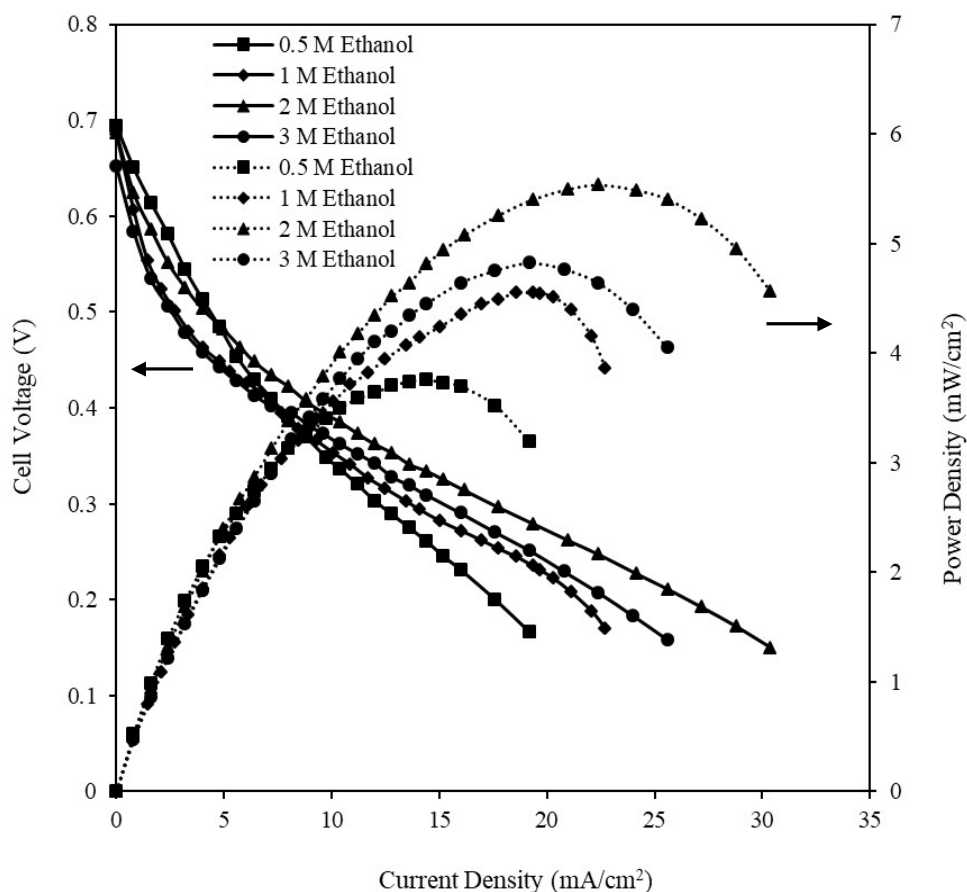


Figure C.1 Single cell performance characteristics for anode electrocatalyst Pt-Ru/C_{AB}-FAM using varying ethanol concentration as anode feed at a cell temperature of 35 °C. Cathode feed: pure humidified oxygen; $P_{\text{cathode}} = 1$ bar (absolute); Dotted line-power density curves; Solid line- polarization curves.

