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Non-Technical Project Task Assignment

Literature survey on fuel cell modeling: Automotive applications

submitted: October 27, 2022

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Task of the Non Technical Project in the Original:

Fuel cell technology is an important pillar for the wider use of regenerative energy, i.e. via intermediate storage as hydrogen. Replacing fossil fuel burning engines in automotive applications with fuel cells and electrical engines is one of the most promising ways to reduce local CO_2 emissions in the mobility and transport sector. Mathematical models of fuel cells can be used to improve their optimal and safe operation in automotive applications.

This work aims at providing an overview on the current state of the art of fuel cell modeling in automotive applications on the system level, namely of the fuell cell stack and peripheral components required for hydrogen supply, air supply, humidification, and cooling. The focus is on identifying high quality publications, i.e. those with well justified and documented models, and high quality active research groups.

The main objective of this work is literature analysis.

Declaration by the candidate

I hereby declare that this thesis is my own work and effort and that it has not been submitted anywhere for any award. Where other sources of information have been used, they have been marked.

The work has not been presented in the same or a similar form to any other testing authority and has not been made public.

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Magdeburg, October 27, 2022

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1 Introduction

Reducing the use of fossil fuels and moving towards sustainable forms of energy has been one of the most important challenges of the 21st century. Fossil fuels are not only dangerous to our environment but are also finite, it is estimated that we have only about 70-150 years until these resources deplete(Sopian and Wan Daud 2006; Daud et al. 2017). In the wide variety of renewable forms of energy, hydrogen is one of the promising fuels that could transform the way we use energy. Automobiles/ Transport sectors is one of the major forms of carbon pollution as well as a huge source of particulate matter emissions. Fuel cells are one potential alternative to replace the fossil fuel burning engine(Daud et al. 2017).

Significant improvements are being made in the design, control and development of fuel cells since their commercialization. This paper aims to provide an overview of the latest trends in Fuel cell modelling and its peripheral components in automotive vehicles. There are various types of fuel cells such as alkaline fuel cells (AFCs), direct methanol fuel cells (DMFCs), microbial fuel cell (MFCs), molten carbonate fuel cells (MCFCs), proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs)(Sopian and Wan Daud 2006; Daud et al. 2017). The focus of this paper is on Proton Exchange Membrane Fuel Cell also referred to as PEMFC's or PEM Fuel Cells. This field is a highly active area for research with research groups from various universities, research institutes and countries publishing their research in top journals. This paper aims to paint a big picture about the latest trends on Fuel cells in automotive applications particularly the work being done in modelling of fuel cells and its peripheral components such as humidifiers, air supply, hydrogen supply and cooling.

The research in PEM fuel cell modeling started with the works of Springer et al. and Bernadi and Verbrugge in 1990's, these were simple one dimensional models and continuous research has led to the development of complex 3D models since then(Secanell et al. 2017). There are currently different types of models that are being developed for different investigations, a fuel cell model would be broadly categorized in three categories "analytic, semi-empirical, or mechanistic (theoretical)"(Cheddie and Munroe 2005).A detailed chronological review about modeling of fuel cells can be found in the article by M.Secanell et.al(Secanell et al. 2017) however our study is focused on identifying the current state of art models which are well documented and are specifically focused towards fuel cells and its auxiliary components in an automotive setting.

This paper is mainly divided in four parts which are Data Collection, Quantitative

Analysis, Qualitative Analysis and Summary. In the first part we discuss on the selection of database and the method of collecting articles by means of a search expression. The method of formulating the search expression is discussed and the final outcome from the search is detailed. In the second and third part we interpret and analyse the collected articles with a variety of parameters and arrive at the conclusion in the last part.

2 Data Collection

2.1 Selection of database

To find an initial list of research articles three databases were compared which were Google scholar,Web of Science(WoS)and Scopus(Elsevier). The database was chosen based on a couple of criteria such as Advanced search, ability to add filters for multiple categories, ability to export the data for further processing. Although the results provided by these search engines were similar, each one of the databases had different features to search and filter the data. Google Scholar and WoS had an advanced search feature but the former did not have filters and the ability to export all results. Scopus had less filter options than WoS with the option of Publisher missing, it also did not have the ability to keep a history of searches and the export option provided a link in the mailbox to download the results with more papers taking higher processing time whereas WoS directly downloaded the result. Among the three databases only WoS provided the most features like Advanced Search, filters and the ability to export results in multiple formats such as excel and text and also provided extra insights such as author profiles, citations with its trends in a nice graph with a history of all the search results. Based on the criteria of having the most features and ease of use, WoS was chosen as the database to search the publications.

