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Review Article

Bibliometric analysis of prognostics and health management (PHM) in hydrogen fuel cell engines

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HIGHLIGHTS

- A bibliometric based approach is used to organize the structure of the review.
- The hotspot and driving force of hydrogen fuel cell engine are visualized.
- Development direction PHM in the PEMFC was analyzed.
- Many fault causes and health management architecture are analyzed.

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ABSTRACT

Because of its superior cold-start effect and lack of pollution, the proton exchange membrane fuel cell (PEMFC) engine has gained a lot of interest as the most common application type of hydrogen fuel cell engines. However, the difficulty in forecasting the remaining life and monitoring the operation state for a lengthy period limits its commercialization. As a result, PEMFC Prognostics and Health Management (PHM) is critical. A method based on bibliometrics is introduced into the research on this topic. In this work, the research in this field is divided into three stages. The characteristics of different stages are summarized through keywords, subject background, and other aspects. We can observe the transformation of the field from the idea based on analytical reduction to systematic theoretical control. Based on the results of bibliometric analysis, we have conducted a literature review, and we can see the typical research results and development direction of each topic clustering.

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Contents

Abbreviations

PEMFC	Proton Exchange Membrane Fuel Cell
PHM	Prognostics and Health Management
MPL	Micro Porous Layer
GDL	Gas Diffusion Layer
HFR	High-Frequency Resistance
ORR	Oxygen Reduction Reaction
EMS	Energy Management Strategy
RNN	Recurrent neural network
DT	Digital Twin
PF	Particle Filter
EMR	Energetic Macro Presentation
AEfP	Acoustic Emission as a function of Polarization
EIS	Electrochemical Impedance Spectroscopy)
Pt	Platinum
SEM	Scanning Electron Microscope
EDS	Energy Dispersive Spectrometer
ATR-IR-S	Attenuated-Total-Reflection Infrared Spectroscopy
CS	Compression Set
LSR	Liquid Silicone Rubber
CHP	Combined Heat and Power
LSA	Lightning Search Algorithm
CCP	Combined Cooling and Power
CCHP	Combined Cooling, Heat, and Power
CWP	Combined Water and Powe
WHR	Waste Heat Recovery
PEMFC-Lib-SC	PEMFC system, hydrogen-electric hybrid power, hydrogen-electric supercapacitor
CWT	Continuous Wavelet Transform
SVM	Support Vector Machine
DST	D-S Evidence Theory
CFD	Computational Fluid Dynamics
CPS	Cyber-Physical Systems

Introduction

With the increasingly serious environmental problems, the use of traditional fossil fuels will be greatly limited [1,2]. However, the development of society is inseparable from the continuous supply of energy, especially in the field of transportation [3]. The demand for a large amount of energy has become a contradiction with environmental protection restrictions. Therefore, the development of clean energy has become a breaker. As an important way to convert hydrogen energy into electric energy, various fuel cell engines have been developed. As the benefits of proton exchange membrane fuel cell (PEMFC), which include strong cold start performance, low operating temperature, and so on [4], research on the new generation fuel cell engines represented by PEMFC has been conducted in all nations. With the development of clean hydrogen production process, vehicle-mounted PEMFC has ushered in an excellent opportunity for development. Vehicle-mounted PEMFC has ushered in a fantastic chance for progress with the development of a clean hydrogen production technology. The principle of PEMFC is very simple. Hydrogen and air are introduced into the anode and cathode respectively. Under the action of diffusion layer, catalyst, and exchange membrane, they exchange ions on both sides of the membrane to generate current and generate water. However, it is not easy to keep PEMFC running efficiently all the time. Due to the difficulties of on-line diagnosis and forecast of flaws and remaining life [5], the pace of PEMFC commercialization is delayed, and various researchers have varied emphases in the development process.

In the early research on PEMFC, people focused on the performance and materials of PEMFC [6]. Until 2013, Jouin et al. [7] applied the concept of PHM to PEMFC for the first time, and reviewed the relevant progress. A seven-layer PHM framework was established (as seen in Fig. 1), and the research methods of each layer were carefully reviewed. They believed that the main challenges in PEMFC at that time were how to find appropriate indicators, how to find key aging factors. In 2017, Zhang et al. [8] summarized the common problems and solutions of lithium batteries and fuel cells, reviewed the methodology of PHM in PEMFC from the perspective of aging, and provided a first step to establish an appropriate PHM model. However, with the prosperity of computer and information science, PHM method develops rapidly and has been applied in many fields [9–11], some problems have been changed in the recent ten years, and the PHM also has a broader definition. The prognostics and health management in traditional PHM are combined with intellectualization, and the single fault diagnosis in traditional PHM is also developing towards comprehensive diagnosis and intelligent diagnosis [12]. Further, PHM is extended to the exploration of integrated full life cycle management of products from design to scrapping, including data collection and transmission, data processing (condition monitoring, health assessment, predictive diagnosis), decision support, and information management methods [9,13,14]. Therefore, it is essential to study the development and evolution of PHM in fuel cell engines.

The development of artificial intelligence provides a new idea for the study of development and growth. Visual analysis of bibliometrics can be used to analyze the development path and trend of research from massive sample data. This method has been applied in many fields [16–19]. In the field of hydrogen energy, people have reviewed the history in detail and provided suggestions for future development in aspects such as in the development of high-performance cathode for low and intermediate temperature solid oxide fuel cells [20], hydrogen energy storage materials [21] and the development of hydrogen economy [22].

In this paper, we deeply analyzed the development and research of PHM in fuel cell engines by searching and collecting relevant data in the Web of Science Core Collection, using literature visualization tools such as CiteSpace, which provides a reference for the development of PHM in fuel cell engines.

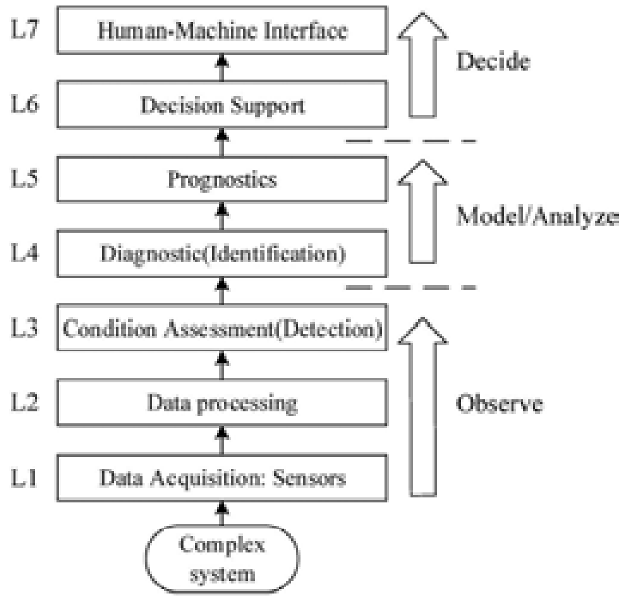


Fig. 1 – A PHM framework for PEMFC [7,15].

Data and methodology

Research methods

In this paper, the visual analysis method in bibliometrics is used to visually analyze the data using graphical analysis tools such as CiteSpace. CiteSpace is a document visualization tool developed by Professor Chen based on JAVA [23,24]. It can be used in many fields by quantitative analysis of document collections derived from different databases to carry out multivariate, time-sharing, and dynamic co-occurrence analysis among many elements like knowledge units, citation analysis, research groups, institutional or national/regional cooperation analysis and so on [25–27]. Statistical methods based on CiteSpace are introduced in Appendix 1. The information required for bibliometrics can be obtained from the core database of Web of Science Core Collection, and CiteSpace can be used to analyze this information without additional semantic processing.

Important indicators such as frequency and centrality can be obtained through the number of articles and citations of an element, which can be used to show the role of the element in the development process of the field.

Data collection

Many high-level international papers are included in the Web of Science database, so we use the Web of Science Core Collection to retrieve relevant pieces of literature and export them to build a literature analysis database. We select PEMFC, which is most widely used in hydrogen fuel cell engines, as the search object, and PHM related entries as keywords to explore the application of PHM in PEMFC. By constructing advanced topic (TS) retrieval formula: (TS=(PEMFC)) AND TS=(PHM), the PHM method in the PEMFC field was preliminarily searched, but only 12 literatures were retrieved, which was not enough to constitute samples. Therefore, the retrieval formula is extended through the connotation of PHM. The extended retrieval formula is: (TS=(PEMFC)) AND (TS=(Prediction) OR TS=(Forecast) OR TS=(prognostic)OR TS= (Management Strategy) OR TS=(PHM) OR TS= (Residual Life) OR TS=(Fault)), a total of 763 references were retrieved by retrieval in December 2021, and a primary database was constructed.

Data preprocessing

Before using CiteSpace to carry out literature data visualization, the retrieved literature data should be preprocessed. This is because the recognition of the CiteSpace internal mechanism is not perfect for some majors and neglecting data preprocessing may lead to the final analysis being unreliable. Data processing in this study mainly includes preliminary quantitative analysis, merge synonyms and supplementary missing content. Preliminary quantitative analysis is shown in Fig. 2. Before 2010, there were few published data every year, which was basically flat from 2010 to 2015 and rapid growth has taken place since 2016. Therefore, the development can be divided into three stages, namely early development period, stable development period and prosperous development period. Since there were only two pieces of literature before 2010, the impact on subsequent development was small after preliminary analysis. As the retrieval date was in 2021, the statistical data of 2021–2022 were incomplete but sufficient to illustrate the trend. Therefore, the subsequent analysis only analyzes the stable development period from 2010 to 2015 and the prosperous development period from 2016 to 2022. Through literature screening, a total of 757 pieces of literature were finally left for subsequent analysis.

CiteSpace provides powerful analytical capabilities. However, manual processing is needed to improve the analysis accuracy when encountering some specialized words. In this paper, keywords analyzed in CiteSpace are preprocessed. Details are shown in the Appendix 2.

Results

The PHM concept was first used in aerospace and military equipment, and has become a key technology to achieve autonomous logistics and reduce life cycle costs for modern weapons and equipment, and is quickly being applied in other fields [28–30]. There are not many PHM applications in the PEMFC field, so the research hotspots and evolution analysis of PHM in the area of PEMFC are studied from the aspects of fault prediction, life prediction and health management. The following results represent the evolution process of PHM in PEMFC from different perspectives and reveal the direction of development. For each perspective, we visualized the results of the analysis, and selected papers with high centrality (which means they played an important role) in different stages of the analysis for content analysis.

Research driving forces of PHM in PEMFC

Firstly, a preliminary analysis is made on the subject categories in the PEMFC field. Fig. 3 shows the results of subject categories visualization in two stages. Among them, the subjects marked in the purple circle are those with high centrality, that is, the categories with considerable importance in this stage of development. The energy discipline and engineering discipline both played essential roles in the two phases. With the development of multi-disciplinary in the engineering field, PHM gradually became active in PEMFC. The comparison between Fig. 3(a) and (b) shows that the links between various disciplines are increasingly close. As can be seen from Fig. 3(c), PHM research has gradually developed from a multi-disciplinary combination of traditional engineering and materials to a new engineering combination of computer science and information technology.