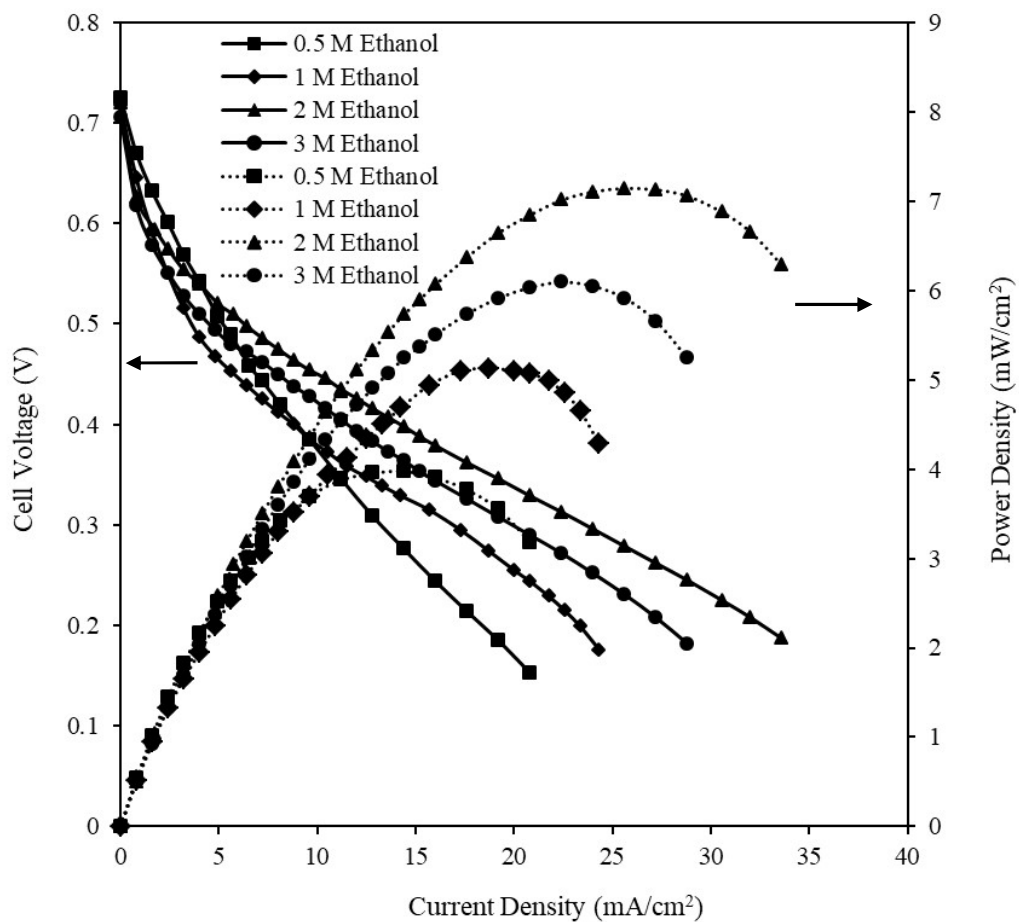


Figure C.2 Single cell performance characteristics for anode electrocatalyst commercial Pt-Ru/C using varying ethanol concentration as anode feed at a cell temperature of 35 °C. Cathode feed: pure humidified oxygen; $P_{\text{cathode}} = 1$ bar (absolute); Dotted line-power density curves; Solid line- polarization curves.