2.2 Formulating the Search Expression

The search for articles was done by adding relevant words to the search expression such as "PEM fuel cells", "automotive", "modelling", the words along with the logical operators(AND, OR, NOT) were added in the advanced search option available in the database. The aim was to formulate a search expression that could be used to collect a list of articles which would then be further analyzed. The search was done in sequential manner, first a broad set of search results were achieved and then the specific sub domain was singled out by adding more and more words to the search expression to further narrow our search.

The initial keywords used in the search expression were "PEM fuel cells" AND "automotive" AND "modelling" which gave an initial list of publications, in order to further focus the results which contain the words associated with auxiliary components we added more relevant words. Keywords such as "peripheral components", "auxiliary components", "humidifiers", "compressors" and "sensors" with an OR operator made sure that we include all the articles with the given search terms. The search terms also were added with an

capital letters and similar words such as"PEMFC", "modelling" and "modeling" however it was found that that the search engine provides both results regardless of the minor changes in search expressions. The 'All Fields' expression indicates that the database search was conducted on all the searchable fields inside the article such as topic, author, title, etc. The final search expression that provided the best set of results is given in Table2.1 below,

Search Expression
("automotive" OR "engine" OR "vehicle"(All Fields)) AND ("modelling" OR "modeling" OR "model"(All Fields)) AND ("PEMFC"OR "PEM fuel cell" OR "proton-exchange membrane fuel cells "OR "Hydrogen fuel cell"(All Fields)) AND ("systems" OR "system" OR "auxiliary component" OR "auxiliary components" OR "peripheral components" OR "air supply system" OR "compressors" OR "compressor" OR "Sensor" OR "sensors" OR "humidifiers" OR "humidifier" OR "pressure regulator" OR "controller "(All Fields))

Table 2.1: Final Search Expression

2.3 Outcome

The search was conducted in May 2022 hence the results include articles published before the given date. The initial key words yielded a total number of 865 publications, these publications however contained a huge number of articles which were not related to the intended search area, we also had to reduce these results to a practical number of publications which could then be further analyzed. A total of 571 published articles were found to be associated with the final search expression which is given in Table 2.1. After adding a filter to reduce the scope further to the most recent articles published from 2018 to 2022, a total of 293 publications were obtained. These publications were used for quantitative analysis, this further helped in choosing the articles for qualitative analysis.

3 Quantitative Analysis

Quantitative Analysis is a technique where analysis is done based on numerical figures rather than reason or logic. In our paper we analyse different aspects such as yearly distribution of articles, top publishers, top journals, etc. The data is helpful in knowing when and where most of the research is originating and being published.

3.1 Year-wise Distribution of articles

The number of articles published every year is plotted in Figure3.1, we observe that around 35 articles were published in 2018, 46 articles were published in 2019, 91 articles were published in 2020, 89 articles were published in 2021 and around 32 were published until May 2022. The figure shows the upward trend in the number of articles published every year indicating that research and publications in this field have been steadily rising.