Research cooperation of PHM in PEMFC

CiteSpace was used to analyze the cooperation between countries/regions and authors in two periods. The specific results are shown in Fig. 4. The data was exported from CiteSpace, and the publication heat maps of documents in two periods were constructed using QGIS, as shown in Fig. 5. As can be seen from Fig. 4, in the period of stable development, the cooperation between countries/regions and among authors is sparse, and this situation has been improved in the period of prosperous development. As can be seen from Fig. 5 and Table 1, during the period of steady development, the United States played the most important role, followed closely by China and European countries, and the orders of magnitude of published by all countries were basically the same. During the period of prosperous development, the quantity and importance of posts issued by China were qualitatively improved. In Fig. 4(c) and (d), it can also be seen that the cooperation of the authors networks gradually shifted from the team with DANIEL HISSEL as the core to QI LI and WEIRONG CHEN. This shows the research hot spot migration of regions and groups of PHM in PEMFC.

Research focus and hotspots of PHM in PEMFC

Pathfinder theory is used to analyze keyword co-occurrence, and the Jaccard algorithm is used to measure the connection intensity. The keyword co-occurrence map of two periods is shown in Fig. 6. In the same setting, the research topics are more prosperous during the prosperous period, the connecting lines between keywords are tight, the color of the connection lines represents the co-occurrence time between keywords, and the warmer the connection lines represent, the closer the co-occurrence time of two keywords. It shows that in the two stages, the research methods of PHM in the PEMFC field are concentrated. In the prosperous period, more keywords appear in people's related research, and the relationship between keywords is closer. There are small branches at the edge of both periods, which means that some new research methods and research ideas are being formed. Using time and branch distribution, we can study the forming process of some research ideas.

The two-stage research involves the most significant keyword statistics were recorded as shown in Table 2. Combined with the keyword citation bursts analysis in Fig. 6(c), we can see that the research focus is from the design of PEMFC ontology to the optimization of PEMFC control system. Finally, with the development of machine learning, pattern recognition and optimal control are realized, which is consistent with the prominence of computer science and information technology in this field in Fig. 3(c). In Table 3, during the prosperous development period, the frequency of related keywords has been dramatically improved, with the frequency of “membrane”, “transport” and “cathode” for fuel cell ontology design decreasing, while the frequency of “optimization”, “strategy” and “durability” for fuel cell system increasing. And the centrality of “management” and “prediction” is rising, which means that they are playing an increasingly important role in the research in recent years.

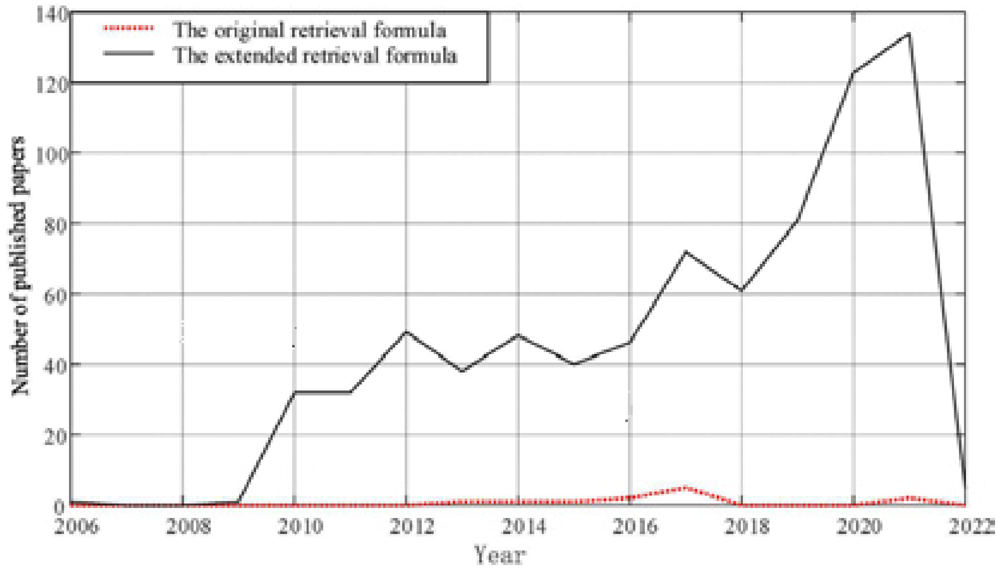
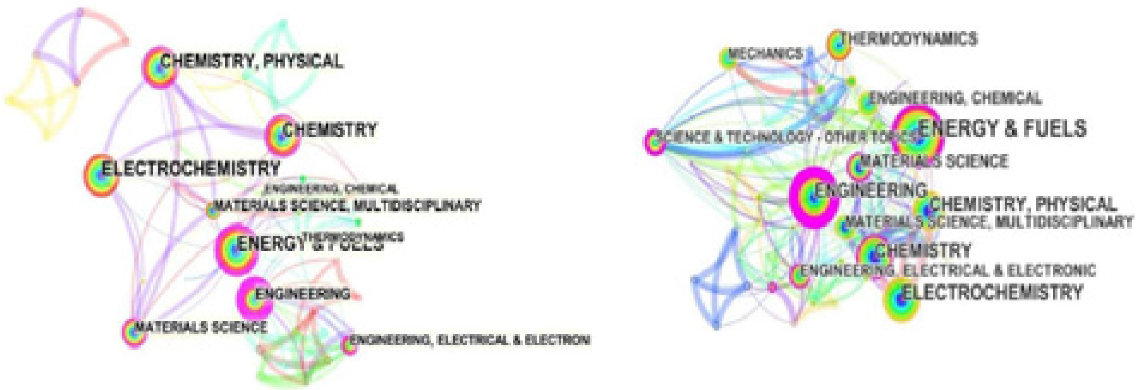


Fig. 2 – Number of published papers.



a. Map of categories in stable development period.

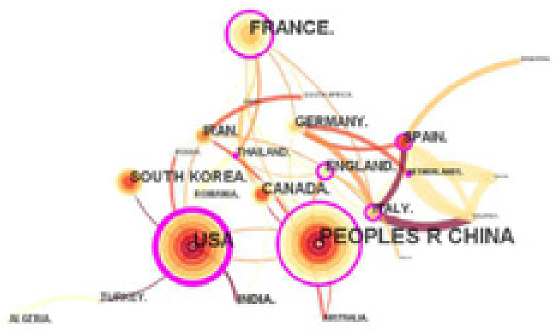
b. Map of categories in prosperous development period.

Top 10 Subject Categories with the Strongest Citation Bursts

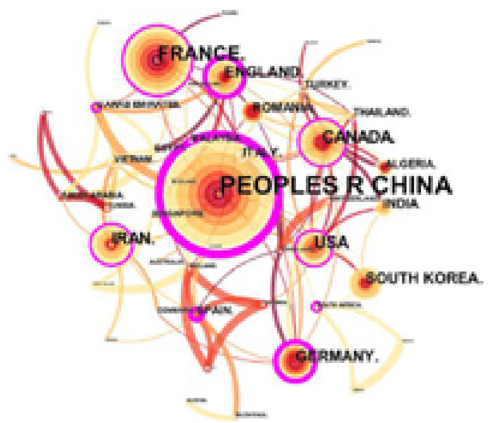
Subject Categories	Year	Strength	Begin	End	2010 - 2022
MATERIALS SCIENCE, MULTIDISCIPLINARY	2010	2.36	**2010**	2011	
MATERIALS SCIENCE	2010	1.86	**2010**	2011	
ENGINEERING, MECHANICAL	2010	2.54	**2011**	2013	
NUCLEAR SCIENCE & TECHNOLOGY	2010	1.59	**2011**	2013	
ENGINEERING, MULTIDISCIPLINARY	2010	1.53	**2015**	2016	
TELECOMMUNICATIONS	2010	1.25	**2018**	2019	
TRANSPORTATION	2010	2.38	**2019**	2022	
TRANSPORTATION SCIENCE & TECHNOLOGY	2010	2.38	**2019**	2022	
INSTRUMENTS & INSTRUMENTATION	2010	1.43	**2019**	2022	
COMPUTER SCIENCE, INFORMATION SYSTEMS	2010	1.43	**2019**	2022	

c. Top 10 Subject categories with the strongest citation bursts

Fig. 3 – Categories map and citation bursts of PHM in PEMFC.



a. Map of cooperation among countries/regions in stable development period.



b. Map of cooperation among countries/regions in prosperous development period.

c. Map of cooperation among authors in stable development period

d. Map of cooperation among authors in prosperous development period

Fig. 4 – Map of cooperation among countries/regions and authors of PHM in PEMFC.

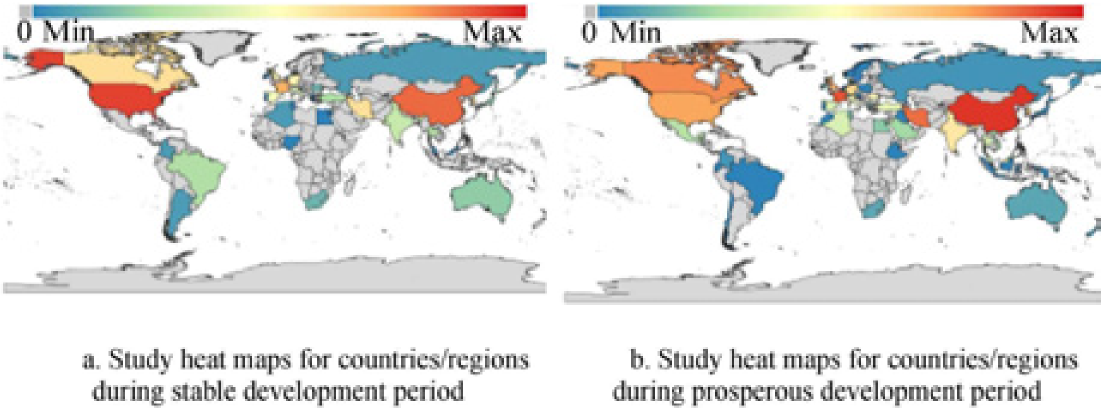


Fig. 5 – Evolution of national/regional published heat in two stages.

Table 1 – Main countries published in the two stages (top 10 in importance).

Stable development period			Prosperous development period		
Countries/Regions	Number of papers published	Centrality	Countries/Regions	Number of papers published	Centrality
USA	51	0.29	PEOPLES R CHINA	250	0.62
ITALY	10	0.20	SPAIN	11	0.32
PEOPLES R CHINA	81	0.15	GERMANY	25	0.23
GERMANY	12	0.13	ENGLAND	28	0.22
SPAIN	11	0.12	CANADA	38	0.16
FRANCE	26	0.11	U ARAB EMIRATES	7	0.16
IRAN	14	0.09	FRANCE	82	0.14
ENGLAND	12	0.08	SOUTH AFRICA	3	0.13
THAILAND	6	0.07	USA	37	0.12
NETHERLANDS	3	0.02	IRAN	44	0.12

From the evolution of categories, cooperative environment, and keywords in the two stages, we can see that the common development of different disciplines and the joint efforts of scholars from different regions have contributed to the prosperity of this field.

