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Lattice Boltzmann Method for Fluid-Thermal Systems: Status, Hotspots, Trends and Outlook

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ABSTRACT Great advances have been made with the lattice Boltzmann (LB) method for complicated fluid phenomena and fundamental thermal processes over the past three decades. This paper presents a systematic overview of the LB method from 1990 to 2018, based on bibliometric analysis and the Science Citation Index Expanded (SCI-E) database. The results show that China took the leading position in this field, followed by the USA and UK. The Chinese Academy of Sciences had the most publications, while the Los Alamos National Laboratory was first as far as highest average citation per paper and h-index are concerned. Physical Review E was the most productive journal and ''Mechanics'' was the most frequently used subject category. Keyword analysis indicated that recent research has focused on the natural convection and heat transfer of nanofluid or multiphase flow in complex porous media. Hydrothermal treatment of nanofluid with shape factor on the conditions, such as variable magnetic fields, thermal radiation and slipping boundary, were the research hotspots. Further research perspectives mainly explore the multiscale models for coupling multiple transport phenomena, morphology optimization of porous parameters, new nanoparticles with shape factor, multicomponent LB method considering Knudsen diffusion effect, LB-based hybrid methods, radiation performance or boiling-heat transfer of nanofluid, and the active control of droplets, may continue to attract more attention. Moreover, some new applications, such as phase change of metal foam, erosion induced by nanaofluid, anode circulating, 3D modeling in thermal systems with vibration, and magnetohydrodynamics microfluid devices, could be of interest going forward.

INDEX TERMS Lattice Boltzmann method, fluid systems, thermal processes, multiscale modeling, multidisciplinary, bibliometrics.

I. INTRODUCTION

Fluid phenomena and fundamental thermal processes are frequently encountered in many fundamental disciplines and engineering applications such as physics, chemistry, biomedicine, energy science and various branches of industrial research. Widespread applications involving fluid-thermal processes exist in fuel cells and flow batteries, thermal power systems, energy storage equipment, chemical reactors nuclear power plants and micro-energy systems. Viable numerical strategies evaluate complex fluid-dynamic phenomena such as multiscale transporting, phase change, chemical reaction and heat transfer, and in turn determine the fine property and technical reliability of these strategies. With the development of numerical technologies, the lattice Boltzmann (LB) method has become one of the most rapidly growing hotspot topics; its rising prominence in academia suggests its enormous potential as a powerful methodology and strategy for fluid systems and associated thermal processes [1]–[4]. The LB method is based on molecular dynamics theory; it constructs a microcosmic particle model and then utilizes the particle distribution function to obtain

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the flow field attributes of macroscopic fluids. Benefitting from its clear physics, the LB method can both describe the interaction of particles on a mesoscopic scale and reflect the macroscopically dynamic variation of the flow field better in complex structures and multicomponent multiphase flows [5]–[8]. Despite its promising future, this research field is still infancy. Throughout the literature search, the LB method made its original appearing in 1988 [9] and raised great prospects as an emerging paradigm for the simulations of fluid systems and fundamental thermal processes. Thereafter, the LB method has gradually been applied to various scientific documents, and has been demonstrated to be an effective and powerful computational strategy for diverse complicated fluid-thermal phenomena that have been problematic for conventional computational methods [10]–[24].

Traditional computational methods are usual based on the hypothesis of continuum and reach numerical solutions using appropriate schemes. However, these approaches are always hard or even improbable to resolve some physical phenomena (e.g. surface wettability and interfacial slip), especially in the microscales and mesoscales. Moreover, particle-based microscopic methods, like molecular dynamics (MD), study the movements and collisions of individual molecules where the molecular structure and interactions of intermolecular potentials are well demonstrated. However, the considerable computational requirements limit such methods to tiny space and time scales—unsuitable for the majority of practical problems [25]. The LB method, which lies in the middle area between the microscopic and macroscopic methods, is a mesoscopic approach that originates from the Boltzmann equation-based kinetic theory. According to the kinetic theory, the LB equation is described as a minimum lattice formulation of the continuous Boltzmann equation in which the macroscopic hydrodynamic properties can be recovered by the preservation of the microscopic kinetic principles [26]–[28]. Hence, the LB method is on the basis of a particle model but is practical for predicting hydrodynamic behaviors on the macroscopic scale. Because it can bridge such scales, the LB method facilitates incorporation of microscopic or mesoscopic physics models whilst the physical regularities and properties at macroscopic scale can be recovered at a lower computational cost.

The LB method, since its emergence, has experienced rapid development and been an accurate and reliable tool for thorough understanding underlying physical processes, such as flows in porous flow [29]–[37], multiphase flows [38]–[50], particle suspension flows [51]–[57], turbulence [77]–[90], fuel cells/ flow batteries [91]–[97], heat/mass transfer [98]–[105], phase change [106]–[114], magnetic fluids [115]–[120], and crystal growth [121]–[123]. Because of its particle nature and local kinetic properties, the LB method has several distinctive advantages over conventional computational methods. Firstly, while the convective term in the Navier-Stokes (N-S) equations is nonlinear, the convective operator is completely linear in the LB equation [124], [125]. Secondly, the LB method can be applied relatively easily to complex boundary conditions using some essential mechanical regulations like imposing bounce-back [126] or modified reflection schemes to fluid particle distributions. These regulations, based on the momentum phenomenon reflected by the colliding between particles and solid surface, can be easily to address the interactions at the fluid-solid interface. This is demonstrated in many simulations of porous flows [127]–[130] and particulate suspension flows [131]–[134]. A third advantage of the LB method is the high efficiency of parallel computing with its explicit scheme and local microscopic interactions, which is ideally suited to massively parallel supercomputers. Moreover, it is necessary and expensive in conventional methods to acquire the pressure field with solving a Poisson equation, but in the LB method the pressure field can be easily derived from the density distribution [27]. It is worth noting that the parallel computation property and the simplified boundary condition implementation of the LB method have achieved considerable success with the fluid problems of various complex structures, especially in turbulence modeling across scales, and in nature convection and heat transfer, multicomponent diffusion and phase change, and other issues regarding mesoscopic dynamics. Despite its great advantages, the LB method does have some drawbacks. For example, it is unsuited to body-fitted coordinates and self-adapted time step, and may present obstacles to some engineering flows [135]. As a congenital dynamic program, the standard LB method is also unsuitable for steady-state computations [135]. Furthermore, the realizations of complicated boundary conditions are conceptually simple, but the practical programming may be difficult. Nevertheless, the above advantages of the LB method largely shade its weaknesses, whence the prosperity of applications.

At present, the applications of the LB method in fluid systems and fundamental thermal processes are one of the most important themes of the method. In 1989, the LB method was first used by Succi to measure the permeability of flow in random medium, and verified the Darcy's law [4]. Since then, various underlying physical processes, including interfacial instability, phase separation and surface wettability in complex geometric structures (e.g. pore-scale structure), have been studied by many researchers using the LB method [29]–[33], [91]–[94]. Among others, quantities such as permeability, porosity, and other statistical attributes of pore-scale medium that can be obtained through the up-scaling of the pore-scale LB results. On this basis, some fundamental issues such as heterogeneity, pore-scale interconnectivity and morphologies and non-uniform flow behavior can be assessed quantitatively [35]–[37]. Meanwhile, the detailed partial information of fluid velocity and distribution can also be quantified, whence constructed and tested the constitutive equations of macroscopic scales.

Moreover, regarding to interface moving and deformation mechanisms of multiphase or multicomponent flows, the LB method still faces with great challenges. Physically, the fluid-fluid interface (e.g., liquid and vapor) defined as a diffuse interface with a finite width, derives from the specific interactions among molecules [40]–[45]. The effective slip near the interface is caused by the relative diffusion between two fluid components. In the LB method, the diffuse interface does not depend on complex interface tracking or capturing techniques. Rather, the underlying microscopic interactions such as phase separations can be achieved by a relatively simple and uniform way, and not needed special treatment for manipulating the interfaces. For these great advantages, several multiphase LB models, such as the color-gradient model [6], [34], the free-energy model [1], [42], [48], the pseudopotential model [35], [110] and the phase-field model [39], [49], have been developed and successfully applied in various complex fluid-thermal systems. Great advances have been made in the above LB models, but their abilities still exist difference for simulating dynamic multiphase flow at large gas-liquid density radios and maintaining non-diffuse interface thickness at long-time evolution [34], [49]. For instance, the color-gradient and the free-energy LB models usually need additional correction terms to eliminate the non-Navier-Stokes terms of the macroscopic equations. Many density-gradient terms involved by the correction terms always bring in some additional sources of the numerical instability. This explains why the numerical instability occurring in the color-gradient and the free-energy LB models when simulating dynamic multiphase flows at large density radio and high Reynolds number. On the contrary, the pseudopotential and phase-field LB models have achieved success in the above flow situation. Moreover, in terms of achieving the flexibility of wettability boundary condition in complex geometric structures, the abilities of various multiphase LB models are also diversity. Thereafter, a series of developments of the LB method made great contributions to the numerical simulations and the investigations of complex fluid systems and fundamental thermal processes in the following dozen years [36]–[40], [144]–[153].