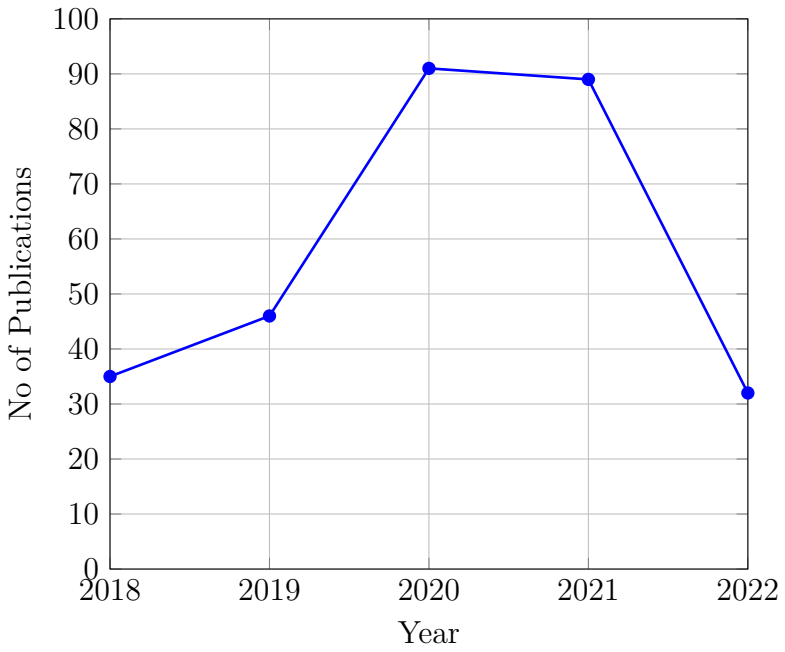

Figure 3.1: Year-wise distribution number of articles published

3.2 Top Publishers

The articles were published by a total of 26 different publishers, Figure 3.2 shows the distribution of articles among the top 5 publishers. It is observed that a huge majority

of articles are published by Elsevier which has published around 190 articles, followed by Mdpi which has published around 51 articles, IEEE which has published around 14 articles, Wiley which has published around 11 articles and Taylor and Francis which has published around 7 articles.

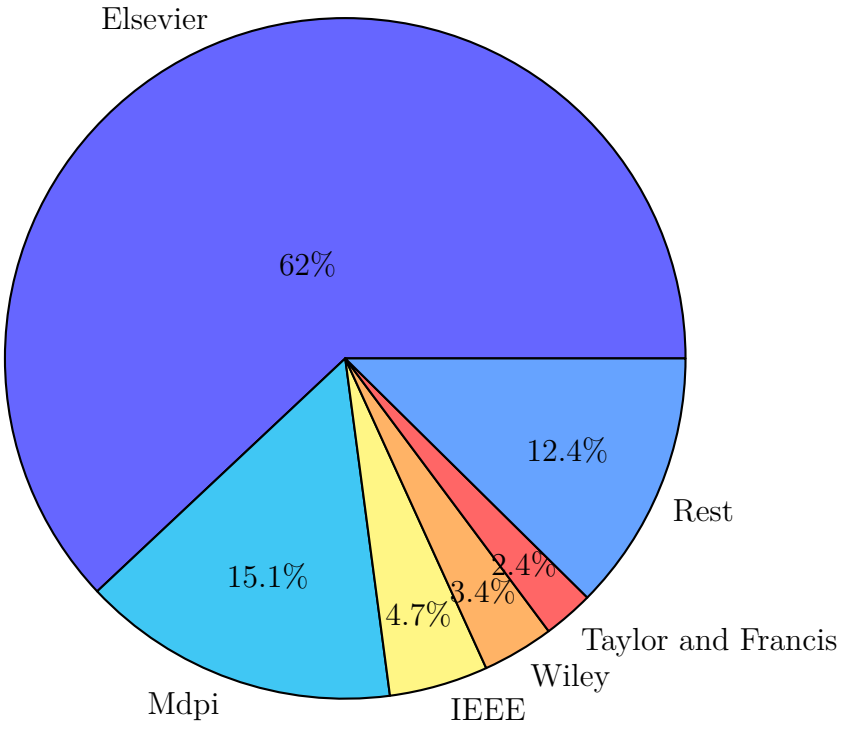

Figure 3.2: Distribution of articles by various Publishers

3.3 Top Journals

The Published articles were checked for their journal titles and it was found that the articles were published under a total of 77 journal titles. Table3.1 shows the the individual number of articles published by the top journals in the field of automotive PEM Fuel cells, applied energy and hydrogen energy. The top 7 Journals contributed around 176 articles which were around 60% of published articles.

Name of the Journal	Number of published articles
International journal of hydrogen energy	65
Energies	33
Energy conversion and management	26
Applied energy	19
Journal of power sources	12
Energy reports	11
Energy	10

Table 3.1: Table of journals with the number of published articles

3.4 Top Organizations/ Institutions

From the shortlisted articles for quantitative analysis it was found that globally around 200 institutions are publishing articles in the field of PEM Fuel cells. The top institutes are filtered with the criteria of number of publications, Table3.2 shows the top institutions and their contribution of articles. It is found that that top 10 institutions accounted for 43.8% of the articles published.

3.5 Country-wise distribution

Among the listed 56 countries it is observed that just 9 countries provided a significant contribution. The criteria for selecting the number of articles for each country was to look at the published articles per country, since a published article can have multiple authors from multiple countries, the figure is not a accurate representation of contributions of individual countries but shows the country of origin of the authors. The highest contribution of articles is by China having 132 articles followed by USA with 34 articles, France with 30 articles, South Korea with 21 articles, Canada with 20 articles, Iran with 18 articles, Turkey with 17 articles, England with 16 articles and Germany with 10 articles while the rest of the countries had published less than 10 articles. The distribution of the contribution of articles can be visualized effectively with the figure3.3 shown below.