APPENDIX D

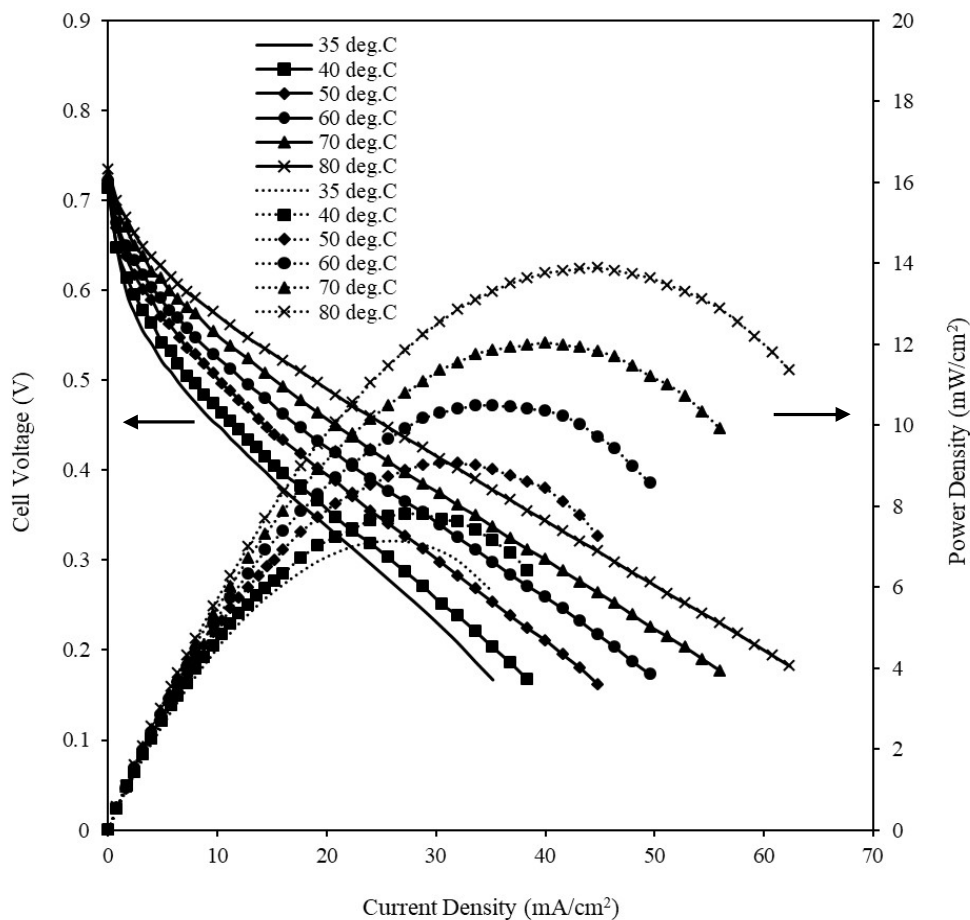


Figure D.1 Single cell performance characteristics for anode electrocatalyst commercial Pt-Ru/C using 2 M ethanol concentration as anode feed at varying cell temperature range of 35 °C to 80 °C. Cathode: Pt/C_{HISPEC} of 1 mg/cm²; Cathode feed: pure humidified oxygen; P_{cathode} = 1 bar (absolute); Dotted line-power density curves; Solid line-polarization curves.

APPENDIX E

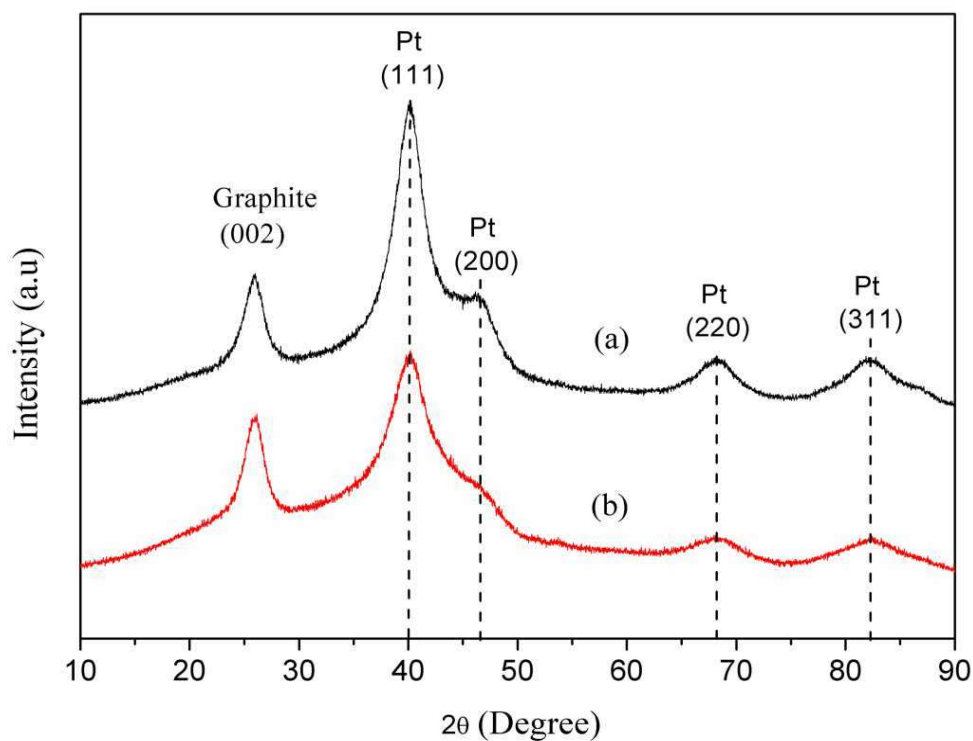


Figure E.1 XRD patterns of (a) Pt-Ru (1:1)/p-MWCNT and (b) Pt-Ru (1:1)/f-MWCNT electrocatalysts.

Table E.1 The Pt (220) peak, lattice parameters, and crystallographic properties of the electrocatalysts from XRD analysis.