During the stable development period, the core of PHM in the field of PEMFC is to fundamentally reduce the failure probability of PEMFC and thus reduce the difficulty of PHM through the development of materials. On the other hand, from the perspective of physics, chemistry and electrochemistry, the internal reactions of different types of PEMFC are described from the reaction mechanism. In order to improve the understanding level of the internal reaction of PEMFC, to better solve some PEMFC failures by regulating the input and output, to improve its durability. From its early development, PEMFC's PHM was multidisciplinary from the very beginning.

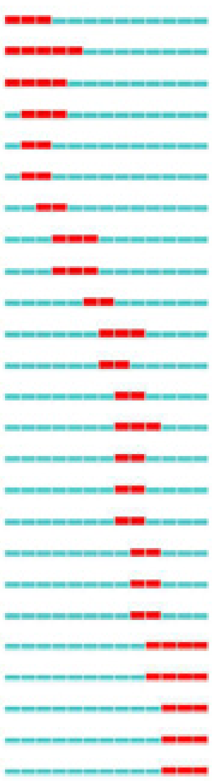
As one of the important papers in this stage, Asghari et al. [31] studied electrochemical impedance spectroscopy in PEMFC, because electrochemical impedance spectroscopy is a non-invasive method compared with other research method. It can analyze individual contributions of the interfacial charge transfer and the mass transport resistances in PEMFC in the catalyst layer and diffusion layer. Because the reaction of PEMFC is an electrochemical process, the use of electrochemical impedance spectroscopy to study the reaction of PEMFC also has a good fit, which provides a good research method to understand the influence of the main reaction process of PEMFC on the final output. They also used this method to measure the relationship between impedance and current density of reaction in each part of PEMFC through equivalent circuit Fig. 7 (a) improved based on reference [32], which provides a strong reference for further PHM. The R_{Ω} is the High-Frequency Resistance (HFR) which represents total ohmic resistance of the fuel cell; R_{ct} is the charge transfer resistance due to oxygen reduction reaction (ORR); CPE_1 is a constant phase element which reflects the R_{ct} associated catalyst layer capacitance properties; R_{mt} is the resistance related to the mass transport of O_2 in both the catalyst layer and the GDL; and CPE_2 represents the associated capacitance. However, the method of electrochemical impedance spectroscopy is not suitable for on-line monitoring, which causes great difficulties for real-time health status assessment of PEMFC.

Akhtar et al. [33]constructed a two-phase, half-cell, non-isothermal model that performs at various operational current densities and battery temperatures over this time period. The influence of flow channels with different rib widths on the output of PEMFC was studied, and other models in this stage were similar, which improved the cognition of PEMFC response to some extent. However, these breakthroughs mostly stayed on one research problem, such as the influence of flow channel or diffusion layer, and few models considered

a. Map of keywords among countries/regions in stable development period

b. Map of keywords among countries/regions in prosperous development period

Top 25 Keywords with the Strongest Citation Bursts



Keywords	Year	Strength	Begin	End	2010 - 2022
cathode	2010	3.83	**2010**	2012	
media	2010	3.65	**2010**	2014	
electrode	2010	3.47	**2010**	2013	
liquid water	2010	4.62	**2011**	2013	
field	2010	4.58	**2011**	2012	
bipolar plate	2010	3.66	**2011**	2012	
dynamics	2010	4.91	**2012**	2013	
hybrid	2010	3.29	**2013**	2015	
control strategy	2010	3.28	**2013**	2015	
methodology	2010	3.22	**2015**	2016	
storage system	2010	3.21	**2016**	2018	
integration	2010	3.14	**2016**	2017	
experimental validation	2010	5.57	**2017**	2018	
electrocatalyst	2010	4.2	**2017**	2019	
energy management strategy	2010	3.7	**2017**	2018	
energy management	2010	3.69	**2017**	2018	
electric vehicle	2010	3.38	**2017**	2018	
performance degradation	2010	4.58	**2018**	2019	
transport phenomena	2010	3.47	**2018**	2019	
chp system	2010	3.05	**2018**	2019	
state	2010	4.66	**2019**	2022	
kalman filter	2010	3.97	**2019**	2022	
forecast engine	2010	12.96	**2020**	2022	
feature selection	2010	12.91	**2020**	2022	
excess ratio control	2010	5.02	**2020**	2022	

c. Keywords with the strongest citation bursts

Fig. 6 — Keywords map and citation bursts of PHM in PEMFC.

the global influence. At this stage, more scholars pay attention to performance and Model of PEMFC and try to clarify the working process of PEMFC and the simplified model.

However, during the prosperous development period, the situation changed greatly and more research tools were introduced into the research of PEMFC's PHM field (in Fig. 3 (b)). More disciplines are involved in this field, and the combination of different disciplines can be used to further understand the internal reaction process of PEMFC and control it accordingly. Different from the previous stage, more researchers focused on how to quickly reflect PEMFC internal response at the same time keep its accuracy, and through a great deal of control algorithm for fault rather than the fault mechanism research, more consider global method has been implemented, more consideration of PEMFC and its effect on the attachment between the relevant model was set up. As one of the important papers in this stage, Ettihir et al. [34] established a global Energy Management Strategy (EMS) in the

Table 2 – High-frequency keyword analysis in the two stages.

Main keywords in stable development period			Main keywords in prosperous development period		
Keywords	Frequency	Centrality	Keywords	Frequency	Centrality
Performance	93	0.01	PEMFC	187	0.06
PEMFC	88	0.04	Performance	180	0.02
Model	63	0.05	Model	114	0.08
Membrane	37	0.10	System	98	0.01
Transport	37	0.10	Optimization	90	0.05
System	37	0.06	Management	78	0.08
design	36	0.13	Prediction	74	0.22
Prediction	36	0.04	Strategy	67	0.04
Management	32	0.04	Design	64	0.02
Cathode	28	0.04	Durability	48	0.12

hybrid power system, which could divide power between two power sources. It was found in the experiment that the working environment of PEMFC was improved and the remaining life was enhanced. In this work, a variety of algorithms such as Maximum Tracking Techniques, Pontryagin's Minimum Principle and other algorithms are applied to realize the optimization of online power distribution. Thanks to the improvement of information technology and computer technology. These combined algorithms can complete the calculations in a very small amount of time and derive the optimal power allocation strategy, thus achieving online energy management and providing a direction for PHM.

In recent studies, the overall PHM architecture of fuel cell engines has been gradually established. Ibrahim et al. [35] constructed a PHM framework for life prediction in PEMFC based on wavelet transform. Zuo et al. [36] used the attention mechanism in deep learning to improve the accuracy and speed of PHM. They proposed an attention-based Recurrent Neural Network (RNN) model to improve the prognostics of PHM in PEMFC. In the following experiments, this method is combined with different algorithms to compare the optimal combination. Their results show that this method has a high prediction accuracy. In the latest study, Meraghni et al. [37] further fused the algorithm with PHM. They used the deep learning framework to construct the Digital Twin (DT) of PEMFC (Fig. 8) for life prediction and proved this method has reached an average accuracy higher than 0.9 and near 0.95 through multiple groups of experiments. Compared with traditional methods, such as particle filter (PF) algorithm, DT has greatly improved the solution time and accuracy in many groups of experiments.

It can be observed from these that as computer technology advances, more advanced algorithms are being applied to the sector. Information science and computer technology are the most prominent in the process of replacing the two PHM stages in the PEMFC area, showing that computer technology has become a vital instrument in PEMFC PHM research. The focus of scholars' attention shifted throughout the affluent period. The focus of researchers' attention shifted to how to design a comprehensive system, how to foresee, and how to devise timely measures to eradicate flaws in advance. How to implement PHM, there is a general structure [15], but it is worth discussing what aspects should be started from PEMFC to implement effective PHM. More detailed discussions are presented below.

Discussion

Mapping and analysis on clusters

The research keywords are clustered, and the final clustering results are shown in Fig. 9, where Q = 0.559, S = 0.808. By comparing of indicators, it can be considered that the clustering is reasonable and the clustering structure is remarkable [38]. Each cluster is the intersection of each other, such as energy management, model-based method (#6) and deep learning (#12), which may be used in water management (#0), but each cluster is still quite representative. Through cluster analysis, all pieces of literature are clustered into 13 topics from #0 to #12, which can be considered as an extension of the 7-layer PHM structure, that is, through the method of bibliometrics, we have found several research focuses in the PHM problem of PEMFC.

Similarly, CiteSpace's automated grouping findings will reveal phenomena such as topic redundancy and others. In this analysis, #5 Proton Exchange Membrane Fuel Cell and #8 steam reforming are manually excluded, because strictly speaking, the clusters are all sub-items of #5 proton exchange membrane fuel cell, and it is of little significance to study the clustering results, while #8 steam reforming is a PHM related to the process of preparing hydrogen, which has little correlation with this research topic.

After the manual screening, connect the clustering results with keywords to construct the keyword clustering map from the timeline perspective. As shown in Fig. 10, the discussion of clustering will be carried out in the fourth section.

Review of PHM in PEMFC field based on literature visualization results

According to the results of visual analysis clustering, literature research and analysis were carried out on the development of PHM in PEMFC field, and there were overlaps among different clustering. Through analysis, the cluster can be further divided into two directions. The PHM research objects of PEMFC include water management, carbon corrosion failure, stress relaxation & membrane failure, thermal management, and energy management. The PHM research methods such as structure optimization method, model-driven method, deep learning method, etc.

Table 3 – Commonly used methods in PHM of PEMFC.

Focus	Means	Specific methods or models	PHM layer	Ref.
Water management	EIS	1.Charge transfer resistance at high frequencies; 2. Mass transfer resistance at low frequencies.	L1, L2	[41,44,45,94,161–166]
		Improved model	L1 – L5	[94,163–166]
	Voltammetry (For example: cyclic voltammetry and linear sweep voltammetry	Polarization curve model.	L1 – L3	[40,42,66,139,150]
		Improved models: The semi-empirical model is mainly improved by introducing new physical quantities, such as film thickness, dynamic temperature and other parameters ignored by the original model.	L1 – L6	[95,139,167–169]
	CFD methods	UDF model with numerical analysis	L1 – L4	[70,121,140,141]
		DT model based on CFD	L1 – L7	[160]
	Structural improvement	Novel flow channel	L1	[124,127,128,130]
	Visualization	Optical fuel cell or visualization of droplet	L1 - L4	[43,52,121,135,147]
		Neutron imaging	L1 - L4	[145,146]
		X-ray scanning imaging	L1 - L4	[148]
		TEM	L1 – L4	[170]
	Operation parameter sensor and corresponding algorithm	Micro sensors	L1 – L6	[55]
		Pressure drop management	L1 – L6	[46,47,49–51]
		External magnetic field	L1 – L5	[54]
		Humidity Management	L1 – L7	[137,171,172]
		Prediction based on Neural Network	L1 – L7	[58,94,95,172]
	Acoustic methods	Acoustic intensity signal	L1 – L5	[48]
		Acoustic signal after processing	L1 – L5	[173]
	Global management	EMR (Energetic Macro Presentation) model	L1 – L7	[57]
		Water management strategy	L1 – L7	[94,174]
Carbon corrosion failure	Electrochemical and spectral analysis	TEM	L1 – L3	[63,64,175]
		Chromatography	L1 – L3	[60,176]
		Chronoamperometry	L1 – L4	[177]
		On-line mass spectrometry	L1 – L4	[65,178,179]
		X-ray photoelectron spectroscopy (XPS)	L1, L2	[175,180]
		SEM	L1, L2	[67,68,175]
		EIS	L1 – L4	[62,66]
	Operating parameter sensor	Temperature sensor and gas sensor	L1, L2	[71]
		Electronic load, cell temperature, HFR and voltage	L1, L2	[66]
		Cyclic voltammetry	L1 -L4	[69,139]
	CFD methods	Numerical experiment	L1 -L6	[70]
		Novel flow field	L1	[127,128,181,182]
	New material	Catalyst	L1	[73,75,77,79,183]
		Electrodes	L1	[74,184]
		New structure	L1	[124,126]
	Global management	Model-Based Predictive Diagnosis and Control	L1 – L7	[78]
Stress relaxation & membrane failure	Electrochemical and spectral analysis	SEM	L1 – L3	[81,82,85]
		EDS	L1 – L3	[81]
		ATR-IR	L1 – L3	[81]
		Thermogravimetric analyzer (Including the preparation of novel membranes)	L1 – L4	[82,185]
		TEM	L1 – L3	[85]
		Small angle and wide-angle X-ray scattering techniques (SAXS/WAXS)	L1 – L3	[85,180]
	Parameter measurement	Mass loss	L1, L2	[81]
		Compression set	L1, L2	[81–84,89]
		Coefficient of thermal expansion (CTE)	L1 – L2	[84,86]
		CFD methods	L1 – L4	[89]