Throughout its increasing practical applications, the LB method has attracted extensive attention and is becoming an important, fast-growing field, resulting in an explosive growth in both the quality and quantity of published papers [147]–[155]. As this method is gradually recognized by researchers in related field such as physics, chemistry, material science, biomedicine and energy science, an increasing number of scientists and engineers are contributing to this research field. It is worth noting that this phenomenon is reflected by the ever-growing publications, patents, collaborating between countries and institutions, and a variety of international professional meetings, events, and activities. In LB community, many comprehensive reviews including Aidun and Clausen [1], Zhang [48], Zeng *et al.* [50], Mukherjee *et al.*, [92] and Sheikholeslami and Rokni [63], have been published that complete fundamental theories, summarize such research outcomes, explore the technical developments and put forward the research direction and challenges in the future. However, these reviews have been conducted based on technological content but we wish to propose an unusual perspective with bibliometric analysis to construct a historic map and overview of the LB method in fluid-thermal systems. Afterwards, challenges and prospects of LB method were summarized through most cited highly papers and hot papers, and explore the potential applications.

Bibliometric analysis is a powerful tool for quantitatively investigating scientific publications to evaluate research trends, find hotspots, and describe the research distributions and collaboration relations of countries/regions, institutions and authors. It has been widely used in various disciplines, such as chemistry [156]–[160], economics [161]–[163], computing [164]–[166], medicine [166]–[171], energy [172]–[176], mechanics [177], [178] and management [179], [180]. In recent years, the interest of bibliometric analysis for various research topics has increased rapidly [181]–[186]. It is worth mentioning that this paper is the first bibliometric analysis to evaluate LB method research globally. The purpose of this paper is to conduct a general overview and discuss on this research topic, including: 1) a historical overview of the topic; 2) main contributors: countries, institutes, research groups, authors and leading research areas; 3) collaboration relationships between institutes, research areas and countries/regions; 4) key journals of the topic; 5) papers with the highest citation number; 6) research trends by analyzing author keywords; 7) research hotspots by most popular papers; 8) research interests and perspectives. This study highlighted the research focuses and hotspots of fluid systems and associated thermal processes with the LB method, which have enabled scholars to understand the developing trajectories, the key factors of theoretical practical contributions and future challenges of the LB method.

The remainder of this paper is organized as follows. Section 2 gives a detailed introduction on the methodology of the LB method research in this paper. A historic map and overview of the LB method research is comprehensively reviewed in Section 3. In Section 4, the research trends and hotspots of the LB method are reviewed through keywords, hot papers and highly cited reviews. Section 5 summarizes the key points of the present review and provides a brief discussion about the further developments of the LB method in fluid-thermal systems.

II. METHODOLOGY

The data here analyzed was based on publications related to the LB method published between 1990 and 2018. Published articles were conducted from the Science Citation Index-Expanded (SCI-E) on 29 August 2018, with the search formulas "Lattice Boltzmann method*", "lattice Boltzmann model*", "lattice Boltzmann equation*", "lattice Boltzmann simulate*", "lattice Boltzmann scheme*" or "Lattice Boltzmann*". Articles deriving from England, Scotland, Northern Ireland and Wales were classified as the headline of "United Kingdom (UK)". Data of the top 20 authors in the LB method research and citation analysis was obtained on 25 February 2019. Keyword and

TABLE 1. Distribution of document type from 1990 to 2018.

Article Type	TP	%
Article	8729	89.57
Proceeding paper	937	9.62
Review	192	1.97
Correction	28	0.29
Editorial material	21	0.22
Book chapter	13	0.13
Letter	12	0.12
Meeting abstract	7	0.07
Note	5	0.05
Correction Addition	1	0.01
Total	9825	100

TP total papers, % the percentage of document type.

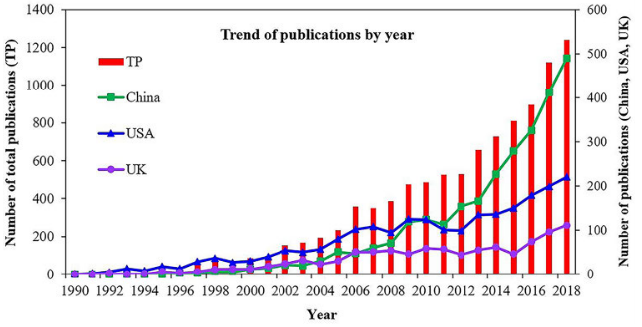

FIGURE 1. Trend in the number of published papers related to LB method by year.

international collaboration were conducted through the Dervent Data Analyzer (DDA) software. The development trends of keyword and journals in LB method research were displayed intuitively through bubble charts. Cross-relationship and DDA cluster maps were utilized to highlight the cooperative relations between different research areas, countries/regions and institutions. The journal's impact factor (IF) was conducted based on the 2018 *Journal Citation Reports* (JCR). It is important to note that some related publications that do not use the above search formula may be excluded in this study. this study does have some limitations. Since the topic searching styles in Web of Science only included the title, abstract, and keyword, some other publications may not be covered if the topic components have no words matching the search formula. These issues might cause some deviations.

III. RESULTS AND DISCUSSION

A. TYPES OF DOCUMENTS AND LANGUAGE OF PUBLICATIONS

There were 9825 documents that met the search standard mentioned above, including nine article types. Over 89% of the LB method documents were original articles. The next most frequent were proceedings papers and reviews. Items such as corrections, editorial material, book chapters, letters, meeting abstracts occupied less than 1% of the total publications. The following analysis was only based on the articles and reviews which have high shares of the publications in this field. More than 98% of the articles and reviews were published in English; other languages were Chinese (99 articles), Korean (10), Japanese (8), German (6), Spanish (5), French (4), Polish (2), Russian (1) and Welsh (1) (Table 1).

B. GLOBAL CONTRIBUTION OF LEADING COUNTRIES

1) NUMBER OF PUBLICATIONS AND CITATION

From 1990 to 2018, 84 countries contributed 11,744 papers to the LB method research fields, 129 of which are highly cited. These are papers which received enough citations to rank in the top 1% of the academic field based on a highly cited threshold within the field and publication year. Highly cited papers help to identify breakthrough research within a research field and are used to identify and refine the most influential research papers. 14 papers are ESI (*Essential Science* Indicator) hot papers. These are papers selected by virtue of being cited among the top 0.1% in a bimonthly period and must be published within the last two years. The number of total publications was in relatively stable during 1990–2001, but quickly increased from 2002, except for a decrease in 2007 (Fig. 1). Furthermore, a sharp increase was apparent from the high rising rate after 2012. In 2018, 1239 papers were published, 12.62% of the total number of publications. It is calculated that more than 76% of the papers were published from 2009 to 2018, more than thrice as many published on this topic as in the previous ten years. This suggests that this topic has become increasingly attractive to scientists and engineers. The three most productive countries/regions are China, the USA and the UK: publications from China were fewer than from the USA before 2010, but China's output sharply increased from 2011 to exceed those of the USA and UK. This may be attributable to the nurture of Chinese talent and rapidly increasing investment in scientific research funds.

Analysis of academic research results from national or regional levels reveal which countries/regions have given more attention to LB method research. That is of important to contribute the international collaboration of relevant scholars. Table 2 shows the contribution of the 20 most productive countries/regions in LB method research. It is worth mentioned that the average citations per publications (ACPP) of countries/regions can reflect their academic influence on this topic. Many (23.93%) are international papers, 68.31% of which are from Spain and 63.87% from Switzerland. China was the most productive country, with a total of 2752 papers (27.38%), followed by the USA (2237; 22.73%) and the UK (986; 10.12%). The USA still led the list of total citations and average citations per publications (ACPP), as well as the highest h-index. In terms of publishing quantity, China held a relatively low ACPP, only 13.13 (Table 2). This is illustrated that the USA has higher academic influence than that in China for the research on the LB method. It is unclear whether this is due to issues including language barriers, deviation in acquiring different publications or the scope and quality of the research itself. In summary, all this high quantity

TABLE 2. Contribution of the 20 most productive countries/regions in LB method research.

Rank	Country/Region	TP	TC	ACPP	h-index	SP(%)	nCC
1	China	2752	36144	13.13	74	31.54	42
2	USA	2237	87423	39.08	129	45.82	56
3	UK	986	24583	24.93	75	56.70	47
4	Germany	851	19642	23.08	64	48.18	49
5	Iran	703	13079	18.6	57	31.01	39
6	Italy	578	13368	23.13	56	60.38	29
7	France	634	17585	27.74	50	59.78	47
8	Japan	549	8395	15.29	46	27.55	26
9	Canada	368	7108	19.32	43	48.91	34
10	Netherlands	356	9999	28.09	50	57.58	33
11	India	342	5072	14.84	34	38.30	31
12	Switzerland	310	7132	23.01	45	63.87	29
13	Australia	289	6414	22.19	40	61.59	24
14	Singapore	256	7594	29.66	43	53.91	17
15	South Korea	217	1852	8.53	20	39.17	19
16	Spain	142	2250	15.85	27	68.31	25
17	Taiwan	117	2261	19.32	24	23.93	10
18	Russia	94	1390	14.79	18	61.70	23
19	Malaysia	92	1053	11.45	17	39.13	23
20	Brazil	86	637	7.41	14	48.84	18

TP total papers, *TC* total citations, *ACPP* average citations per publication, *SP* share of publications, *nCC* number of cooperative countries/regions.

and proportion of international publications indicate that the LB method has attracted scholars worldwide to exchange productive ideas and cooperate with each other.