Electrocatalysts	Pt (220) position (°)	Lattice parameter (nm)	Average crystallite size (d_c) (nm)	Ru fraction (x_{Ru})	Alloyed Ru (wt. %)
Pt-Ru (1:1)/p-MWCNT	68.10	0.3889	2.9	0.21	27
Pt-Ru (1:1)/f-MWCNT	68.30	0.3881	2.7	0.28	39

APPENDIX F

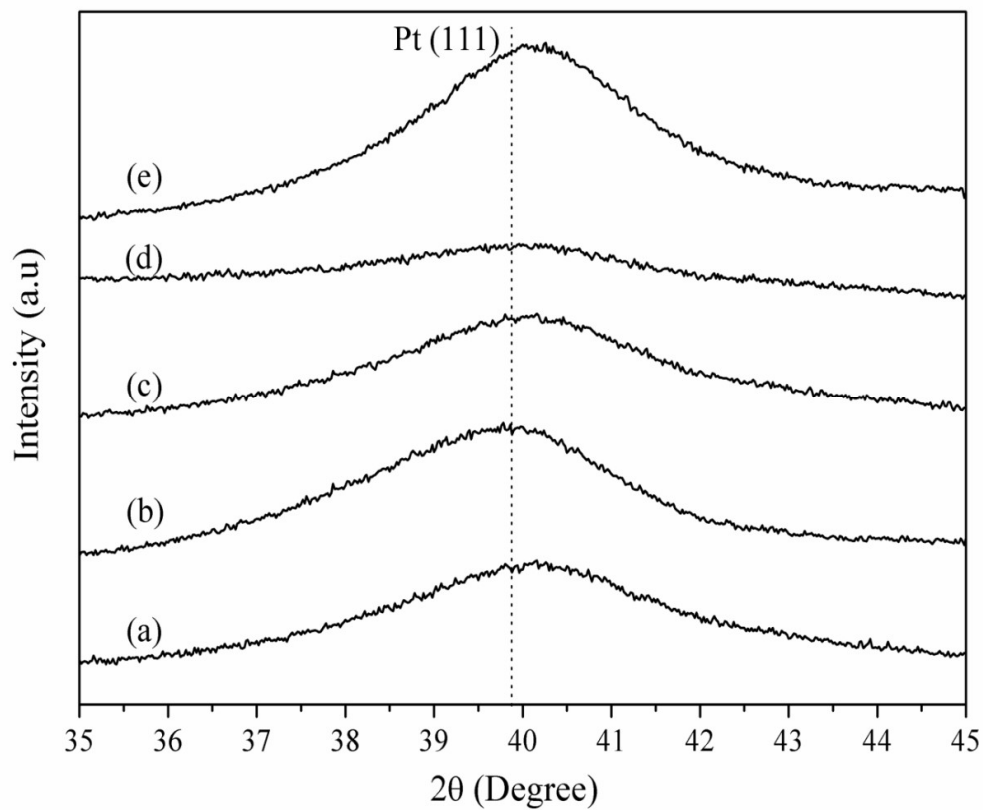


Figure F.1 Comparison of peaks (111) of (a) Pt-Ru (1:1)/f-MWCNT, (b) Pt-Re (1:1)/f-MWCNT, (c) Pt-Ru-Re (1:1:1)/f-MWCNT, (d) Pt-Ru-Re (1:1:0.5)/f-MWCNT and (e) Pt-Ru-Re (1:1:0.25)/f-MWCNT electrocatalysts.