(continued on next page)

Table 3 – (*continued*)

Focus	Means	Specific methods or models	PHM layer	Ref.
Lifetime prediction	Model driven	Aging model (Key Indicators: Stack voltage, mean cell voltage, impedance, and polarization curves)	L1 – L6	[90–92,96,97,100–107,186]
		Fault model (Main types: Water management failures, heat management failures, energy management failures, and membrane degradation)	L1 – L6	[5,58,94–96,106,117,130,174,187]
		CFD methods	L1 – L6	[99,103,106]
	Data driven	Data-driven approaches (including neural networks, deep learning, and improved algorithms)	L1 – L7	[11,30,37,58,94,96,101,105,106,172,174]
		Based on fault tree	L1 – L7	[188,189]
Thermal management	Operation parameter sensor and corresponding algorithm	Monitoring and optimization of cooling system	L1 -L4	[108,109,130]
		Micro sensors	L1 – L2	[56,108,109]
		Polarization curve model.	L1 – L4	[62,136,168]
		Optimization of structure	L1	[124,125]
	Global management	Thermal management strategy	L1 – L7	[107,111,113,130]
	Numerical analysis	CFD methods	L1 – L6	[142,149]
		Numerical modeling of thermal analysis	L1 – L4	[110]
	Structural improvement	Novel flow channel, flow field and cooling circuit	L1	[125,128,130]
Energy management	Model-based	Fuzzy logic	L1 – L7	[114–116]
		Adaptive robust	L1 – L7	[117]
		Optimization based strategies	L1 – L7	[115,119,120,125]
	Data driven	Neural networks	L1 – L7	[123]
		Global management	L1 – L7	[37,190,191]

Different from Ref. [15], in the analysis, we can find that the PHM of PEMFC not only depends on data collection, fault diagnosis and prediction, life prediction, etc., but also depends on the application of new materials and new structures, which will solve the problem of short using life, difficult diagnostic and others in root. An expended framework of PHM in PEMFC was shown in Fig. 11.

The object clusters of PHM in PEMFC

(1) Water management

The literature study on water management in PEMFC corresponded to cluster analysis #0 water management and #1 water transport.

Water is the only reactant in the fuel cell during operation, although problems such as water flooding and membrane drying can occur owing to the fuel cell's small internal structure, imbalanced reaction on the membrane, and other factors. Early water flooding and membrane drying will lead to the decrease of the output power of the fuel cell, and serious ones will lead to risks such as membrane rupture, which will cause irreversible damage to the fuel cell and restrict the further improvement of the service life of the fuel cell. Many research teams have conducted in-depth research and discussion on water management of PEMFC [39–42]. The development of droplets in the channel [43]. Is shown in Fig. 12.

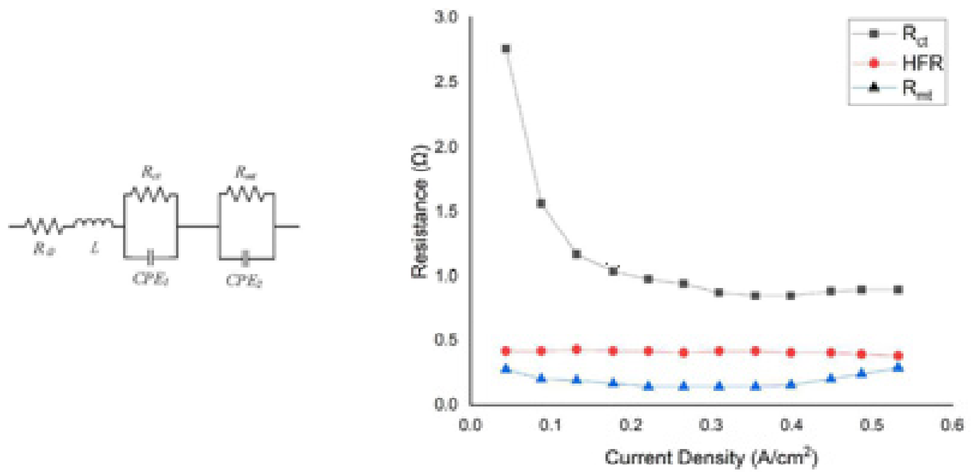
Many parameters can be used to diagnose water management faults, such as impedance spectrum [44,45], pressure drop [46,47], acoustic signal [48]. Different structural designs of fuel cell channels, MPL [49] and GDL [50] will also affect water management to varying degrees. In fact, many scholars have studied the development process of flooding. For example, a flooding process in a double platform period is established based on the anode pressure drop [51], and the process of droplet development has also been concerned by many scholars [52,53]. Some new sensors [54–56] are used for monitoring, and some advanced algorithms [57,58] are also used for water management of fuel cells.

In the application of PHM, water management focuses on L1-L5, which indicates that most studies focus on the prediction of water generation, flooding and membrane drying, and there are relatively few studies on overall management strategies. One reason is some fuel cell inspection systems introduce the probability of risk in the process of use [59], which is not suitable for online monitoring and management.

In order to achieve better water management, more timely and accurate detection should be achieved, which depends on people's further exploration of the development process of flooding, and on the other hand, it depends on the development of monitoring technology. At the same time, the design of the new channel is also very important.

(2) Carbon corrosion failure

Corresponding to #2 carbon corrosion in cluster analysis, literature analysis was conducted on carbon corrosion failure in PEMFC.



a The Equivalent circuit of the fuel cell[31, 32]

b The dependence of the ohmic resistance (RU), the charge transfer resistance (Rct) and the mass transport resistance (Rmt) of the short stack with different output current densities[31].

Fig. 7 – A typical model in the stable development period.

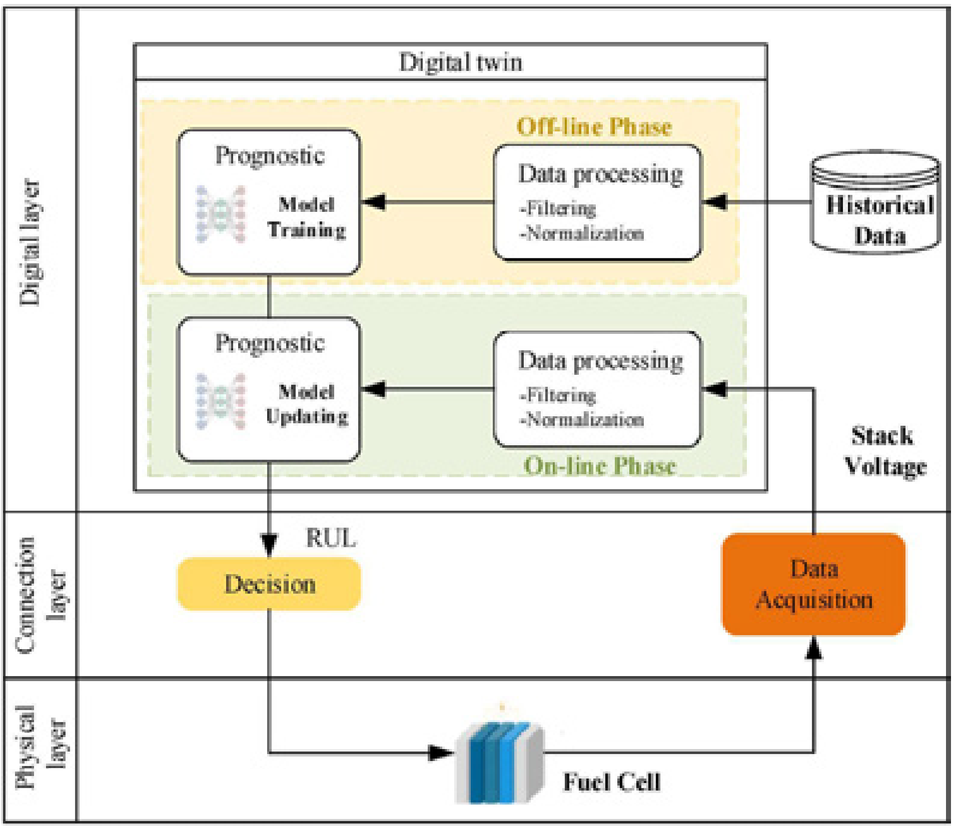


Fig. 8 – A digital twin model of PEMFC [37].

The reaction process of PEMFC depends on the catalysis of Pt (Platinum). Therefore, there is a catalyst layer in PEMFC. To increase the contact area between reactant and catalyst, the catalyst Pt is often placed on porous media. Because of its rich structure and stable properties, carbon is usually used to make porous media layers. However, in the process of PEMFC reaction, due to the bad working environment, the phenomenon of carbon corrosion often occurs. Once the carbon corrosion of PEMFC carbon carrier appears, it will cause the reduction of electrochemically active surface area, the

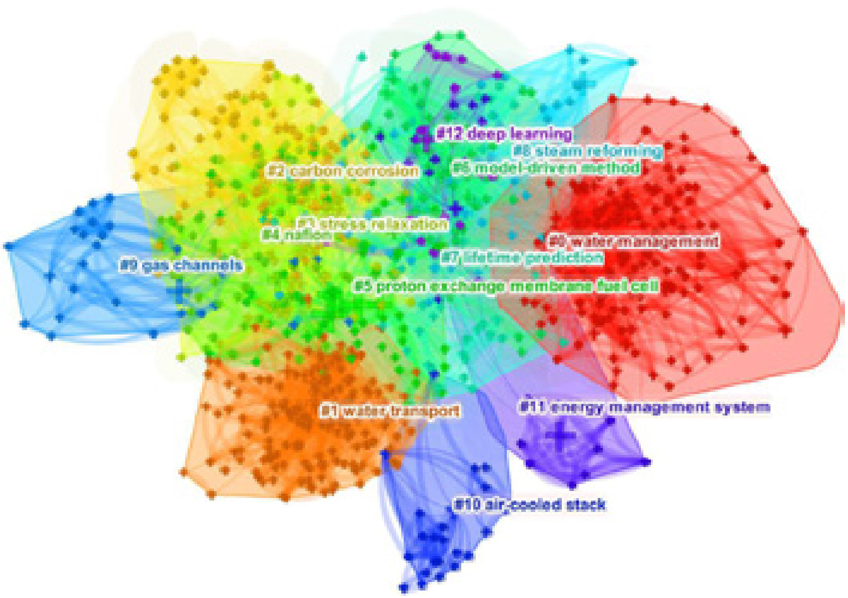


Fig. 9 – Result of keywords cluster.

collapse of porous structure of carbon-based catalyst carrier, accelerate the detachment and agglomeration of Pt ions from carbon-based catalyst carrier, and cause irreversible damage to PEMFC. The carbon corrosion degree of different carriers under working cycle is discussed in Ref. [60] (as shown in Fig. 13 and Fig. 14). Some carbon corrosion failures will result in abnormal membrane [61].