2) COOPERATION OF COUNTRIES

Of the 20 most productive countries/regions, seven from Europe had a higher share (over 48.18%) of publications published by international collaboration (Table 2). One possible reason is European visa policy, enabling European research institutes to more easily attract researchers from other countries. Another reason might be the benefit of the European Research Council, which supplies many cooperation opportunities for researchers from different European countries. It may also be observed that the share of publications with international collaboration was relatively low, in spite of highly productive publications in China (first) and Iran (fifth). This is possibly due to the problems posed by different cultures or the lack of good collaborative research environments. According to the collaboration relationships among countries/regions, researchers or learners can find appropriate collaborations or countries for further research. Figure 2 shows the collaborative relationships of the 20 most productive countries/regions. The size of the nodes is proportional to the total number of publications in each country/region. The lines show collaboration between different countries/regions and their thickness reflects the intensity of cooperation. In terms of collaborative relationships, the USA was the most active country, cooperating with other 56 countries/regions, particularly China, the UK and Italy. Germany was listed second for collaboration, followed by the UK and France.

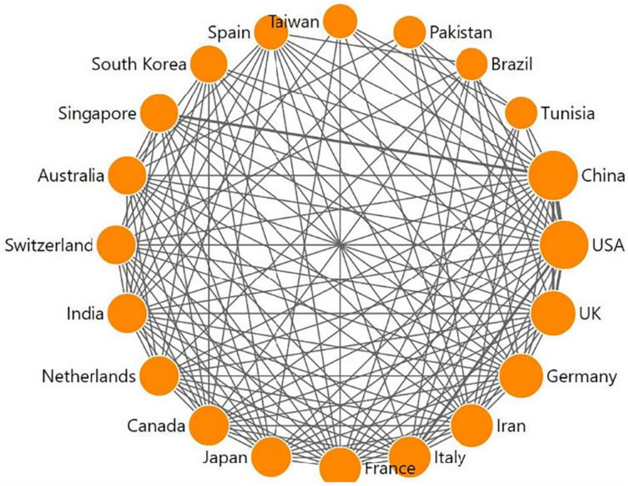

FIGURE 2. Collaboration matrix map among the 20 most productive countries/regions.

C. CONTRIBUTION OF LEADING INSTITUTIONS

Statistical analysis of research institutions provides more detailed and more specific information for scholars than the analysis of countries/regions. Table 3 shows the 20 most productive institutions in LB method research along with the number of publications, citations and h-index. Most of them are in the ten most productive countries/regions. Consiglio Nazionale delle Ricerche had the most publications, followed by Huazhong University of Science and Technology and the Chinese Academy of Sciences. The ACPP of these top 20 institutions was 29.84 during 1990–2018. Six institutions had higher citations than average. Los Alamos National Laboratory led the list with 133.43 average citations per publication, followed by Babol Noshirvani University of Technology (47.58), Exa Corporation (46.82), the University of Oxford (35.20), the University of Roma Tor Vergata (34.86), and the National University of Singapore (31.72). These institutions are clearly prominent in developing and promoting the field. Seven of the top 20 research institutions

TABLE 3. The 20 most productive institutions in LB method research during 1990-2018.

Rank	Institutions	TP	TPR%	TC	ACPP	h-index	Country
1	Chinese Academy Sciences	328	3.35	4696	14.32	37	China
2	Huazhong University of Science Technology	280	2.86	6892	24.61	38	China
3	Consiglio Nazionale delle Ricerche CNR	271	2.77	6212	22.92	42	Italy
4	Xi An JiaoTong University	249	2.54	4278	17.18	34	China
5	Indian Institutes of Technology	233	2.38	3462	14.86	30	India
6	National University of Singapore	198	2.02	6280	31.72	38	Singapore
7	Tsinghua University	185	1.89	2826	15.28	26	China
8	Babol Noshirvani University of Technology	182	1.86	8659	47.58	54	Iran
9	Los Alamos National Laboratory	164	1.67	21882	133.43	65	USA
10	ETH Zurich	160	1.63	4121	25.76	32	Switzerland
11	University of Oxford	137	1.40	4823	35.20	34	UK
12	University of Roma Tor Vergata	132	1.35	4601	34.86	32	Italy
13	Islamic Azad University	127	1.30	1877	14.78	22	Iran
14	University of Edinburgh	113	1.15	3145	27.83	31	UK
15	Harbin Institute of Technology	110	1.12	739	6.49	14	China
16	Delft University of Technology	98	1.00	2790	28.47	29	Netherlands
17	University of Geneva	97	0.99	1848	19.05	23	Switzerland
18	University of Science and Technology of China	94	0.96	1836	19.53	25	China
19	Shanghai Jiao Tong University	94	0.96	1730	18.40	23	China
20	Exa Corporation	83	0.84	3886	46.82	30	USA

TP total papers, *TPR*% the percentage of articles of journals in total publications, *TC* total citations, *ACPP* average citations per publication.

were from China, which had a relatively low ACCP value; two of the others were from the USA with high ACPP, as well as two each from Italy, Iran, Switzerland and the UK, and one each from Singapore and Netherlands. The influence of Chinese research institutions was limited compared to the US institutions. The former need to improve their work in this field and enhance learning with institutions of higher ACPP to improve their position in the publication list.

The collaboration network among the top 10 institutions during 1990–2018 is shown in Figure 3. Through the collaboration network, the collaboration relationship with different institutions can be more intuitively observed on this topic so as to help search more beneficial collaboration institutions. The data next to the institution names are the total number of publications from that research institution. The yellow points located in the intersections between the institutions show collaborative publications with other top ten research institutions. It is worth noting that the number of the yellow points can show the collaboration outputs, and meanwhile can reflect the cooperative intensity of different institutions. The data in the nodes without intersections represents publications arising from the independent work of this research institute or from collaboration with research institutions outside the top ten. The Consiglio Nazionale delle Ricerche, Xi An JiaoTong University, Los Alamos National Laboratory, and Tsinghua University had built up a largecollaborative network (Fig. 3). Moreover, Xi An JiaoTong University and Los Alamos National Laboratory had the most collaborative publications, followed by Babol Noshirvani University of

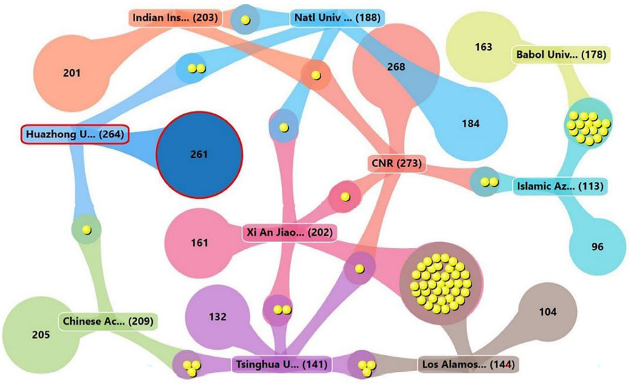

FIGURE 3. DDA cluster map on cooperation of the top 10 institutions.

TABLE 4. Contribution of the top 20 research areas in LB method research.

Rank	Research area	TP	TPR%	TC	ACPP
1	Mechanics	2515	27.02	49673	19.75
2	Physics, Mathematical	1860	19.98	62225	33.45
3	Physics, Fluids & Plasmas	1583	17.01	56481	35.68
4	Computer Science, Interdisciplinary Applications	1367	14.69	31129	22.77
5	Thermodynamics	1236	13.28	20939	16.94
6	Engineering, Mechanical	1058	11.37	17298	16.35
7	Physics, Multidisciplinary	806	8.66	21299	26.43
8	Engineering, Chemical	711	7.64	15993	22.49
9	Chemistry, Physical	582	6.25	13123	22.55
10	Materials Science, Multidisciplinary	532	5.72	9847	18.51
11	Mathematics, Applied	493	5.30	6572	13.33
12	Mathematics, Interdisciplinary Applications	408	4.38	5458	13.38
13	Energy & Fuels	357	3.83	8236	23.07
14	Physics, Applied	318	3.42	3831	12.05
15	Engineering, Multidisciplinary	290	3.12	3112	10.73
16	Water Resources	239	2.57	5892	24.65
17	Physics, Atomic, Molecular & Chemical	199	2.14	6277	31.54
18	Nanoscience & Nanotechnology	192	2.06	2738	14.26
19	Physics, Condensed Matter	172	1.85	2638	15.34
20	Multidisciplinary Sciences	167	1.79	3885	23.26

TP total papers, *TPR*% the percentage of papers of journals in total publications, *TC* total citations, *ACPP* average citations per publication.

Technology and the Islamic Azad University. The Indian Institutes of Technology were relatively independent in this research field.