[1]UNIVERSITY OF QUEBEC TROIS RIVIERES is a university within UNIVERSITY OF QUEBEC network which is a system of 10 provincially run universities
[2]INSIS is a research organization within CNRS

Institutions	Number of Publications
Centre National De La Recherche Scientifique (CNRS)	23
Universite De Technologie De Belfort Montbeliard(UTBM)	20
Tongji University	17
Tsinghua University	15
Chungnam National University	9
Islamic Azad University	9
Udice French Research Universities	9
University Of Quebec	9
University Of Quebec Trois Rivieres [1]	9
CNRS Institute For Engineering Systems Sciences (INSIS) [2]	8

Table 3.2: Top 10 Institutions and the number of publications

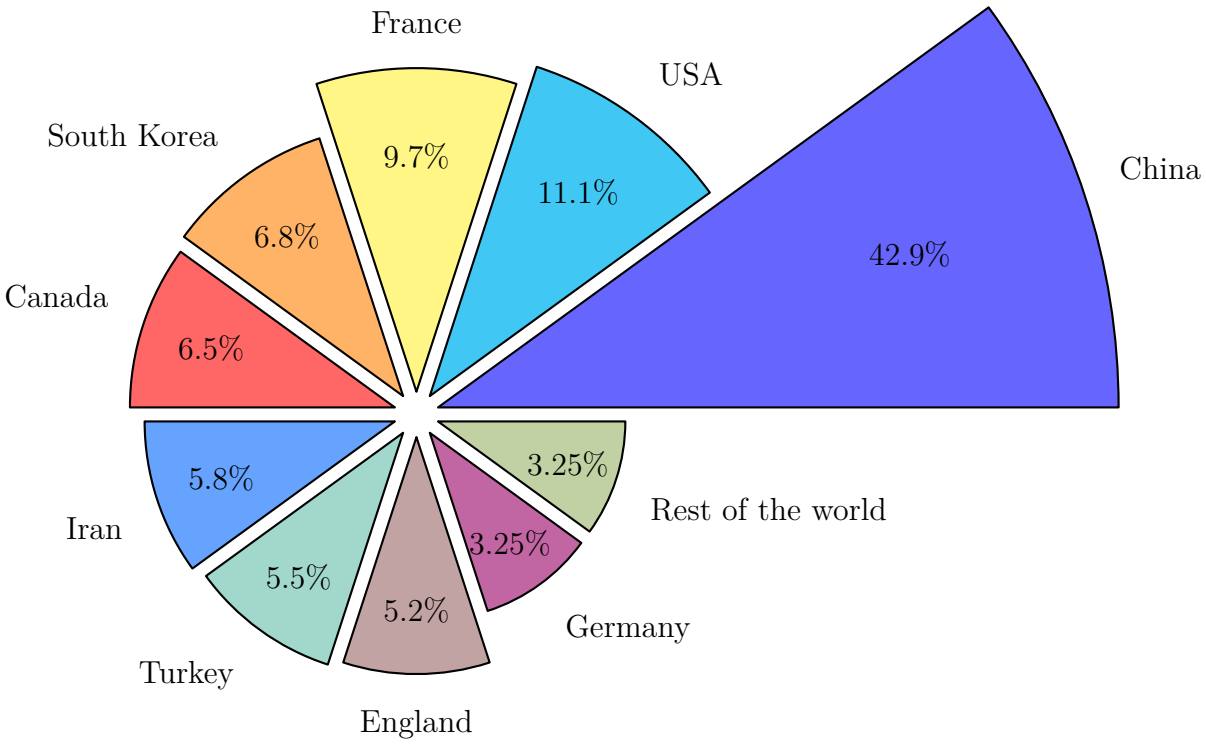

Figure 3.3: Polar Area Chart showing the distribution of articles among countries

3.6 Top Authors

A total of 200 authors have published articles in the field of PEM Fuel cell modeling. The criteria to select the top authors was the number of publications, since the field of PEM Fuel cell modeling is diverse the number of citations per article is very low. The list of authors with more than 6 publications is given below in Table3.3.