For carbon corrosion fault, CO and CO2 are very important external detection indicators [62]. SEM (Scanning Electron Microscope) and TEM (Transmission electron microscopy) are often used to study the development and extent of carbon corrosion [60,63–65]. The optimization of the structure will be conducive to the distribution of flow field and thermal field, which has been proved to be conducive to the mitigation of carbon corrosion [66–70]. In fact, reasonable strategies and the application of new materials have also reduced the degree of carbon corrosion [71–79].

In fact, more in-depth water and thermal management of fuel cells is required to mitigate carbon corrosion failures. On the other hand, developments in materials and structures are required.

(3) Stress relaxation & membrane failure

Corresponding to #3 stress relaxation and #4 nafion in cluster analysis, literature analysis was conducted on stress relaxation and membrane failure in PEMFC.

Fuel cells use a variety of polymers, the most common of which being proton exchange membranes and seals. The integrity of the proton exchange membrane and adequate sealing conditions are required for fuel cells to function properly. The interior environment of the PEMFC varies due to the complicated operating circumstances, has an influence on the polymer, and can even cause stress relaxation, leakage failure, and membrane rupture. The PEMFC's remaining service life and operational status are in force. The creep experiment is a useful approach to evaluate the film characteristics. A set of creep experiment results [80] can be seen in Fig. 15.

Due to the longer natural aging time, accelerated aging experiments [81] are often used in the study of fuel cell compounds. Many methods [82–85] such as SEM, EDS (Energy Dispersive Spectrometer), ATR-IR-S (Attenuated-Total-Reflection Infrared Spectroscopy), mass loss and CS (Compression Set) were been used to assess the extent of failure. Some improved models, such as the Maxwell equation [86], are also often used in the prediction of membrane degradation.

The aging mechanism of these polymers has also attracted a lot of attention [87–89], through experimental methods such as mechanical dynamic thermal analyzer, explore the influence of stress and state of the membrane under different load conditions.

In the area of stress relaxation & membrane failure, PHM research is mainly focused on L1-L4. Different loadings have a large impact on these polymers, so pressure management at different loadings, temperature management, and the application of new materials will help alleviate this problem.

(4) Lifetime prediction

Corresponding to #7 lifetime prediction in cluster analysis, literature analysis was conducted on prediction of the remaining life of PEMFC.

The difficulty in predicting the residual life of PEMFC is one of the factors limiting its large-scale commercialization. Different scholars mainly predict the residual life through the aging model establishment and fault prediction. Comparison of several PEMFC remaining life prediction methods [90] is shown in Fig. 16.

Research on remaining life prediction [91–93] mainly focuses on aging prediction and failure prediction. Like

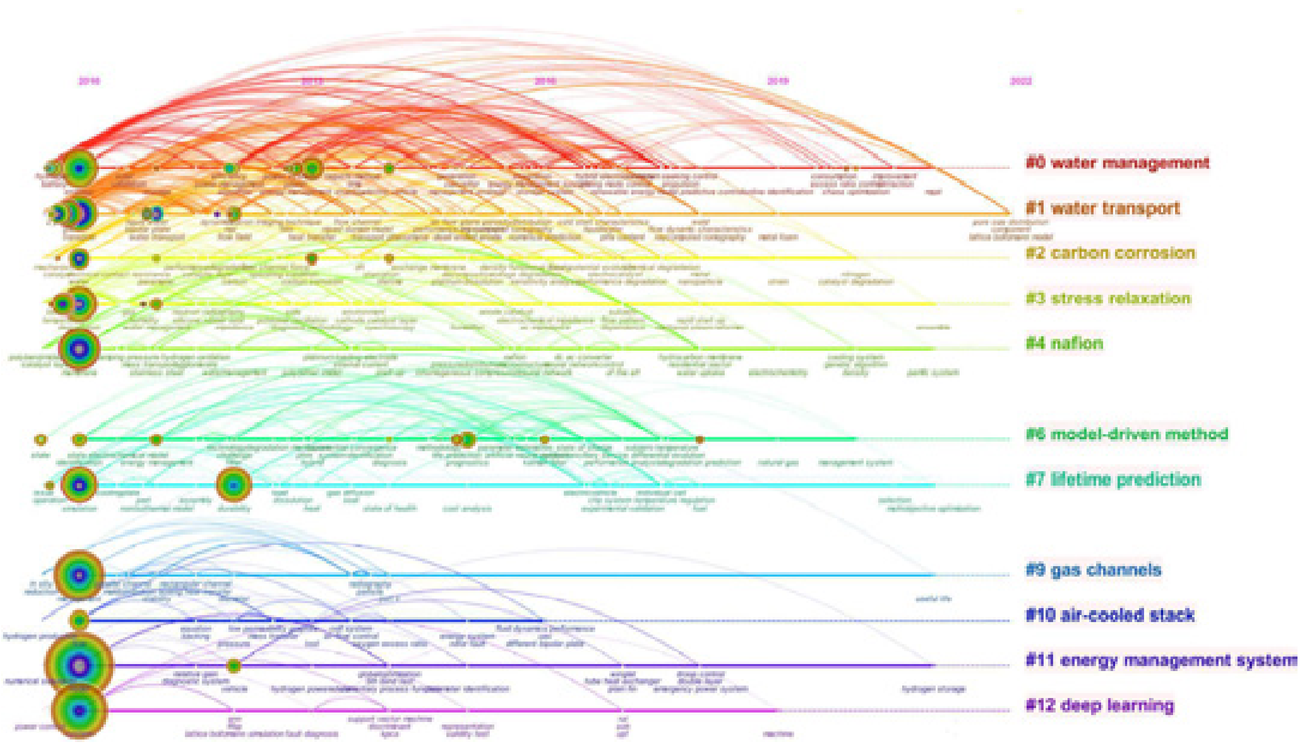


Fig. 10 – Keyword clustering atlas from the timeline perspective.

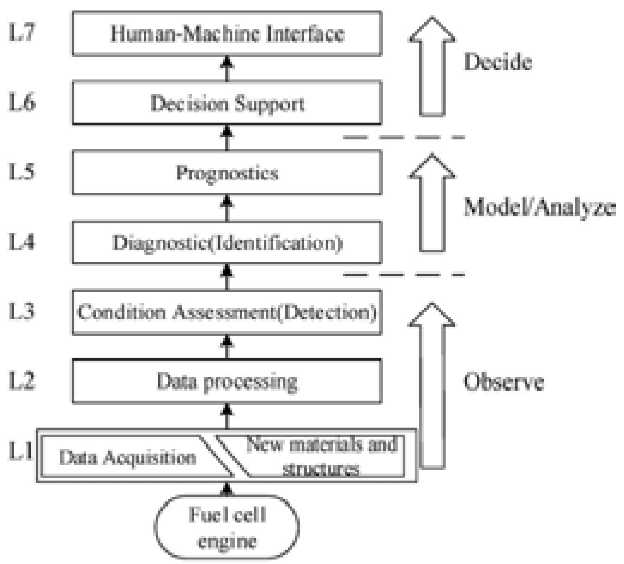


Fig. 11 – An expended framework of PHM in PEMFC analyzed by bibliometrics.

membrane failure, prediction of lifetime also requires many experiments with different loads at large time scales to validate the model [35,94–97]. Therefore, the research of this kind of problem is more dependent on the collaboration of world-class teams. Like the team of Pei and the team of Zhang worked closely together in this respect, focusing on the remaining life of vehicle fuel cells under complex working conditions [98–101]. Similarly, there are many strategies for failure elimination in the clustering of remaining life prediction [102–104]. From this perspective, the related research on remaining life prediction has covered all the scope of PHM definition. Similarly, with the development of computer science, some new algorithms [105,106] are helping the commercialization of PEMFC from the perspective of accurately and quickly predicting the remaining life and optimizing the service life, which will be discussed in the PHM method.

(5) Thermal management

Corresponding to #10 air-cooled stack in cluster analysis, literature analysis was conducted on thermal management and cooling system design of PEMFC.

Thermal is an essential factor affecting the operating efficiency of PEMFC. Running at low temperature will lead to flooding and low operational efficiency of PEMFC. Running at a high temperature will affect the remaining life of seals and the service life of membranes of the PEMFC. Therefore, the thermal management of PEMFC is an important direction of its PHM, which is mainly realized by the power control of PEMFC stack and the design of the cooling system. Fig. 17 is a framework for PEMFC thermal management [107].

Thermal faults are relatively easy to detect from parameters such as temperature sensors [108] and cooling circuit temperature data [109]. However, there is a certain lag in these data, which makes the data insufficient to support prognostics and advance decision-making. Therefore, numerical analysis [110] and theoretical model [111] establishment of fuel cell heat are also very important for thermal management. Multi-field coupling analysis and control is an important support in fuel cell PHM. Multi-field

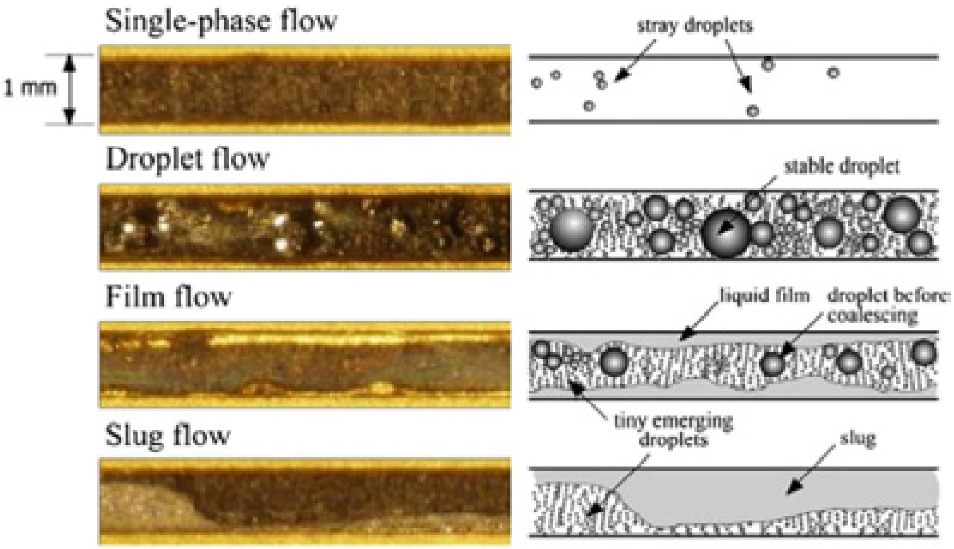


Fig. 12 – Development and transportation of droplets in PEMFC channel [43].