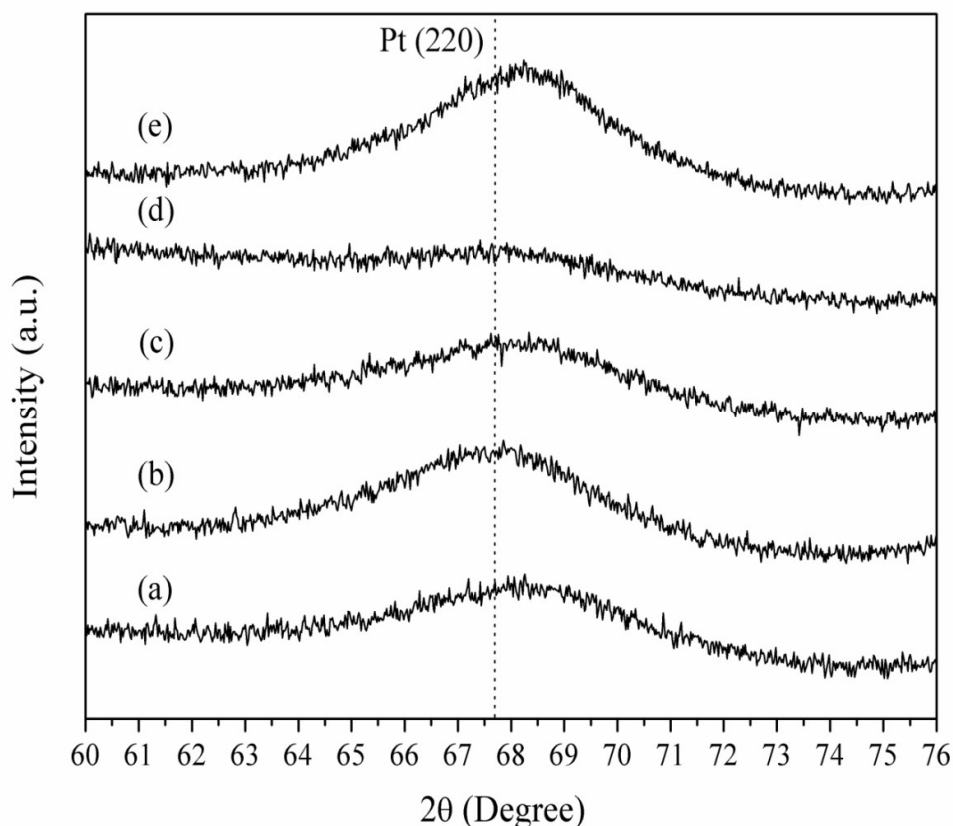


Figure F.2 Comparison of (220) peaks of (a) Pt-Ru (1:1)/f-MWCNT, (b) Pt-Re (1:1)/f-MWCNT, (c) Pt-Ru-Re (1:1:1)/f-MWCNT, (d) Pt-Ru-Re (1:1:0.5)/f-MWCNT and (e) Pt-Ru-Re (1:1:0.25)/f-MWCNT electrocatalysts.

Table F.1 The peak position 2θ ($^{\circ}$) values of the electrocatalysts from XRD analysis.

Electrocatalyst	Peak position, 2θ ($^{\circ}$)			
	Pt (111)	Pt (200)	Pt (220)	Pt (311)
Pt-Ru (1:1)/f-MWCNT	40.30	N.A	68.30	82.31
Pt-Re (1:1)/f-MWCNT	39.86	46.27	67.63	81.74
Pt-Ru-Re (1:1:1)/f-MWCNT	40.09	N.A	68.14	82.16
Pt-Ru-Re (1:1:0.5)/f-MWCNT	40.15	N.A	68.20	82.23
Pt-Ru-Re (1:1:0.25)/f-MWCNT)	40.20	46.47	68.24	82.26
Pure Pt (JCPDS card 04-0802)	39.76	46.24	67.45	81.28

NA- not available due to peak broadening.

APPENDIX G

The selected area electron diffraction (SAED) patterns of the synthesized electrocatalysts are shown in Fig (G.1a) to Fig (G.1e). The SAED patterns obtained for the Pt-Ru-Re (1:1:1)/f-MWCNT and Pt-Ru-Re (1:1:0.5)/f-MWCNT (Fig G.1c and Fig G.1d) electrocatalysts were found to be rather diffused with lower intensity of concentric fringes due to very small crystallite sizes as explained in XRD section. The XRD analysis (Fig G.1d and Fig G.1e) also showed broad diffraction peaks for these electrocatalysts. The electronic diffraction patterns of electrocatalysts reveal the polycrystalline phase of nanoparticles, which is also confirmed by annular patterns in SAED images (Fig G.1a to Fig G.1e). Moreover, the series of concentric rings together with some diffuse but distinct spots are assigned to hlk planes, which are characteristic of the Pt (fcc) crystal structure and consistent with the XRD results.

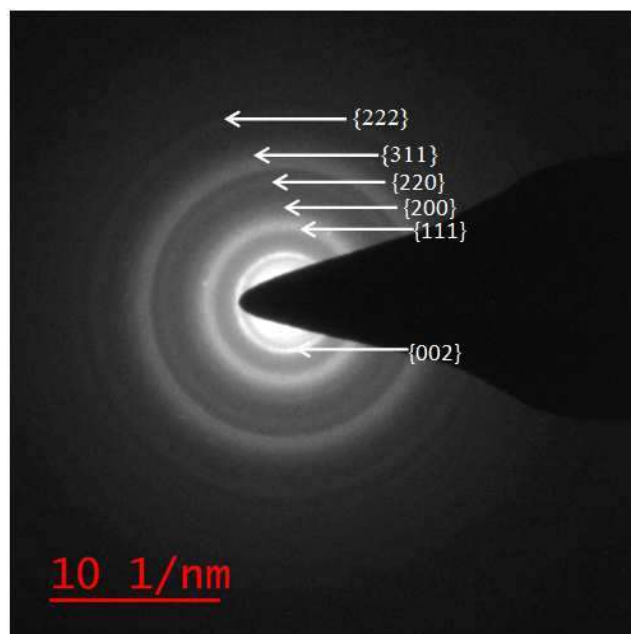


Figure G.1a SAED pattern of Pt-Ru (1:1)/f-MWCNT electrocatalyst.