Author	No of Articles	Affiliation
Boulon, Loic	9	University of Quebec Trois Rivieres
Tu, Zhengkai	7	Huazhong University of Science & Technology
Djerdir, Abdesslem	7	Universite de Technologie de Belfort-Montbeliard (UTBM)
Laghrouche, Salah	6	Universite de Technologie de Belfort-Montbeliard (UTBM)
Zhang, Caizhi	6	Chongqing University
Kandidayeni, Mohsen	6	University of Quebec Trois Rivieres

Table 3.3: Top Authors

3.7 Active Research Groups

The list of active research groups were identified by considering the most recent articles published by a group of authors from the list of countries and institutes that had significant contribution to PEMFC research, these were identified while doing the analysis of top institutions and countrywise distribution. Given below is a list of top research groups and their Group leaders/ Researchers.

Short Summary of research groups

1. CEA which is the French Alternative Energies and Atomic Energy Commission is a research lab that participates is collaborative research along with research bodies, local authorities and universities. CEA is focused on two applications which is energy transport and storage. More information can be found at this link.

2. SHARPAC is a research team working on Hybrid electric systems, electric actuators, fuel cell systems under the institute “Franche-Comté Electronics Mechanics Thermal Science and Optics – Sciences and Technologies”(FEMTO-ST) which is a joint research institute under four universities.

Research Group/ Organization	Group Leaders/ Researchers
Commissariat à l'énergie atomique et aux énergies alternatives(CEA)	Sebastien Rosini
SHARPAC	Daniel Hissel
Energy Conversion System laboratory	Sangseok Yu, Jaeyoung Han
Institute for Hydrogen Research (IHR)	Sousso Kelouwani
Clean Energy Automotive Engineering Center (CEAEC)	
State Key Laboratory of Automotive Safety and Energy	Minggao Ouyang

Table 3.4: Research Groups

3. Energy Conversion System laboratory is a research team headed by Professor Sangseok Yu under the department of mechanical engineering of Chungnam National University. The institute conducts research in dynamic modeling of fuel cells, HILS based control strategy and many other topics that can be found on their website.

4. Institute for Hydrogen Research (IHR) is a research institute under Université du Québec à Trois-Rivières (UQTR), the institute is involved in fundamental as well as applied research. There are many groups working in the field of hydrogen production, storage, delivery, infrastructure as well as fuel cells.

5. CEAEC is a R&D center under the Tongji University, it has 5 R&D departments with one of them involved in Fuel Cell Systems. The researchers from this institute have published over 28 articles collaborating with different research institutes.

6. State Key Laboratory of Automotive Safety and Energy is a research institute under the Tsinghua University. The researchers working at this institute have published a significant amount of articles by collaborating with different international research institutes.

4 Qualitative Analysis

Qualitative analysis is a technique where data is gathered regarding a topic for research and analysed with words, attributes and properties rather than numbers. In our paper we select a list of articles and qualitatively analyse them based on a quality criteria as described below, the aim is to identify articles with the latest modelling techniques with well justified models.

4.1 Articles selected for Qualitative Analysis

The list of articles published by the top institutions was taken and a select list of articles which were found to be interesting were shortlisted for qualitative analysis, Table below lists the selected articles for the review.

Articles	Description
Performance analysis of PEM fuel cell in mobile application under real traffic and environmental conditions(Chen, Laghrouche, and Djerdir 2021)	Study on PEMFC performance under real traffic and environmental conditions with the help of semi empirical voltage model
Prognostic methods for proton exchange membrane fuel cell under automotive load cycling: a review(Jacome et al. 2020)	Study on the degradation mechanisms caused by Automotive load cycling and prognostics method review for automotive PEMFC's
Real time adaptive efficient cold start strategy for proton exchange membrane fuel cells(Amamou et al. 2018)	Proposal of a novel adaptive strategy for the cold start of PEMFC to control its internal current in real time
Numerical Study on Humidification Performance of Fuel Cell Test Platform Humidifier(T. Ma, K. Wang, et al. 2019)	Developing a numerical model of the humidifier and verification of its performance under the influence of various operating conditions
Research on Control Algorithm of Proton Exchange Membrane Fuel Cell Cooling System(T. Ma, Lin, et al. 2019)	Study on developing a control algorithm for cooling system on PEMFC's by developing a model and validating experimentally