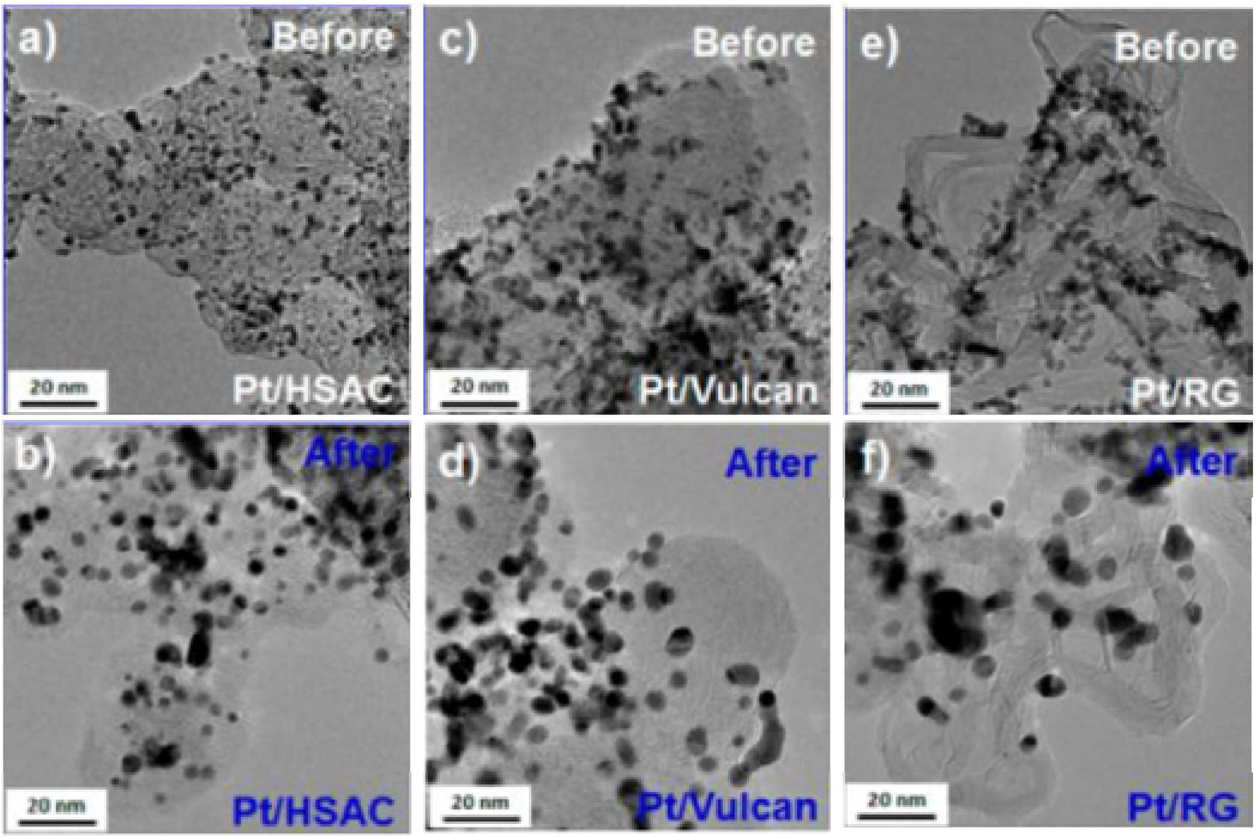


Fig. 13 – Comparison of different catalyst carriers before and after 5000 load cycles [60].

coupling analysis and control is an important support in fuel cell PHM [112,113], which requires the model to add temperature effects and consider other physical quantities.

Therefore, real-time multi-field coupled models such as CHP (Combined Heat and Power), CCP (Combined Cooling and Power), CCHP (Combined Cooling, Heat, and Power), CWP (Combined Water and Powe) and WHR (Waste Heat Recovery), would be a way to improve the PHM layer in terms of thermal management.

(6) Energy management

Corresponding to #11 energy management system in cluster analysis, literature analysis was conducted on energy management of PEMFC.

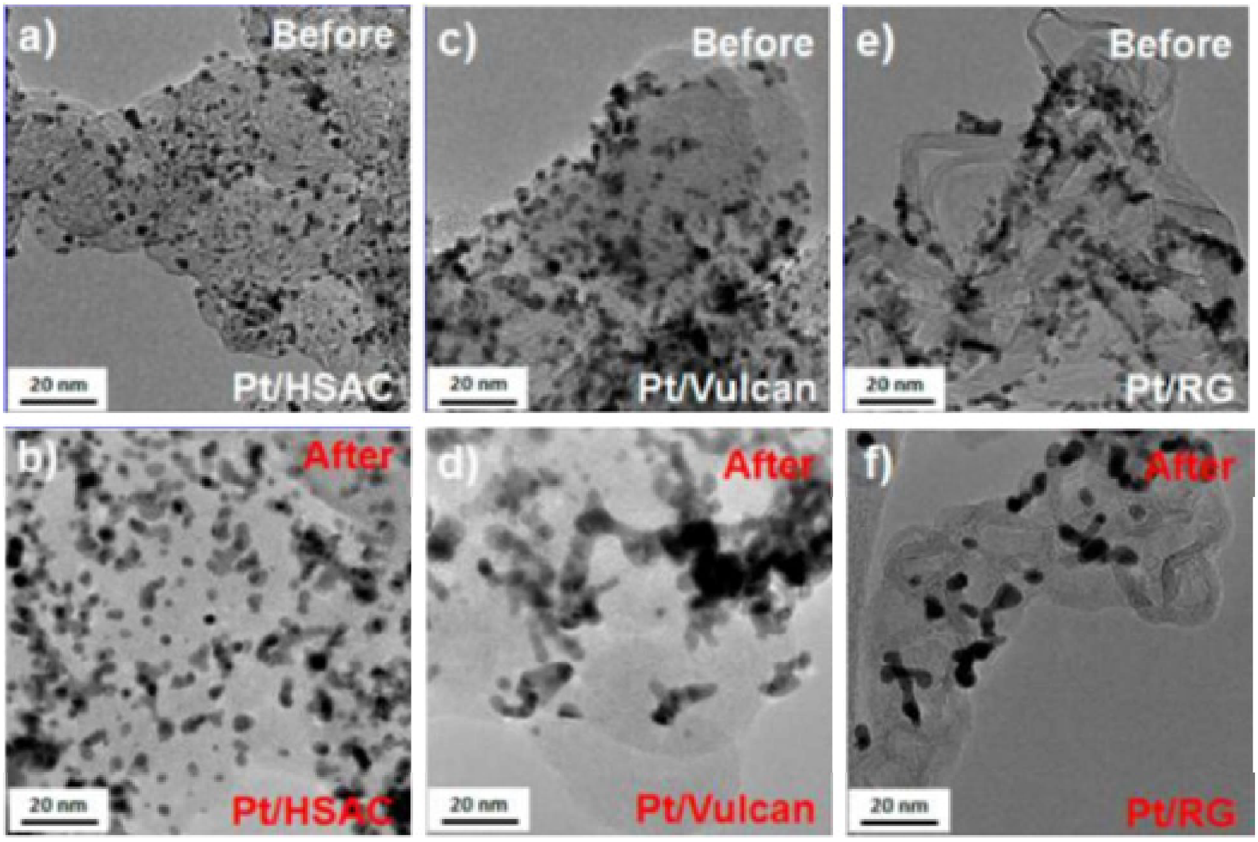


Fig. 14 – Comparison of different catalyst carriers before and after 5000 start/stop cycles [60].

Vehicle PEMFC usually works with batteries to reduce the impact of changes in working conditions on PEMFC. Therefore, for the PEMFC arranged in the vehicle power system, especially the multi-pile PEMFC-Lib-SC (PEMFC system, hydrogen-electric hybrid power, hydrogen-electric supercapacitor) hybrid power, how to manage the energy of the system becomes a vital part of PHM in PEMFC. A typical PEMFC-Lib-SC system from Ref. [114] is shown in Fig. 18.

Energy management in conjunction with the environment in which the fuel cell is used is a key point [115]. As when fuel cells are in use, they often share energy with other batteries and supercapacitors, so the power distribution between them is very important for fuel cell life extension [116–118]. Depending on the usage scenario, the goals of energy management strategies may not be similar [119,120], such as protecting PEMFC, maximum output, minimum energy consumption, etc.

The method clusters of PHM in PEMFC

(1) Structure optimization method

Corresponding to #9 gas channels in cluster analysis, literature analysis was conducted on the structure optimization method of PEMFC.

During the operation of PEMFC, the structure of each part, especially the gas flow channel, plays an essential role in the internal reaction rate, gas organization, water management and temperature management of the PEMFC. Therefore, structural optimization is an important method for PHM from the design stage.

Many scholars [52,121,122] have studied the effects of channel type and channel contact angle on the generation and discharge of water in PEMFC, temperature and PEMFC performance. Abundant simulation experiments can be carried out by using some neural network algorithms to explore the relationship between various parameters [123,124]. Conventional flow channels are difficult to achieve balanced performance for the operation of PEMFC [125]. Therefore, more and more scholars are studying bionic flow channels [126–128] and 3D flow channels [129,130].

In addition, many scholars [131,132]have paid attention to the design of the stack structure and the design of the pre-tightening force between the various parts, which also have a great impact on the regular operation and life of the PEMFC.

(2) Model-driven method

Corresponding to #6 model-driven method in cluster analysis, literature analysis was conducted on the model-driven method of PEMFC.