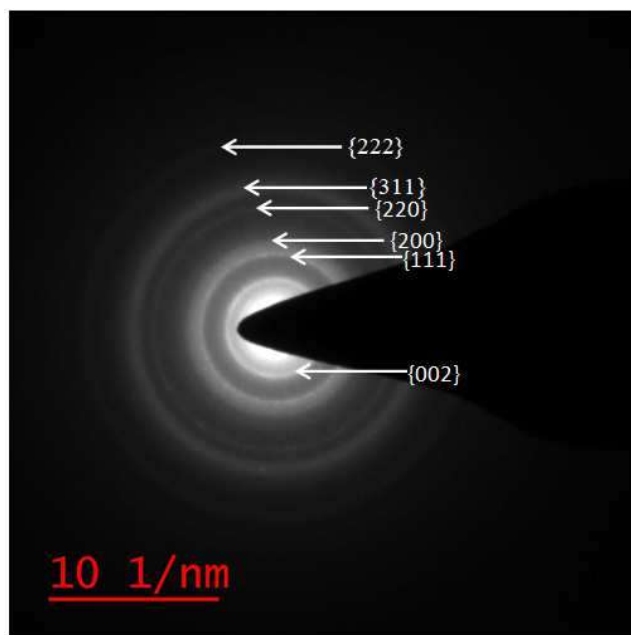


Figure G.1b SAED pattern of Pt-Re (1:1)/f-MWCNT electrocatalyst.

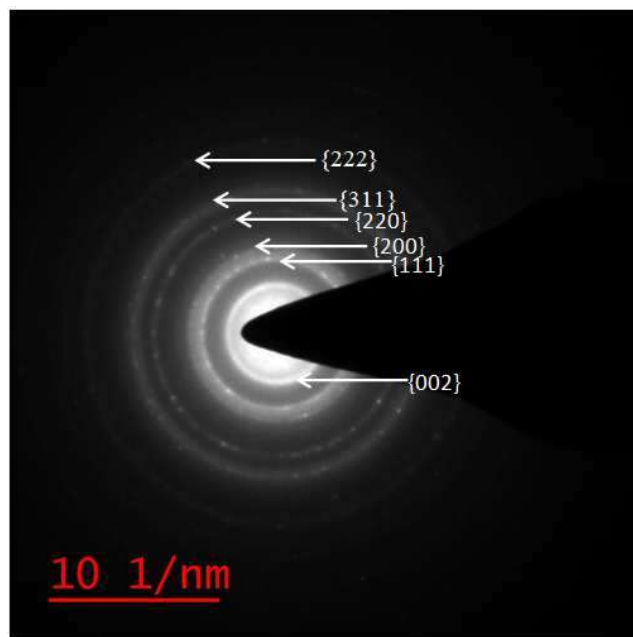


Figure G.1c SAED pattern of Pt-Ru-Re (1:1:1)/f-MWCNT electrocatalyst.

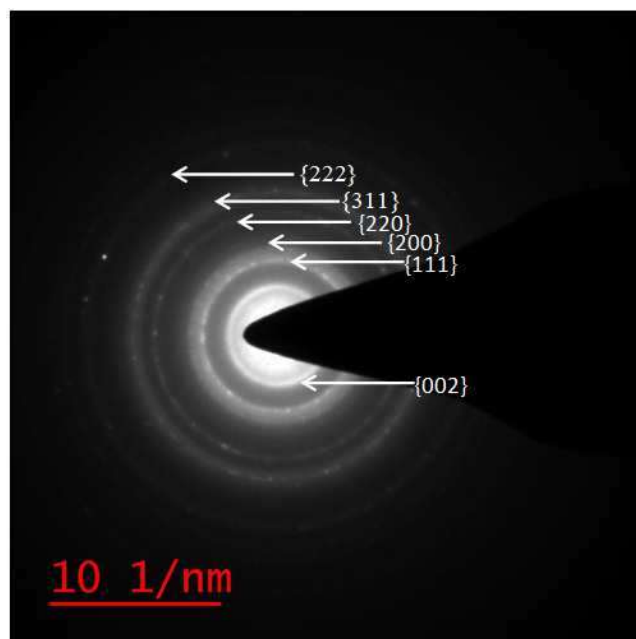


Figure G.1d SAED pattern of Pt-Ru-Re (1:1:0.5)/f-MWCNT electrocatalyst.