Table 4.1: Table of articles selected for qualitative analysis

4.2 Short Review on Selected Articles

The shortlisted articles are reviewed with the criteria based on the article "Qualitative Quality: Eight ”Big-Tent” Criteria for Excellent Qualitative Research"(Tracy 2010), this article presents 8 criteria for excellent qualitative research. The list of the quality criteria chosen for the short review is given below,

Criteria for quality	Various means, practices and methods through which to achieve
Worthy Topic	The topic is relevant, significant and interesting
Rich Rigor	The study uses appropriate and complex theoretical constructs, data, analysis processes
Credibility	The research is marked by thick description, concrete detail
Resonance	The research influences readers through transferable findings
Significant contribution	The research provides significant contribution practically, methodically and heuristically
Meaningful Coherence	The study achieves what it purports to be about and meaningfully interconnects literature, research and findings.

Table 4.2: Criteria for qualitative research(Tracy 2010)

The articles will also be reviewed based on the criteria of mathematical rigor, language/writing style, figure quality, formulas quality. The qualitative analysis of the above articles is given below.

Performance analysis of PEM fuel cell in mobile application under real traffic and environmental conditions(Chen, Laghrouche, and Djerdir 2021)

The article studies the effect of PEM fuel cells of an automotive vehicle(mail delivery van) under real traffic and environmental conditions, the topic of research is relevant and significant to our study, the article was published in 2021 and hence the findings are recent. The article provides a detailed explanation of the historical and current methods and models used to study PEMFC performance, Performance degradation and Remaining useful life. The article also has detailed description of processes, the article details the different modelling methods available in literature and lists out the advantages and disadvantages and then explains the best modelling technique that can be used and hence also fulfills the criteria of credibility. The findings of the research will also be helpful for further research and hence the knowledge is transferable. This article contributes significantly towards research of fuel cell performance in the automotive domain, since

the study is conducted in real life conditions there is a huge contribution in practical research. The article also fulfills the last criteria of meaningful coherence since the research interconnects the theoretical and practical aspects of fuel cell modelling, the findings of practical experiments prove that the theoretical research and modelling is accurate.

This article has the model described in mathematical formulae, the writing style is simple and understandable, the figure quality is average however it provides the necessary information, the labels on the axis have poor formatting, the formula quality is good. Overall this article fulfills the quality criteria listed above.

Prognostic methods for proton exchange membrane fuel cell under automotive load cycling: a review(Jacome et al. 2020)

The article studies the durability of automotive PEMFC's under automotive load cycling(ALO), since the fuel cells used in vehicles undergo ALO this topic is highly relevant in understanding the degradation effects over PEM Fuel cells. This article was published in 2020 and is relatively recent. The article has a detailed description of all the operational conditions of a automotive PEMFC and the degradation that it undergoes with references to literature, it also lists out the prognostic methods which essentially is a model based approach to predict the failure of the fuel cells hence the criteria of credibility is fulfilled. The findings of the research will be helpful in further research as the article points out some challenges that need to be worked upon. The article has significant contribution towards understanding the different prognostic methods used and their limitations and it also fulfills the last criteria of achieving the objective of the research.

This article is a review paper and hence has no mathematical formulae, the language is simple and the writing style is good with appropriate citations, the figures quality is good and informative. There are no formulae in the article. Overall the article fulfills the quality criteria listed above, but the article does not contain any fuel cell model or any mathematical description and simulation of the same.

Real time adaptive efficient cold start strategy for proton exchange membrane fuel cells(Amamou et al. 2018)

The article proposes a novel strategy to cold start a PEMFC and control the current of the fuel cell in real time to maximize the heat flux. Cold start is a practical problem that needs to be addressed and this article tries to develop a strategy and experimentally validate the proposed technique. This fulfills the criteria of relevancy, however this paper was published in 2018 which is not very recent. The article introduces the different techniques that were proposed in literature such as potentiostatic and galvanostatic solutions and their shortcomings which are that these techniques are unable to adapt to degradation and changing operating conditions, and hence the article proposes a new technique to overcome

the shortcomings. The proposed solution has a experimentally confirmed improvement of 50% over the existing methods and hence has significant contribution towards the understanding of Fuel cell start up, the findings of this research also contribute towards further theoretical and practical research in the field.

The article describes the model using mathematical formulae, the language and writing style is good, the figure quality is decent with relevant information but they lack detail and sharpness, the quality of the formulae is also good. The article fulfills the quality criteria as listed above.