The model-based methods are mainly divided into two categories, one is to establish a numerical model, and the other is to establish a visual equivalent fuel cell model. In the early research, the model-based method was mainly used for the research and parameter optimization of the internal

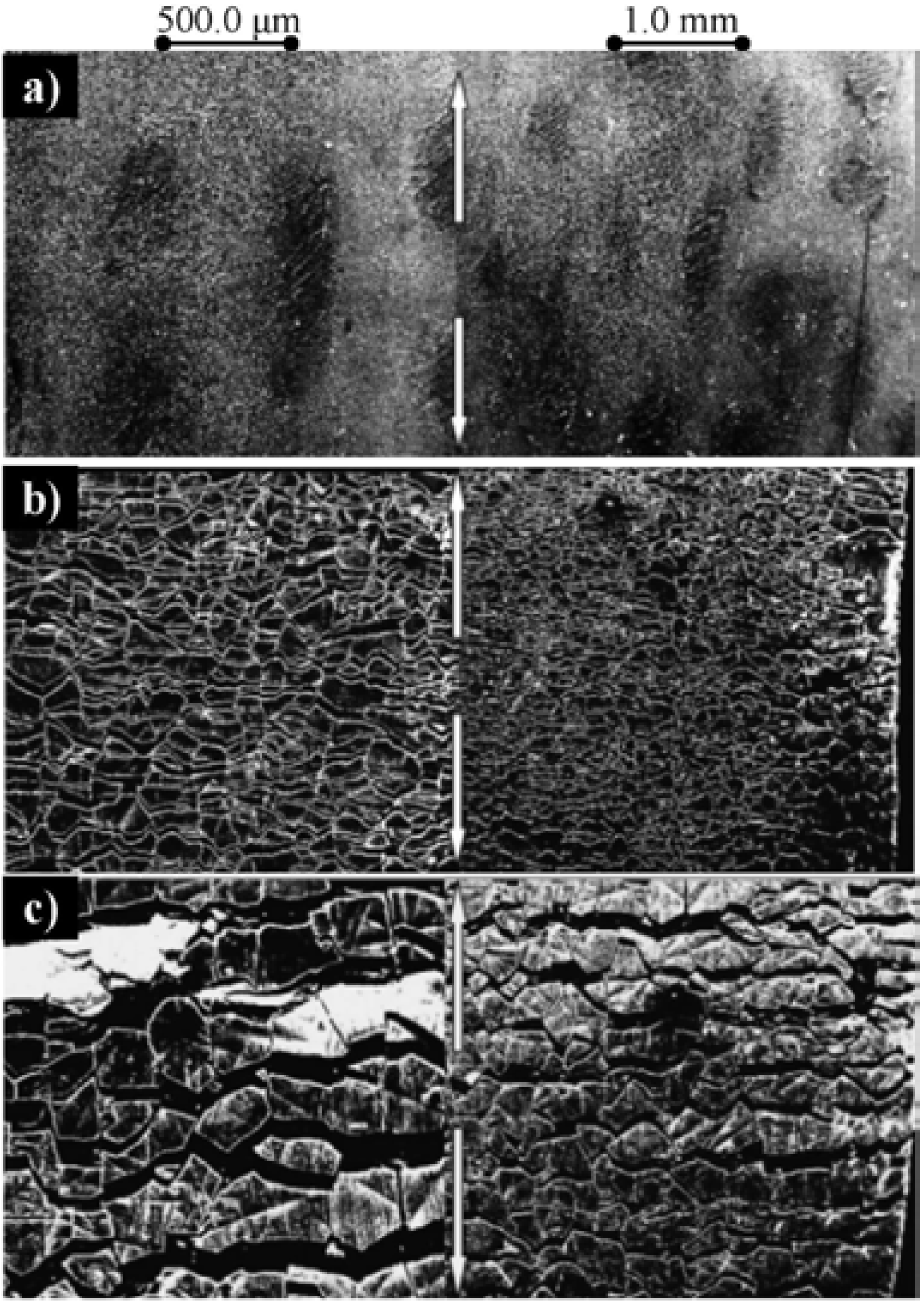


Fig. 15 – Creep experiment of membrane under different conditions. Arrow indicates the direction of applied stress. a. Under the condition of surface pressure 10 MPa; b. Acting for 45 h under the condition of surface pressure 10 MPa; c. Acting for 72 h under the condition of surface pressure 10 MPa [80].

structure of the fuel cell [133] and the research of its internal water transport, force [134] and microporous layer [135]. Gradually develop towards the overall description of PEMFC and the direction of water management, temperature management, and life prediction [58].

In developing of numerical models, some scholars have devoted themselves to improving the accuracy of general models, such as the PEMFC polarization curve model and the pressure drop model with the influence of temperature and humidity [136,137]. Some scholars [138,139] established a semi-mechanical and semi-empirical dynamic model by combining PEMFC theoretical derivation and empirical model derivation. Compared with pure numerical models, this type of model has higher calculation speed based on higher consistency with the experiment, which is faster and more suitable for online testing. CFD was used in PEMFC fault diagnosis by many scholars [140–142]. They derived PEMFC in detail theoretically, established a three-dimensional two-phase flow fuel cell model considering cooling water channel using FLUENT, and analyzed the output under eight different faults, respectively considering insufficient gas supply, water flooding, membrane drying

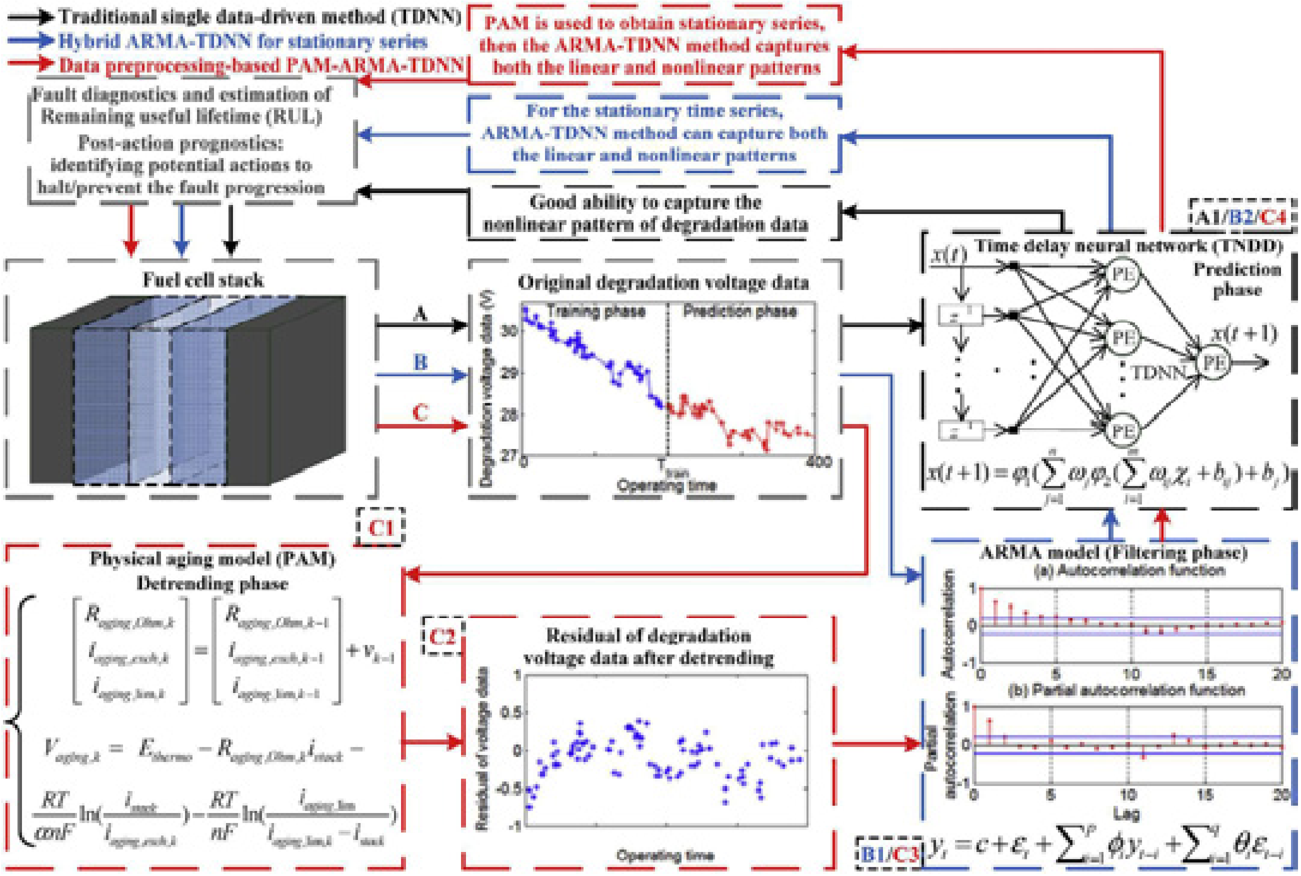


Fig. 16 – Comparison of different life prediction methods [90].

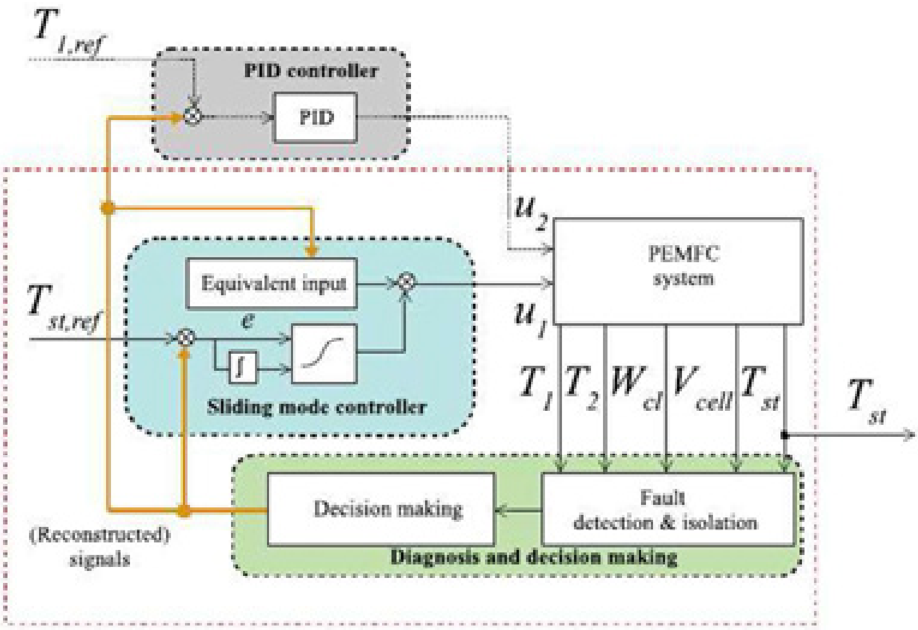


Fig. 17 – Model-based fault-tolerant control model for PEMFC thermal management [107].

and degradation of the platinum catalyst layer. It is found that the temperature change of cooling water is also beneficial for the fault diagnosis of PEMFC, but for the oxygen supply fault and catalyst layer degradation, further details are needed, such as the application of electrochemical impedance spectroscopy. In this aspect, the team of Daniel

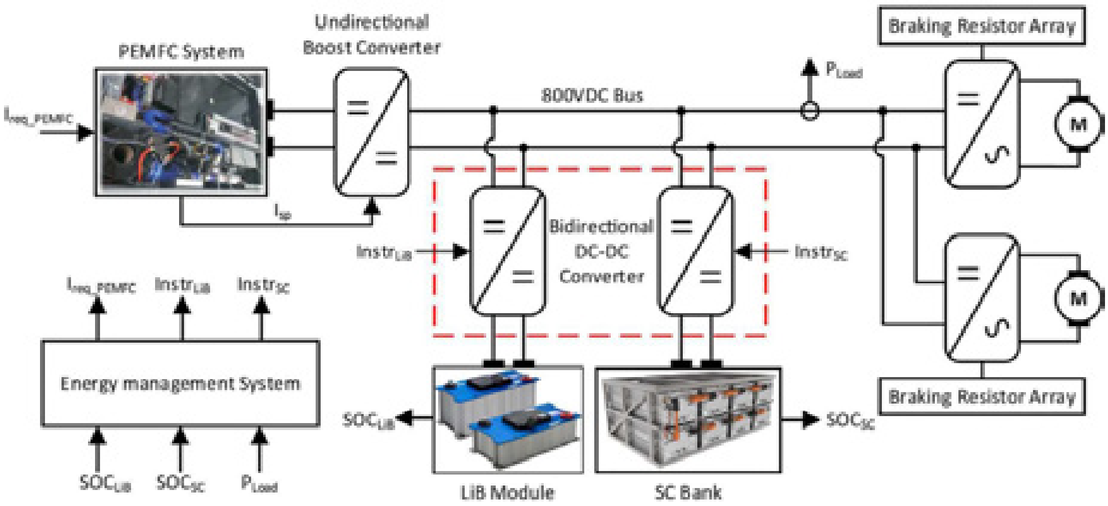


Fig. 18 – Power system schematic of the PEMFC-LIB-SC hybrid power tramway [114].