D. CONTRIBUTION OF LEADING RESEARCH AREAS

The LB method is a relatively new and developing multidisciplinary field [187]–[200] which is supported by papers distributed over 122 research areas. According to the distribution of the LB method in different research areas, relevant scholars can study the cross-disciplinary status in this topic, whence search the potential cross-application prospect of the LB method. Here, the total papers (TP) and the percentage of papers of journals in total publications (TPR%) are the most worthy attention. In this study, the top 20 research areas ranked by the number of papers related to the LB method were examined. It is clear that "Mechanics" is the top research area with 2515 papers and the highest TPR% (27.02%), followed by "Physics, Mathematical", "Physics, Fluids & Plasmas", "Physics, Fluids & Plasmas", "Computer Science, Interdisciplinary Applications", "Thermodynamics" and "Engineering, Mechanical" (Table 4). The remaining research areas contributed less than 10%. "Physics, Fluids & Plasmas" led in ACPP, followed by "Physics, Mathematical" and "Physics, Atomic, Molecular & Chemical". The contributions of these areas reflect the latest focus topics in LB method research such as nanofluid hydrothermal treatment, multiscale modeling, soft matter system and phase change heat transfer. More specifically, various physical phenomena and interactions, including interface instability and wettability, viscosity-dependent permeability, thermal flux continuity of interface conjugate heat transfer interface deformation and slipping of electrohydrodynamic and magnetohydrodynamic, non-slip velocity at the solid-liquid interface and bubble/droplet dynamics, can be addressed by diversified LB methods. The higher ACPP in these fields verified the widely accepted opinion that the LB method had enormous potential to dispose fluid systems and the associated thermal processes of various complex structures.

With the growing maturity of theoretical methods and complex multiple requirements of practical problems, the cross relationships of different research areas are emerging. The collaboration network among the top ten research areas is illustrated in Figure 4. Through the DDA cluster map of different research areas, the publication outputs on the LB method can be more directly reflected, which is helpful to xplore the interdisciplinary application prospect in this e topic. "Mechanics", "Thermodynamics", "Engineering, Mechanical", and "Materials Science, Multidisciplinary" formed a large cross-network. The research areas of "Physics, Mathematical" and "Physics, Multidisciplinary" had the most cross-publications. "Physics, Mathematical" and "Mechanics", "Mechanics" and "Chemistry, Physical", and "Engineering, Mechanical" and "Engineering, Chemical" also had many cross publications. It seems that the collaboration of different engineering fields in the LB method has achieved considerable success. Although only reflecting the collaboration outputs of the top 10 institutions, we believe that the LB method has more extensive application areas that needs more scholars and researchers with interdisciplinary to communicate and make contribution for its development.

TABLE 5. **The 20 most productive journals in LB method research.**

Rank	Journal title	TP	TC	ACPP	IF
1	Physical Review E	846	34182	40.40	2.284
2	International Journal of Heat and Mass Transfer	409	8163	19.96	3.891
3	Computers & Fluids	357	5719	16.02	2.221
4	Journal of Computational Physics	296	15569	52.60	2.864
5	International Journal of Modern Physics C	260	3119	12.00	0.919
6	Computers & Mathematics with Applications	228	3829	16.79	1.860
7	Physics of Fluids	228	8520	37.37	2.279
8	Communications in Computational Physics	142	1562	11.00	1.762
9	International Journal for Numerical Methods in Fluids	131	2551	19.47	1.673
10	Journal of Fluid Mechanics	138	5344	38.72	2.893
11	Chemical Engineering Science	127	3312	26.08	3.306
12	Physica A-Statistical Mechanics and Its Applications	118	2170	18.39	2.132
13	Journal of Chemical Physics	99	2694	27.21	2.843
14	International Journal of Thermal Sciences	96	3793	39.51	3.361
15	Numerical Heat Transfer Part A-Applications	89	1267	14.24	2.409
16	Transport in Porous Media	89	1304	14.65	2.211
17	Advances in Water Resources	88	3397	38.60	3.512
18	Europhysics Letters	86	6152	71.53	3.748
19	Journal of Statistical Physics	84	5709	67.96	1.496
20	Soft Matter	84	1330	15.83	3.709

TP total papers, *TC* total citations, *ACPP* average citations per publication, *IF* impact factor.

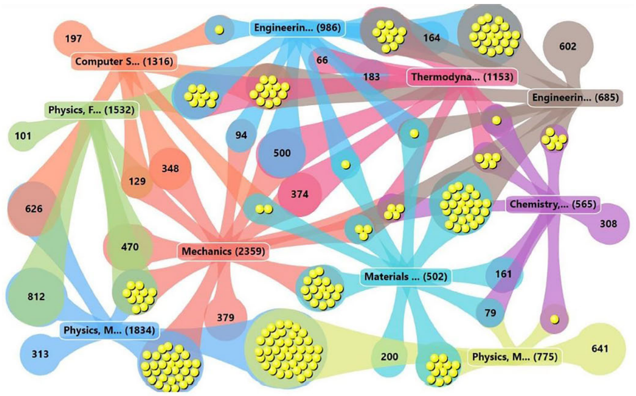

FIGURE 4. **DDA cluster map on cooperation of top 10 research areas.**

E. LEADING JOURNALS IN TERMS OF NUMBER OF PUBLICATIONS IN LB METHOD RESEARCH

It is essential that scholars who are interested in the LB method know which journals publish LB method research and decide which journal to read or submit their research papers to. During 1990–2018, 9825 papers related to LB method research were published in 1398 journals. *Physical Review E* took the lead, with 846 (8.61%) papers, as the most productive journal (Table 5). It was followed by *International Journal of Heat and Mass Transfer* (409; 4.16%) and *Computers & Fluids* (357; 3.63%). These three journals shared 16.61% of the total published papers; the top 20 journals published 4048 papers with a share of 41.20% (Table 5). All the remaining journals contributed a share of less than 1% each. *Europhysics Letters* had the highest ACPP of 71.53, followed by *Journal of Statistical Physics*(67.96) and *Journal of Computational Physics* (52.60). In terms of impact factor (IF), *International Journal of Heat and Mass Transfer* had the highest value of 3.891 indexed by Web of Science in 2018, followed by *Europhysics letters* (3.748) and *Soft Matter* (3.709).

To represent a historical map of LB method-related publications in journals, a bubble chart of the top 20 productive journals by year was constructed (Fig. 5). The number of each bubble is the annual number of publications on this topic. According to the number in each horizontal bubble, the publications of each journal over time can be observed. Vertically, the hot journals of each year can be found out. Journals including *Physical Review E*, *Journal of ComputationalPhysics*, *International Journal of Modern Physics C*, and *Physics of Fluids* have relatively stable annual publications on LB method research. Except for these four journals, a few papers were sparsely distributed in the top 20 journals from 1992 to 2007. After five years of significant increase, the LB method research field witnessed a significant growth in publications from 2013, a continually increasing trend. This pattern accorded with that in Figure 1. Furthermore, *Physical Review E* is the predominant source of LB method research, publishing more

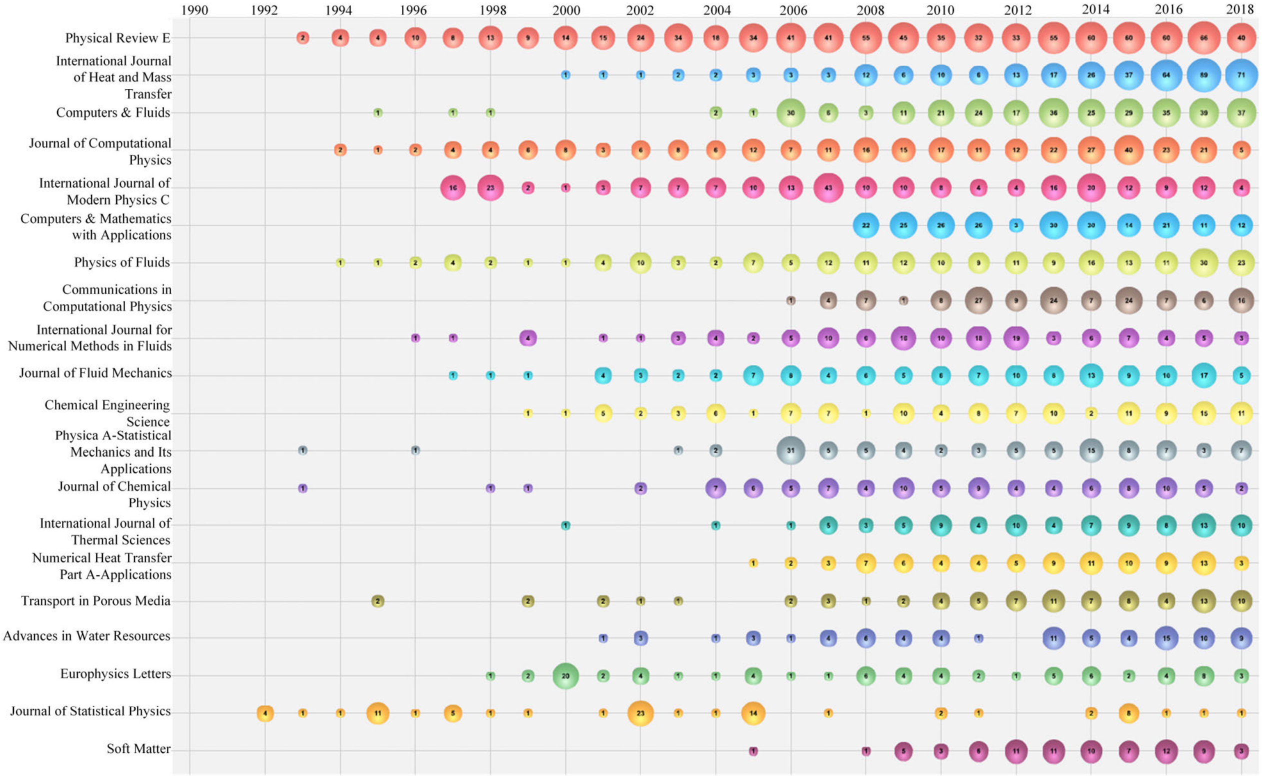

FIGURE 5. Bubble chart of the top 20 productivity journals by year.