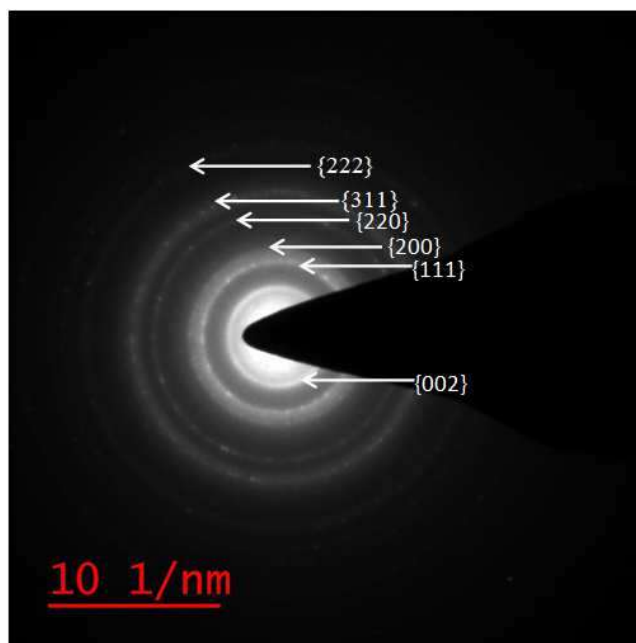


Figure G.1e SAED pattern of Pt-Ru-Re (1:1:0.25)/f-MWCNT electrocatalyst.

Publications from the work**Papers published in International Journal:**

Choudhary A.K., and Pramanik H., "Optimization and validation of process parameters via RSM for minimizing use of resources to generate electricity from a DEFC," **International Journal of Energy Research**, 2021, v. 45, pp. 20413-20429.

Choudhary A.K., and Pramanik H., "Effect of rhenium (Re) addition to Pt-Ru/f-MWCNT anode electrocatalysts for ethanol electrooxidation in half cell and single direct ethanol fuel cell," **International Journal of Hydrogen Energy**, 2020, v. 45, pp. 13300-13321.

Choudhary A.K., and Pramanik H., "Enhancement of ethanol electrooxidation in half cell and single direct ethanol fuel cell (DEFC) using post-treated polyol synthesized Pt-Ru nano electrocatalysts supported on HNO₃-functionalized acetylene black carbon," **International Journal of Hydrogen Energy**, 2020, v. 45, pp. 574-594.

Choudhary A.K., and Pramanik H., "Synthesis of low-cost HNO₃-functionalized acetylene black carbon supported Pt-Ru/C_{AB} nano electrocatalysts for the application in direct ethanol fuel cell (DEFC)," **Korean Journal of Chemical Engineering**, 2019, v. 36, pp. 1688-1707.

Papers/posters presented in conferences:

Choudhary A.K., and Pramanik H., 2018, "Ethanol Electrooxidation On Modified Polyol Synthesized Pt-Ru Nanocatalyst Supported On HNO₃-Functionalized Acetylene Black In Half Cell," 71th Annual session of IChE, **Chemcon 2018, Jalandhar**, Dec 27-30, 2018.

Choudhary A.K., and Pramanik H., 2017, "Comparative Study Of Influence Of The Synthesis Method On The Properties Of Pt-Ru Catalysts Supported On HNO₃-functionalized Acetylene Black For Ethanol Electrooxidation," 70th Annual session of IChE, **Chemcon 2017, Haldia**, Dec 27-30, 2017.

Choudhary A.K., and Pramanik H., 2017, "Synthesis of Pt-Ru/C electrocatalyst for proton exchange membrane (PEM) based direct alcohol fuel cells (DAFCs)," Institute day, Department of Chemical Engineering & Technology, **IIT (BHU), Varanasi- 221005**, Feb 25-26, 2017.

Choudhary A.K., and Pramanik H., 2016, "Catalysts For Direct Ethanol Fuel Cells (DEFC): An Overview," 69th Annual session of IChE, **Chemcon 2016, Chennai**, Dec 27-30, 2016.