Hissel mainly conducted fault diagnosis of PEMFC based on the model [97,143,144]. They established a behavior model of PEMFC for fault prediction, which played a crucial role in remaining life prediction.

On the other hand, some people use visualization technology to conduct relevant studies on PEMFC. Currently, neutron imaging [145–147], direct imaging [147], nuclear magnetic resonance imaging, X-ray scanning imaging [148] and transparent fuel cell [149] are mainly applied.

(3) Deep learning method

Corresponding to #12 deep learning in cluster analysis, literature analysis was conducted on the deep learning method of PEMFC, which represents a class of data-based methods.

The method of deep learning is essential to build a statistical model based on data or analyze a semi-empirical model in combination with a mechanism. It requires a large amount of historical data of PEMFC operation and historical data of various working conditions to generate the model.

Data-driven fuel cell fault diagnosis requires a large amount of historical data, and data acquisition is inseparable from experiment or model simulation. Therefore, building a data-driven model requires a long time and data support under multiple operating conditions [58]. Yang et al. [150] applied pseudo-random binary sequence signal to PEMFC, used it as perturbation and used electrochemical method to obtain a large amount of impedance data. Through CWT (Continuous Wavelet Transform), continuous data fusion, the fitting function was finally obtained. The numerical model of PEMFC is used for fault diagnosis of fuel cells based on its input and output.

Zhang et al. [151] proposed a PEMFC fault diagnosis method based on the information fusion technology of SVM (Support Vector Machine) and DST (D-S Evidence Theory) given that the complexity of faults and the uncertainty of recognition. With the development of computer computing power, deep learning has also been applied to the PHM of fuel cells. The team of Yu [152–156] used deep learning to experiment with PEMFC's water management, temperature management, energy management, and optimal control. Compared with deep learning, which requires many data training samples, the application of DT technology in the PHM field is also becoming more and more extensive [157–159]. Wang et al. [160] constructed the digital twin of PEMFC with multiple physical fields, and reduced the dimension by reasonable calculation, greatly shortening the traditional CFD (Computational Fluid Dynamics) simulation time, which provided conditions for the application of CFD in online fault diagnosis. Also, DT technology had been applied in this field [37], they constructed a data-driven digital twin model combined the PEMFC reaction mechanism and deep learning model. The results show that this method can achieve a certain accuracy even under limited data. The new approach based on deep learning is being applied in PHM of PEMFC.

Summary of main methods of PHM in PEMFC and highly cited papers

Using the method of bibliometrics, the horizontal PEMFC research concerns can be obtained, and the overall PHM planning can be carried out by combining the vertical structure of PHM applied to each problem. The above methods and the problems addressed are summarized in Table 3.

We made a unified evaluation of the articles in each stage and ranked their influence. Because the newer articles performed weakly in the influence index, we chose the centrality index to reduce the impact of the publishing time on the influence as much as possible. However, the impact of the publishing time cannot be completely eliminated, so this influence ranking is only used as a consideration of the influence of the articles in the past time, does not represent the

Table 4 – Comparison of the average relative accuracy.

No.	Title	Centrality	First Author	First research institution	Source	Main methods or contents	Cited Frequency
1	High temperature PEM fuel cell performance characterisation with CO and CO_2 using electrochemical impedance spectroscopy	0.22	Andreasen S.J. (2011) [62]	Department of Energy Technology, Aalborg University.	INT J HYDROGEN ENERG	EIS method is applied to study the influence of different gas content in high temperature proton exchange membrane fuel cell. A series of experiments with different anode gas contents were conducted on a 45 cm^2 BASF Celtec P2100 high temperature PEM MEA. Then, the electrochemical impedance spectra under different conditions are fitted into the equivalent circuit for further research. The experimenter found that when pure hydrogen was introduced at different temperatures, the performance output was consistent with the empirical value, but when different proportions of CO and CO_2 were added into the anode gas, the performance of the fuel cell changed greatly, especially under the action of low temperature and high concentration of CO.	157
2	Effect of contaminants on polymer electrolyte membrane fuel cells	0.21	Zamel N. (2011) [61]	20/20 Laboratory for Fuel Cells and Green Energy RD&D University of Waterloo.	PROG ENERG COMBUST	A detailed overview of PEMFC gas poisoning is presented. The effects of CO, CO2, H2S and other gases on the performance and remaining life of PEMFC are analyzed from a wide range of literatures. Unlike the general review, this paper also analyses the mechanism of fuel cell gas poisoning from the point of view of chemical reaction kinetics, which is of great significance for people to further understand PEMFC reaction and formulate mitigation strategies.	196
3	Main factors affecting the lifetime of Proton Exchange Membrane fuel cells in vehicle applications: A review	0.20	Pei P.C. (2014) [93]	The State Key Lab. Of Automotive Safety and Energy, Tsinghua University.	APPL ENERG	A review that takes the operating conditions of the fuel cell into account. The remaining life of the fuel cell under experimental conditions is quite different from that of the actual fuel cell. In this paper, the operating conditions of the vehicle fuel cell are considered. The dynamic response characteristics and influencing factors during the operation of the battery are taken into consideration. The reasons for the failure of the fuel cell in use, such as flooding and gas starvation, are systematically reviewed and solutions are proposed.	399

(*continued on next page*)

Table 4 — (*continued*)

No.	Title	Centrality	First Author	First research institution	Source	Main methods or contents	Cited Frequency
4	Electrocatalyst approaches and challenges for automotive fuel cells	0.20	Debe M.K. (2012) [77]	3 M Fuel Cell Components Program, 3 M Center.	NATURE	This is one of the few papers from enterprises. From the commercial point of view, the deficiency of fuel cell catalyst activity was analyzed in detail, and some feasible methods were put forward to solve this problem, such as improving electrochemical design, expanding the area of catalyst layer, using low aspect ratio or unsupported nanoparticles, using platinum-free catalyst, etc.	4446
5	Parameter identification of PEMFC model based on hybrid adaptive differential evolution algorithm	0.20	Sun Z. (2015) [133]	National Laboratory of Industrial Control Technology, Institute of Cyber-Systems and Control, Zhejiang University.	ENERGY	A HADE (Hybrid Adaptive Differential Evolution) algorithm is proposed to identify the operating parameters and states of PEMFC. Two bionic algorithms are also added to HADE. Numerical simulation shows that the algorithm has good applicability and good accuracy for parameter identification of PEMFC.	106
6	A review on polymer electrolyte membrane fuel cell catalyst degradation and starvation issues: Causes, consequences and diagnostic for mitigation	0.18	Yousfi-Steiner N. (2009) [78]	EIFER, European Institute For Energy Research.	J POWER SOURCES	The failure of PEMFC is summarized in two parts, including long-term degradation failure and transient failure. The influence of various parameters in the failure process of PEMFC was analyzed from the reaction kinetics, and it was proved by different references. The phenomena of carbon carrier degradation and gas starvation are analyzed in detail. Finally, based on the fault tree theory, the causes of carbon carrier degradation are analyzed, and some solutions are provided.	407
7	Highly Crystalline Multimetallic Nanoframes with Three-Dimensional Electrocatalytic Surfaces	0.16	Chen C. (2014) [79]	Department of Chemistry, University of California.	SCIENCE	In fact, this is an article to solve PHM in PEMFC from the atomic point of view. A highly active and durable class of electrocatalysts by exploring the structural evolution of platinum-nickel (Pt–Ni) bimetallic nanocrystals was obtained. The experiment proves that this structure has better quality activity, which is very helpful for improving the performance and durability of PEMFC.	2187

8	Water droplet accumulation and motion in PEM (Proton Exchange Membrane) fuel cell mini-channels	0.16	Carton J.G. (2012) [53]	Department of Manufacturing and Mechanical Engineering, Dublin City University.	ENERGY	The formation mechanism of water in PEMFC channel is analyzed. The accumulation and blockage of water in the channel are analyzed by CFD method. A fuel cell with a U-shaped channel was set up, and the formation and transfer of droplets were studied by VOF model. This is very important for improving the PHM level of PEMFC from the point of view of water management.	252
9	Diagnosis of polymer electrolyte fuel cells failure modes (flooding & drying out) by neural networks modeling	0.15	Yousfi-Steiner N (2011) [58]	EIFER, European Institute For Energy Research.	INT J HYDROGEN ENERG	A method based on neural network is applied to the water management of PEMFC. Different from the conventional method, this method uses two independent Elman recurrent neural networks to predict different parameters, which improves the applicability of neural networks. The experimental results show that this method can identify the flooding, membrane drying and working status of PEMFC with limited parameters.	161
10	Optimization-based energy management strategy for a fuel cell/ battery hybrid power system	0.14	Ettihir K. (2016) [34]	Hydrogen Research Institute, Université du Québec Trois-Rivières.	APPL ENERG	Most of the vehicle functional systems with PEMFC are mixed with other energy sources, and the load fluctuation of PEMFC is reduced with the addition of additional power sources. Therefore, this paper tries to find a balance between PEMFC and battery through energy management. Self-adaptive recursive least square method is used for online identification, and power allocation is carried out by optimization algorithm, to minimize the fluctuation of PEMFC working environment, maximize its efficiency and prolong its remaining service life. Through the study of two kinds of PEMFC with different degradation degrees, this method has certain applicability.	186

quality of the article. The specific information of each article is shown in Table 4.

Conclusion

In order to accelerate the commercialization of fuel cell engines, a bibliometrics-based analysis of the development status and future development paths of PHM in PEMFC is constructed. Through the title, keywords, author and other information of the article, the article network can be constructed and visualized through CiteSpace. From the visual analysis of the disciplinary dimension, the regional dimension, and the research hotspot dimension, we can see that the application of PHM in PEMFC is moving towards the characteristics of multidisciplinary crossover, multi-regional cooperation, and multi-hotspot concentration. Furthermore, using the results of the bibliometric analysis, a novel review is presented, and bibliometric clustering is applied as a context for organizing the review. The content represented by different clusters, the reasons for the clustering and the future development direction are analyzed, and the specific PHM methods are summarized in Table 4 by clustering.

Combined with the visual analysis of bibliometrics, from the perspective of the commonly used methods of fuel cell PHM and its PHM level, we can think that fuel cell PHM is in a stage of rapid development.

Through the analysis of the PHM layer, we can know the development path of PHM in PEMFC. First, the development of fuel cell PHM relies on multidisciplinary development, not only in figuring out the failure mechanism, how to diagnose and predict the life, but also how to obtain a better remaining life through optimization, which is easily overlooked in previous PHM research Yes but very important. Second, the role of computer technology in multidisciplinary integration is becoming more and more important, because it is very helpful to PHM in terms of real-time and accuracy. Third, it has become a consensus that data-driven methods are more efficient, however, the lack of high-quality available data in public datasets also limits the development of PHM in fuel cells to a certain extent.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2022.08.024.

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