TABLE 6. Contribution of the 20 most productive authors in LB method research.

Author	TP	TPR%	TC	ACPP	h-index	Institution (current), Country
Succi, Sauro	243	2.483	8161	33.58	45	Consiglio Nazionale delle Ricerche CNR, Italy
Shu, Chang	141	1.439	3641	25.82	33	National University of Singapore, Singapore
Guo, Zhaoli	133	1.348	5419	40.74	33	Huazhong University of Science Technology, China
Shi, Baochang	130	1.327	4346	33.43	28	Huazhong University of Science Technology, China
Sheikholeslami, Mohsen	102	1.041	7004	68.67	50	Babol Noshirvani University of Technology, Iran
Tao, Wenquan	99	1.011	2521	25.46	30	Xi An JiaoTong University, China
Yeomans, Julia M.	96	0.980	4950	51.56	32	University of Oxford, UK
He, Yaling	83	0.847	2525	30.42	30	Xi An JiaoTong University, China
Derksen, Jos J.	82	0.837	2196	26.78	24	University of Aberdeen, UK
Kang, Qinjun	80	0.817	3465	43.31	36	Los Alamos National Laboratory, USA
Chopard, B.	80	0.817	1633	20.41	22	University of Geneva, Switzerland
Karlin, I.V.	74	0.755	2906	39.27	27	ETH Zurich, Switzerland
Chai, Z.H.	70	0.715	1161	16.59	20	Huazhong University of Science Technology, China
Sbragaglia, M.	66	0.674	1692	25.64	24	University of Rome Tor Vergata, Italy
Chew, Y.T.	63	0.643	2613	41.48	27	National University of Singapore, Singapore
Krafczyk M.	54	0.551	3030	56.11	29	Braunschweig University of Technology, Germany.
Li, Qing	52	0.531	1597	23.49	23	Xi An JiaoTong University, China
Mishra, S.C.	50	0.510	1222	24.44	20	Indian Institute of Technology Guwahati, India
Farhadi, Mousa	47	0.480	922	19.62	17	Babol Noshirvani University of Technology, Iran
Melchionna S.	47	0.480	781	16.62	16	Sapienza University Rome , Italy

TP total papers, *TC* total citations, *ACPP* average citations per publication.

than 30 papers every year during 2005–2018. The number of papers related to LB method research published in *International Journal of Heat and Mass Transfer* exceeded *Physical Review E* from 2016, an explosive growth trend indicating this journal's deep interest and close attention to this field.

F. CONTRIBUTION OF LEADING AUTHORS

Leading authors who contribute to a certain area have high reputation and their works can inspire the research direction of other scholars. Table 6 lists the 20 most productive authors based on the number of papers. These authors were from the 20 most productive countries. Succi, Sauro led the list with 243 papers, followed by Shu, Chang (141), Guo, Zhaoli (133), Shi, Baochang (130) and Sheikholeslami, Mohsen (102). In terms of ACPP, Sheikholeslami, Mohsen ranked first with 68.67, followed by Krafczyk M. (56.11) and Yeomans, Julia M. (51.56). Sheikholeslami, Mohsen also achieved the highest h-index of 50, followed by Succi, Sauro (45), Shu, Chang (33) and Guo, Zhaoli (33). Among the 20 most productive authors, six were from China, three from Italy, and two each from Singapore, Iran, the UK and Switzerland; this indicates that LB method research was relatively concentrated in certain countries. The share of papers by the top 20 authors in total publications was only 17.51%, indicating that a large quantity of researchers were working in this field and contributing to the total of 9825 publications. The enormous population in this research community will likely make great progress and many achievements in the coming years.

G. AN ANALYSIS OF MOST CITED PUBLISHED PAPERS

While the citation impact of an article depends on many factors, it is still a widely accepted index for evaluating scientific articles [201]. Table 7 shows the 20 most highly cited publications. The most highly cited paper was "Lattice Boltzmann method for fluid flows" [2] published in the *Annual Review of Fluid Mechanics* by Chen, S. and Doolen, G. It led the list of total citations 4112 and annual citations 195.80. "A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research" [91] authored by Wang, Y. *et al.* was second with annual citations of 157.25. It is worth noting that due to the excellent numerical stability and constitutive generality, the LB method has great advantages to simulate the transfer phenomena in porous electrode. Addressing the water and heat transport issues with high cost and complex, such as uneven temperature distribution, gas-liquid two-phase coupling and interface wettability and instability, are one of the most flourishing application directions of the LB method in polymer electrolyte membrane fuel cells. Moreover, "Heat transfer characteristics of nanofluids: a review" [58] authored by Wang, X. Q. and Mujumdar, A. S. ranked third with annual citations 114.42. This is full illustrated that the natural convection and heat transfer of nanofluids have been well simulated by the LB method, and show better consistency with the traditional method.

Among the 20 most cited papers, six were published in *Physical Review E*, two in *Annual Review of Fluid Mechanics*, two in *Physical Review A*, two in *Journal of Statistical Physics*, with the other eight published in seven different journals such as *Physics Report s-Review Section of Physics Letters*, *Applied Energy* and *Physical Review Letters*. The papers published in those journals were more easily cited by other researchers because of these journals' document type [202], high impact factor [203]–[207] and wide scope and coverage [208]. 90% of the 20 most cited publications were from North America and Western Europe. The USA contributed 15 of these, followed by France (2), Italy (1), Singapore (1) and China (1), indicating that the USA was the leading country in this research field. It is worth noting that the Shan, X. W. group (Nos. 3 and 18), the He, X. Y. group (Nos. 10 and 20) and the Swift, M. R. group (Nos. 16 and 17) from the USA contributed the two most highly cited papers, respectively.

H. AN ANALYSIS OF MOST CITED PUBLISHED PAPERS

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IV. RESEARCH TRENDS AND HOTSPOTS

A. AN ANALYSIS OF KEYWORDS

To reveal the main focus and research trends in LB method research, 10113 author keywords from the retrieved results

TABLE 7. The 20 most highly cited publications during the period of 1990-2018.

No.	Authors	Title	TC	TCY	Journal	Year	Country
1	Chen, S., Doolen, G. [2]	Lattice Boltzmann method for fluid flows	4112	195.80	Annual Review of Fluid Mechanics	1998	USA
2	Qian, Y. H., Dhumeres, D., Lallemand, P. [125]	Lattice BGK models for Navier-Stokes equation	2881	106.70	Europhysics Letters	1992	France
3	Shan, X. W., Chen, H. D. [40]	Lattice Boltzmann model for simulating flows with multiple phases and components	1736	66.77	Physical Review E	1993	USA
4	Wang, X. Q., Mujumdar, A. S. [58]	Heat transfer characteristics of nanofluids: a review	1373	114.42	International Journal of Thermal Sciences	2007	Singapore
5	Benzi, R., Succi, S., Vergassola, M. [4]	The lattice Boltzmann equation: Theory and applications	1325	49.07	Physics Reports-Review Section of Physics Letters	1992	Italy
6	Wang, Y., Chen, K. S., Mishler, J. et al. [91]	A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research	1258	157.25	Applied Energy	2011	USA
7	Zou, Q. S., He, X. Y. [126]	On pressure and velocity boundary conditions for the lattice Boltzmann BGK model	1075	48.86	Physics of Fluids	1997	USA
8	Lallemand, P., Luo, L. S. [45]	Theory of the lattice Boltzmann method: Dispersion, dissipation, isotropy, Galilean invariance, and stability	1000	52.63	Physical Review E	2000	USA
9	Aidun, C. K., Clausen, J. R. [1]	Lattice-Boltzmann Method for Complex Flows	925	102.77	Annual Review of Fluid Mechanics	2010	USA
10	He, X. Y., Luo, L. S. [141]	Theory of the lattice Boltzmann method: From the Boltzmann equation to the lattice Boltzmann equation	921	41.86	Physical Review E	1997	USA
11	Chen, H. D., Chen, S. Y., Matthaeus, W. H. [192]	Recovery of the Navier-Stokes equations using a lattice-gas Boltzmann method	897	33.22	Physical Review A	1992	USA
12	d'Humieres, D., Ginzburg, I., Krafczyk. M. et al. [18]	Multiple-relaxation-time lattice Boltzmann models in three dimensions	864	50.82	Philosophical Transactions of The Royal Society of London Series A-Mathematical Physical and Engineering Sciences	2002	France
13	He, X., Chen, S., Doolen, G. D. [194]	A novel thermal model for the lattice Boltzmann method in incompressible limit	851	40.52	Journal of Computational Physics	1998	USA
14	Guo, Z. L., Zheng, C. G., Shi, B. C. [155]	Discrete lattice effects on the forcing term in the lattice Boltzmann method	843	49.59	Physical Review E	2002	China
15	Gunstensen, A. K., Rothman, D. H., Zaleskl, S. [144]	Lattice Boltzmann model of immiscible fluids	823	29.39	Physical Review A	1991	USA
16	Swift, M. R., Orlandini, E., Osborn, W. R. et al. [7]	Lattice Boltzmann simulations of liquid-gas and binary fluid systems	820	35.65	Physical Review E	1996	USA
17	Swift, M. R., Osborn, W. R., Yeomans, J. M. [198]	Lattice Boltzmann simulation of nonideal fluids	770	32.08	Physical Review Letters	1995	USA
18	Shan, X. W., Chen, H. D. [108]	Simulation of nonideal gases and liquid-gas phase-transitions by the lattice	726	29.04	Physical Review E	1994	USA
19	Ladd, A. J. C., Verberg, R. [51]	Lattice-Boltzmann simulations of particle-fluid suspensions	722	40.11	Journal of Statistical Physics	2001	USA
20	He, X. Y., Luo, L. S. [124]	Lattice Boltzmann model for the incompressible Navier-Stokes equation	647	29.41	Journal of Statistical Physics	1997	USA