Numerical Study on Humidification Performance of Fuel Cell Test Platform Humidifier(T. Ma, K. Wang, et al. 2019)

The article studies the performance of a humidifier in a Fuel cell test platform by means of a numerical simulation. For the efficient performance of PEMFC the efficient working of its auxiliary components such as air supply, humidifier, etc is necessary, in this study various operating conditions are varied and the performance of the humidifier is checked. The article is relevant for our study and is published in 2019. The article has detailed explanation of the various techniques for humidification from literature however it does not have detailed descriptions of the models that were used. A mathematical model of the humidifier is developed and a numerical simulation is performed and the performance is verified, the test experimentally verifies that the designed humidifier is able to fulfil the requirements. The article contributes towards further research and development of humidifiers and there is further opportunity to experimentally validate the results of the simulation.

This article has a detailed description of the model using mathematical formulae, the writing style is simple and understandable, the plot quality is good and provides the relevant information, the quality of the formulae is good but the detail in some of the figures is not great. This article does not feature a practical experiment to verify the results of the simulation like the other articles. Overall this articles also fulfills the quality criteria.

Research on Control Algorithm of Proton Exchange Membrane Fuel Cell Cooling System(T. Ma, Lin, et al. 2019)

The article proposes a control algorithm for the cooling system to have accurate control over temperature during dynamic load conditions. The algorithm is then tested virtually on a model and then experimentally validated. The article is relevant to our study of PEMFC's and its auxiliary components, sufficient literature research has been cited explaining the previous control strategies. The paper was published in 2019 and is relatively recent. The results show that the proposed strategy is able to control the temperature of the fuel cell

under dynamic load conditions.This article fulfills the criteria of significant contribution and meaningful coherence. This findings of this research helps in further development and research of fuel cell cooling strategies and improves the understanding of fuel cells.

The article has detailed description of the model with mathematical formulae, the writing style is good and understandable and the plots provide the necessary information, the quality of plots is good but it has less detail and sharpness. This article completely fulfills the quality criteria listed above.

4.3 Nomenclature of Models

The articles from 2018 to 2022 were analyzed and the types of PEMFC models as described in the articles were studied. The aim was to understand the types of models used, the nomenclature used to describe the models and to study their evolution in the 5 year period. Table describes the nomenclature of different models for automotive PEMFC and its auxiliary components from 2018 to 2022. This can be helpful in understanding the naming convention used by different authors over a period of time, the table also provides an overview of the research being done on modeling of various elements of PEM fuel cells and its auxiliary components.

Models in 2018	Models in 2019	Models in 2020	Models in 2021	Models in 2022
Discrete state machine Model(Roda et al. 2018)	Steady State Thermodynamic Model(Li et al. 2019)	Zero Dimensional Steady state Thermodynamic Model(Biberci and Celik 2020)	Thermodynamic Model(Sun, Peng, and Zhu 2021)	Air Supply system Model(D. Zhao et al. 2022)
High Fidelity Model(Piffard et al. 2018)	Thermal Resistance Network Model(Sulaiman, Singh, and Mohamed 2019)	1 Dimensional Match Model(Jin et al. 2021)	2nd Order Affine oriented Control Model(Tang et al. 2021)	Air compressor dynamic Model(D. Zhao et al. 2022)
Probabilistic Simulation Model(Tuominen et al. 2018)	Local controlled Autoregressive integrated Model(D. Yang et al. 2019)	Macroscopic 1D+1D Model(Grimm et al. 2020)	Electrochemical and dynamic Model(Z. Wang, Yi, and S. Zhang 2021)	Semi-empirical and quasi static Model(Luciani and Tonoli 2022)
Power System Model(R. Ma et al. 2018)	Source to Range Model(Xiong et al. 2019)	Modular and Parametric Model(D'Ovidio, Ometto, and Villante 2020)	Dynamic Detailed Model(Gomez, Serra, and Husar 2021)	Dynamic energetic Model(Fabri et al. 2022)
Dynamic vehicle model integrated with the fuel cell system model(J. Han and S. Yu 2018)	Neural Network Model(AbouOmar, H.-J. Zhang, and Su 2019,C. Guo et al. 2019,Chen, Laghrouche, and Djerdir 2019,D. Yu et al. 2019)	Reduced Order nonlinear Model(Goshtasbi and Ersal 2020)	Numerical Model(Ahsan et al. 2021)	Fuel cell engine mechanism model(Huo et al. 2022)
Multiscale Model(Xu et al. 2018)	Agglomerate Model(J. Han, Hwang, and S. Yu 2019)	3D computational Model(Gong et al. 2020)	Fault Diagnosis Model(Zuo et al. 2021)	Semi Empirical - semi mechanism Model(Jia et al. 2022)