TC total citations, *TCY* total citations per year.

were analyzed. Significantly, some publications do not include author keywords and are excluded from this analysis. A bubble chart showing three dimensions of data—author keywords, year and number of publications—can reveal research trends and issues of concern more obviously by analyzing the distribution change of keywords over different periods (Fig. 6). By analyzing the raw data, keywords with the same meanings are denoted by one uniform word. Bubble chart shows three dimensions of data, i.e., author keywords, year and number of publications. The horizontal variation of bubbles sizes illustrates the growth trend of author keywords over time; the vertical sizes of bubbles reveals the most popular keywords for each year. Through the comparison of keywords in the latest years, the research hotspots and trends

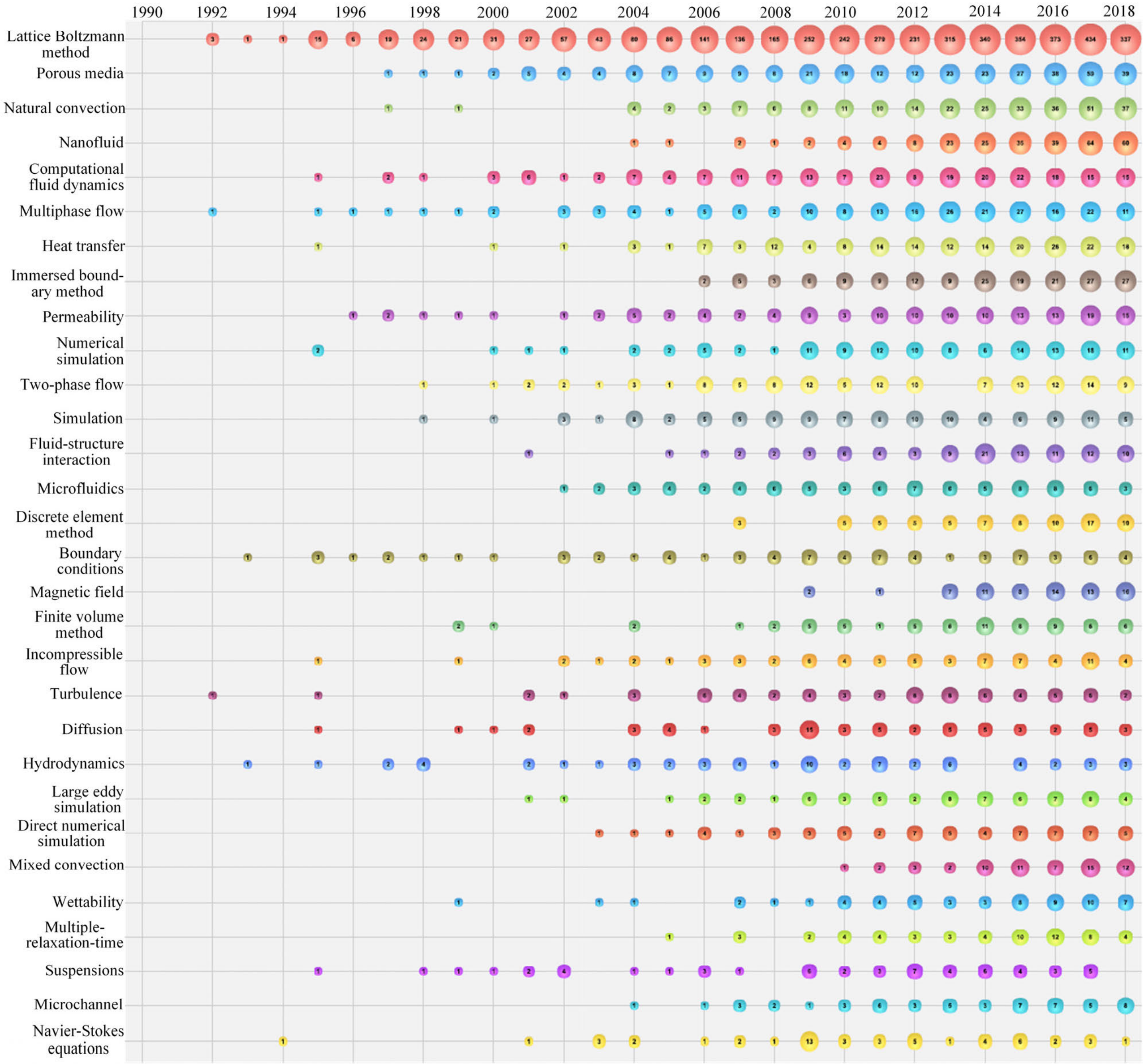

FIGURE 6. **Bubble chart of the top 30 author keywords by year.**

of the LB method can be predicted. This is of important to grasp the research status and explore the new cross application frontier of the LB method.

Among the author keywords, 7243 were used only once, accounting for 71.62% of the total. A large number of once-only author keywords may indicate a wide scope of interests in LB method research. "Lattice Boltzmann method" was the most frequently used keyword in scientific papers, increasing rapidly over the last ten years (2008–2018) and being used more than 4000 times. It is followed by "porous media", "natural convection", "nanofluid", "computational fluid dynamics" and "multiphase flow" with frequencies of 331, 271, 269, 212 and 202, respectively. Compared with higher using frequency of the LB method, these only occupy a little share. It is clear that the LB method, since its emergence, has been widely applied to simulate increasing diverse physical problems.

In addition, "nanofluid", "heat transfer", "immersed boundary method", "fluid-structure interaction", "magnetic field" and "mixed convection" were seldom used in the first 20 years (1990–2010) but increased sharply in the last decade (2010–2018). In view of this transition, we believe that certain publications near 2010, related with the above topics, may make great contributions. According to the author keywords, several highly cited papers were investigated. Based on the natural convection issues, Mohamad et al. conducted the critical evaluation of variable force terms for the LB method, and verified their feasibility and significance in the collision

TABLE 8. **ESI hot papers in LB method research.**

No.	Author	Title	TC	Journal	Year
1	Sheikholeslami, M. [61]	CuO-water nanofluid flow due to magnetic field inside a porous media considering Brownian motion	105	Journal of Molecular Liquids	Jan 2018
2	Sheikholeslami, M., Shehzad, S. A. [59]	CVFEM for influence of external magnetic source on Fe3O4-H2O nanofluid behavior in a permeable cavity considering shape effect	100	International Journal of Heat and Mass Transfer	Mar 2018
3	Sheikholeslami, M., Rokni, Houman B. [63]	Simulation of nanofluid heat transfer in presence of magnetic field: A review	98	International Journal of Heat and Mass Transfer	Dec 2017
4	Sheikholeslami, M. [66]	Numerical investigation for CuO-H2O nanofluid flow in a porous channel with magnetic field using mesoscopic method	96	Journal of Molecular Liquids	Jan 2018
5	Sheikholeslami, M. [117]	Numerical investigation of nanofluid free convection under the influence of electric field in a porous enclosure	96	Journal of Molecular Liquids	Jan 2018
6	Sheikholeslami, M., Sadoughi, M. K. [100]	Simulation of CuO-water nanofluid heat transfer enhancement in presence of melting surface	80	International Journal of Heat and Mass Transfer	Jan 2018
7	Sheikholeslami, M., Shamlooei, M., Moradi, R. [31]	Numerical modeling of nano enhanced PCM solidification in an enclosure with metallic fin	83	Journal of Molecular Liquids	Jun 2018
8	Sheikholeslami, M., Rokni, Houman B. [32]	Numerical simulation for impact of Coulomb force on nanofluid heat transfer in a porous enclosure in presence of thermal radiation	79	International Journal of Heat and Mass Transfer	Mar 2018
9	Sheikholeslami, M., Seyednezhad, M. [33]	Simulation of nanofluid flow and natural convection in a porous media under the influence of electric field using CVFEM	69	International Journal of Heat and Mass Transfer	May 2018
10	Sheikholeslami, M., Shehzad, S. A. [81]	Simulation of water based nanofluid convective flow inside a porous enclosure via non-equilibrium model	67	International Journal of Heat and Mass Transfer	May 2018
11	Sheikholeslami, M. [80]	Solidification of NEPCM under the effect of magnetic field in a porous thermal energy storage enclosure using CuO nanoparticles	56	Journal of Molecular Liquids	Aug 2018
12	Balazadeh, N., Sheikholeslami, M.,Ganji, D. D. et al. [62]	Semi analytical analysis for transient Eyring-Powell squeezing flow in a stretching channel due to magnetic field using DTM	55	Journal of Molecular Liquids	Aug 2018
13	Shah, Z., Islam, S., Bonyah, E. et al. [65]	The electrical MHD and Hall current impact on micropolar nanofluid flow between rotating parallel plates	43	Results Physics	Jun 2018
14	Sheikholeslami, M., Shehzad, S. A., Li, Z. X. [119]	Water based nanofluid free convection heat transfer in a three dimensional porous cavity with hot sphere obstacle in existence of Lorenz forces	32	International Journal of Heat and Mass Transfer	Oct 2018