Quasi 2D Model(Murschenhofer et al. 2018)	Nonlinear Mathematical Model(Cruz-Rojas et al. 2019)	ECSA Degradation Model(Ao et al. 2020)	Voltage Prediction Model(Ou et al. 2021)	Three-dimensional transient computational fluid dynamics model(B. Zhao et al. 2022)
1D and 3D Model(Q. Zhang, Xu, et al. 2018)	Numerical Simulation Model(T. Ma, K. Wang, et al. 2019)	Neural Network Model(Vichard et al. 2020)	3D computational fluid dynamic Model & 2D transcient Model(Lingchao et al. 2022)	Semi-empirical and quasi-static model (Luciani and Tonoli 2022)
2D multiphysics Model(Mayur et al. 2018)	Two Phase Dynamic Model(Kang, L. Zhao, and Brouwer 2019)	Black Box model(ANN's)(Tsakyridis et al. 2020)	Temperature control Model(Hu et al. 2021)	
2 Phase Fuel Stack Model(Xu et al. 2018)	Finite Time Thermodynamic Model(Li et al. 2019)	Parameterized Stack Model(Yiping Wang et al. 2020)	3D Steady State radiator model(Luo et al. 2022)	
Hybrid System Model(Lu et al. 2018,R. Ma et al. 2018,Y. Han et al. 2018)	Validated Emperical Model(Yongqiang Wang et al. 2019)	Periodic Unit Model(Q. Zhang, Tong, et al. 2020)	Framework Model()Ahluwalia et al. 2021	
Three Dimensional and isothermal anode relative humidity Model(Liu et al. 2018)	Combined System Model(Liu et al. 2018)	Optimized Support Vector machine Model(F. Han et al. 2020)	FC electrochemical model(Kravos et al. 2021)	
		Transcient Model/Framework model/MS Excel model(Brooks et al. 2020)	3D multiphysics Model(Nefedkin et al. 2021)	

		Semi emperical Model(Murugesan and Subramaniam 2020)	RHNN Model(Rotor Hopfield Neural Network)(M. Yang et al. 2021)	
		Economical-functional Model(H. Guo et al. 2020)	GFPF-RHNN based Model(M. Yang et al. 2021)	

Table 4.3: Nomenclature of fuel cell models from 2018 to 2022

5 Summary and Conclusion

In this paper we perform a literature survey on PEM Fuel cell modelling, WoS database was used to gather articles by formulating a search expression, the study was performed on articles published from 2018 to June 2022, the results of the literature survey are summarized below.

WoS database was used to find the articles for the literature survey. A search expression was formulated in order to aggregate the relevant articles to our topic. The filter function was used to filter the articles from 2018 to 2022 to obtain the most recent articles and carry out further quantitative analysis. The search expression that is formulated can be used in the future to obtain articles about fuel cell modeling in automotive vehicles.

The year wise distribution of articles showed a upward trend, indicating growing interest in the field of PEM fuel cell modeling and its peripheral components. The country-wise distribution of articles shows that a majority of the research originates from a few countries like China, USA, France, South Korea, Canada, Iran, Turkey, England and Germany. The distribution of articles among the publishers shows that 75% of the articles are published among Elsevier and Mdpi with other publishers having less than 5% of the articles.

Around 200 institutions globally published articles related to the topic however around 43.8% of the research was published by the top 10 institutes. Many research groups were identified that published results in the field of PEM fuel cell modeling. The top authors of the articles were also identified among a total of 200 authors.

Qualitative analysis was done on a select list of papers which were identified and the review was done based on the quality criteria and it was found that most of the articles fulfilled the criteria. Analysis of of the nomenclature of models was done to understand the trends in fuel cell modeling, the table containing the year wise trend in fuel cell modeling shows the diversity of models that are published in the field.

From this literature survey we can conclude that significant research is being done in the field of Fuel cell modeling and modeling of its auxiliary components in automotive vehicles, and the trends show that this is an active as well as a growing field. There is good scope for future experimental as well as practical research which is indicated by the qualitative analysis of the articles. The Search expression that was formulated and the list of research groups can help as a foundation for future research.

literature

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