TC total citations.

process [30]. Some typical strategies, such as force implementation, boundary conditions, and initial conditions, were introduced by Zhang *et al.*, and demonstrated the superiority for microfludic systems, however, the LB method also had certain limits [48]. The detailed microscopic features, for instance, like specific molecular structures and intermolecular interactions, cannot be precisely described. Actually, for the capillary filling in rough microchannel, liquid motion near the critical angle, showed an intense sensitivity to molecular fluctuation, which cannot be explained by the standard LB method. Moreover, for the gaseous microflows with high Knudsen numbers, the reliability and accuracy, simulated by the LB method in larger flow region, was worth to be doubt. It was worth mentioned that the most highly cited publication in recent eight year, written by Aidun and Clausen, concluded the developments and applications for complex flows [1]. Wherein some promising direction and challenges of the LB method, such as higher accuracy and efficiency of microflows with the Knudsen number approaching $O(1)$, implement of interpolated bounce-back method with strict mass conservation, optimization of lubrication and contact models resolving particle interaction in the near-contact region, and higher temperature ratio through reactive LB scheme with low-Mach-number approximation, were presented. These highly cited papers not only review the developments and challenges, but motivate more and more scholars with multidisciplinary background to explore potential applications of the LB method. Meanwhile, this indicates that these research areas will attract more attention in the future.

B. AN ANALYSIS OF HOT PAPERS

ESI hot papers can help identify breakthrough research and the latest research focus within a research field. The definition of ESI hot papers introduced in Section 3 was used to obtain 19 papers (Table 8). “CuO-water nanofluid flow due to magnetic field inside a porous media considering Brownian motion” [61] authored by Sheikholeslami, M. held the first position with the highest total citations, followed by “CVFEM for influence of external magnetic source on Fe_3O_4-H_2O nanofluid behavior in a permeable cavity considering shape effect” [59] and “Simulation of nanofluid heat transfer in presence of magnetic field:

A review" [63]. The Sheikholeslami, M. group had a leading position and influence in current LB method research, contributing 13 hot papers—92.9% of them. All hot papers mentioned the keywords "nanofluid", "porous media" and "magnetic field", which indicated that the latest hot research mainly focuses on the nanofluid hydrothermal treatment existing in magnetic fields. It should be noted that in their recent study, the heat transfer rate of water-based nanofluids, effected by the Lorentz force and shape factor, had been investigated [32], [59], [61], [117]. Results reveal that the Platelet shaped nanoparticle can obtain the greatest Nusselt number and highest heat transfer rate. To improve the heat transfer rate in the solidification process, nanoparticles are the suitable selection that can accelerate the solidification rate [31], [80]. Moreover, the interaction between the nanoparticles and based fluid had been studied by single or two phase models, and the parameters, such as thermal conductivity, heat transfer rate, and thermal radiation, were selected to describe this property, but the latter was better [63], [66], [119]. However, the current two phase models, often assumed the conditions on the homogeneous fluids and no-slip mechanism. Hence, further explore shape factor and heat transfer rate of new nanoparticles, develop better single or two phase thermal models, optimize combination between nanoparticle load and constant or variable magnetic field, had important application prospects. Another direction was investigating the hydrodynamic and thermal characteristics of water-based nanofluids including Fe_3O_4, Cuo, Al_2O_3, and other new nanoparticles. Especially, external factors, such as variable magnetic field, thermal radiation, microchannel boundary slip condition, and conduction mode control, affect the natural or forced convection of nanofluids in various complex porous structures. Many unresolved issues remain in this topic, especially in considering the three dimensions. Therefore, more effort is needed to explore the full application potential of nanofluids' thermal transport properties with the LB method.

C. RESEARCH INTERESTS AND PERSPECTIVES

Over the past three decades, the LB method plays a significant role in investigating hydrodynamic properties and thermal transport processes. Given the number of publications about the LB method that have appeared over the past 30 years, this field has been attracting more attention. To elucidate the research trend and hotspots of the fluid systems with the LB method, 50 review articles based on the five most-cited each year were searched by title, abstract and author keywords during 2009–2018. The multidisciplinary nature of LB method research and diversified authors' backgrounds facilitated multiplicities of research content, analysis perspectives and demonstrated viewpoints (Table 9). Nonetheless, these reviews (Table 9) were all based on a technical standpoint, including multiscale, hydrodynamic, modeling, multiphase, simulation, heat transfer, nanofluid, phase change, diffusion, soft matter, transport and application (Table 10).

A majority of reviews contained the latest research results in the LB research area around the world have their technical points summarized in Table 10. The reviewers always summarize the present research work and issues and outlooks for future research content and direction. It is significant for related and potential researchers to know such summaries, comments and suggestions on the technology developing in this field. Consequently, related scholars were encouraged to refer to these reviews (Table 9). Moreover, these reviews contain discussion and summaries on the latest research directions and viewpoints, which can guide and motivate creative work. It is worth noting that fuel cells and flow batteries (e.g. polymer electrolyte membrane (PEM) fuel cells, aqueous redox and suspension redox flow batteries) as energy conversion equipments are wide applied in energy systems [91], [92], [95], [96], [219], [225], [237], [240]–[242]. These devices involved many complex multiscale and multiphysics phenomena, such as gas-liquid two-phase transport, liquid drop dynamics, proton conduction, water evaporation, and steam diffusion and condensation. LB method-based modeling techniques capable of handling coupled multiphase transport with electrochemical reactions were highly advocated, especially for transport property in CL, MPL, and GDL layers. [91], [92], [96], [240], [241]. However, the porous geometry morphology reconstruction with lower resolution affected the accurate transport properties [91], [96], [237]. Therefore, micro/nano structure reconstructions with high resolution in MPL or CL layers faced great challenges. The modified lattice schemes and models, for instance, D3Q27 lattice scheme and multiphase model with high-density ratio, were the better methods for improving LB simulation precision. However, these needed to consider Knudsen diffusion effect and could cause higher calculation cost. Moreover, some crucial thermal effects—including evaporation and condensation of fuel cells—could not be taken into account [237], [240], [242]. The temperature difference and partial wettability in GDL layer would affect steam condensation, especially in the high current density condition, and non-continuous liquid drop dynamic behavior in GDL layer always was droved by means of capillary acting force [91], [96], [240], [242]. Hence, the above phase change process could be another key parameter on effecting liquid water configuration and capillary pressure. Further develop multicomponent LB models for settling porous structures in CL and MPL layers, such as considering slipping of different matters, high density ratio, Knudsen diffusion effect, needed more efforts. Despite development of various multiphase models with the LB method, due to coupling difficulty and large calculation amount, accurate simulation models for gas and liquid two-phase flow in channels in PEM fuel cells were still faced with great challenges [50], [91], [95], [225], [242]. Actually, in order to simulate gas-liquid two-phase flows and together consider other transport phenomena, the liquid water in channels always assumed mist state that simplified two-phase flows to single-phase flows [50], [225], [242]. This may cause the undervaluation about effects of liquid water,

TABLE 9. The top 5 most highly cited reviews each year in LB method research during 2009-2018.

Year (No.)	Author	Title	TC	TCY	Journal
2009 (1)	Duenweg, B., Ladd, A. J. C. [209]	Lattice Boltzmann Simulations of Soft Matter Systems	175	17.50	Advanced Computer Simulation Approaches for Soft Matter Sciences III
2009 (2)	Cao, B. Y., Sun, J., Chen, M. [210]	Molecular Momentum Transport at Fluid-Solid Interfaces in MEMS/NEMS: A Review	153	15.30	International Journal of Molecular Sciences
2009 (3)	Meakin, P., Tartakovsky, A. M. [211]	Modeling and simulation of pore-scale multiphase fluid flow and reactive transport in fractured and porous media	137	13.70	Reviews of Geophysics
2009 (4)	Kevrekidis, I. G., Samaey, G. [213]	Equation-Free Multiscale Computation: Algorithms and Applications	118	11.80	Annual Review of Physical Chemistry
2009 (5)	Hoelzer, A., Sornmerfeld, M. [212]	Lattice Boltzmann simulations to determine drag, lift and torque acting on non-spherical particles	70	7	Computers & Fluids
2010 (1)	Aidun, C. K., Clausen, J. R. [1]	Lattice-Boltzmann Method for Complex Flows	925	102.78	Annual Review of Fluid Mechanics
2010 (2)	Andersson, M., Yuan, J. L., Sunden, B. [96]	Review on modeling development for multiscale chemical reactions coupled transport phenomena in solid oxide fuel cells	159	17.67	Applied Energy
2010 (3)	Werth, C. J., Zhang, C. Y., Brusseau, M. L. et al. [216]	A review of non-invasive imaging methods and applications in contaminant hydrogeology research	99	11	Journal of Contaminant Hydrology
2010 (4)	Moreno-Atanasio, R., Williams, R. A., Jia, X. D. [214]	Combining X-ray microtomography with computer simulation for analysis of granular and porous materials	78	8.67	Particuology
2010 (5)	Harting, J., Kunert, C., Hyvaluoma, J. [215]	Lattice Boltzmann simulations in microfluidics: probing the no-slip boundary condition in hydrophobic, rough, and surface nanobubble laden microchannels	42	4.67	Microfluids and Nanofluidics
2011 (1)	Wang, Y., Chen, K. S., Mishler, J. et al. [91]	A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research	1252	156.50	Applied Energy
2011 (2)	Jiao, K., Li, X. G. [95]	Water transport in polymer electrolyte membrane fuel cells	257	32.13	Progress in Energy and Combustion Science
2011 (3)	Zhang, J. F. [48]	Lattice Boltzmann method for microfluidics: models and applications	179	22.38	Microfluidics and Nanofluidics
2011 (4)	Gu, H., Duits, M. H. G., Mugele, F. [217]	Droplets Formation and Merging in Two-Phase Flow Microfluidics	110	13.75	International Journal of Molecular Sciences
2011 (5)	Mukherjee, P. P, Kang, Q. J., Wang, C. Y. [92]	Pore-scale modeling of two-phase transport in polymer electrolyte fuel cells-progress and perspective	97	12.13	Energy & Environmental Science
2012 (1)	Woerner, M. [47]	Numerical modeling of multiphase flows in microfluidics and micro process engineering: a review of methods and applications	148	21.14	Microfluidics and Nanofluids
2012 (2)	Haddad, Z., Oztop, H. F., Abu-Nada, E. et al. [60]	A review on natural convective heat transfer of nanofluids	116	16.57	Renewable & Sustainable Energy Reviews
2012 (3)	Fox, R. O. [218]	Large-Eddy-Simulation Tools for Multiphase Flows	93	13.29	Annual Review of Fluid Mechanics
2012 (4)	Grew, K. N., Chiu, W. K. S. [219]	A review of modeling and simulation techniques across the length scales for the solid oxide fuel cell	55	7.86	Journal of Power Sources
2012 (5)	Xu, A. G., Zhang, G. C., Gan, Y. B. [220]	Lattice Boltzmann modeling and simulation of compressible flows	43	6.14	Frontiers of Physics
2013 (1)	Li, X. J., Vlahovska, P. M., Karniadakis, G. E. [221]	Continuum- and particle-based modeling of shapes and dynamics of red blood cells in health and disease	76	12.67	Soft Matter
2013 (2)	Ho, Q. T., Carmeliet, J., Datta, A. K. et al. [222]	Multiscale modeling in food engineering	63	10.50	Journal of Food Engineering
2013 (3)	Mills, Z. G., Mao, W. B., Alexeev, A. [196]	Mesoscale modeling: solving complex flows in biology and biotechnology	38	6.33	Trends in Biotechnology
2013 (4)	Krueger, T., Frijters, S., Gunther, F. et al. [223]	Numerical simulations of complex fluid-fluid interface dynamics	36	6.00	European Physical Journal-Special Topics
2013 (5)	Cito, S., Domenico M. D., Badimon, L. [224]	A Review of Macroscopic Thrombus Modeling Methods	28	4.67	Thrombosis Research
2014 (1)	Chen, L., Kang, Q. J., Mu, Y. T. et al. [225]	A critical review of the pseudopotential multiphase lattice Boltzmann model: Methods and applications	206	41.20	International Journal of Heat and Mass Transfer
2014 (2)	Weber, A. Z., Borup, R. L., Darling, R. M. et al. [226]	A Critical Review of Modeling Transport Phenomena in Polymer-Electrolyte Fuel Cells	165	33.00	Journal of The Electrochemical Society
2014 (3)	Fedosov, D. A., Noguchi, H., Gompper, G. [227]	Multiscale modeling of blood flow: from single cells to blood rheology	95	19.00	Biomechanics and Modeling in Mechanobiology
2014 (4)	Tenneti, S., Subramaniam, S. [228]	Particle-Resolved Direct Numerical Simulation for Gas-Solid Flow Model Development	71	14.20	Annual Review of Fluid Mechanics
2014 (5)	Winkler, R. G., Fedosov,	Dynamical and rheological properties of soft colloid	34	6.80	Current Opinion in Colloid &

TABLE 9. ***(Continued.)*** **The top 5 most highly cited reviews each year in LB method research during 2009-2018.**

	D. A., Gompper, G. [229]	suspensions			Interface Science
2015 (1)	Perigo, E. A., Hemery, G., Sandre, O., et al. [230]	Fundamentals and advances in magnetic hyperthermia	149	37.25	Applied Physics Reviews
2015 (2)	Sheikholeslami, M., Gorji-Bandpy, M., Ganji, D. D. [232]	Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices	94	23.5	Renewable & Sustainable Energy Reviews
2015 (3)	Rantanen, J., Khinast, J. [231]	The Future of Pharmaceutical Manufacturing Sciences	89	22.25	Journal of Pharmaceutical Sciences
2015 (4)	Guo, Y. Y., Wang, M. R. [233]	Phonon hydrodynamics and its applications in nanoscale heat transport	51	12.75	Physics Reports-Review Section of Physics Letters
2015 (5)	Yoon, H., Kang, Q. J., Valocchi, A. J. [234]	Lattice Boltzmann-Based Approaches for Pore-Scale Reactive Transport	33	8.25	Pore-Scale Geochemical Processes
2016 (1)	Sheikholeslami, M., Ganji, D. D. [235]	Nanofluid convective heat transfer using semi analytical and numerical approaches: A review	171	57.00	Journal of The Taiwan Institute of Chemical Engineers
2016 (2)	Li, Q., Luo, K. H., Kang, Q. J. et al. [50]	Lattice Boltzmann methods for multiphase flow and phase-change heat transfer	170	56.67	Progress in Energy and Combustion Science
2016 (3)	Liu, H. H., Kang, Q. J., Leonardi, C. R. et al. [34]	Multiphase lattice Boltzmann simulations for porous media applications	85	28.33	Computational Geosciences
2016 (4)	Vanaki, Sh. M., Ganesan, R., Mohammed, H. A. [236]	Numerical study of convective heat transfer of nanofluids: A review	80	26.67	Renewable & Sustainable Energy Reviews
2016 (5)	Molaeimanesh, G. R., Googarchin, H. S., Moqaddam, A. Q. [237]	Lattice Boltzmann simulation of proton exchange membrane fuel cells - A review on opportunities and challenges	18	6.00	International Journal of Hydrogen Energy
2017 (1)	Sheikholeslami, M. [63]	Simulation of nanofluid heat transfer in presence of magnetic field: A review	96	48.00	International Journal of Heat and Mass Transfer
2017 (2)	Wang, L., Wang, S. H., Zhang, R. L. et al. [238]	Review of multi-scale and multi-physical simulation technologies for shale and tight gas reservoirs	35	17.50	Journal of Natural Gas Science and Engineering
2017 (3)	Liu, H., We, Z. B., He, W. D. et al. [239]	Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review	33	16.50	Energy Conversion and Management
2017 (4)	Xu, A., Shyy, W., Zhao, T. S. [240]	Lattice Boltzmann modeling of transport phenomena in fuel cells and flow batteries	25	12.50	Acta Mechanica Sinica
2017 (5)	Maxey, M. [241]	Simulation Methods for Particulate Flows and Concentrated Suspensions	20	10.00	Annual Review of Fluid Mechanics
2018 (1)	Zhang, G. B., Jian, K. [242]	Multi-phase models for water and thermal management of proton exchange membrane fuel cell: A review	12	12.00	Journal of Powder Sources
2018 (2)	Tjaden, B., Brett, D. J. L., Shearing, P. R. [243]	Tortuosity in electrochemical devices: a review of calculation approaches	8	8.00	International Materials Reviews
2018 (3)	Van den Akker, H. E. A. [244]	Lattice Boltzmann simulations for multi-scale chemical engineering	3	3.00	Current Opinion Chemical Engineering
2018 (4)	Tang, Y. H., Wu, T. H., He, G. W. et al. [245]	Multi-flexible fiber flows: A direct-forcing immersed boundary lattice-Boltzmann lattice-spring approach	4	4.00	International Journal of Multiphase flow
2018 (5)	Schiller, U. D., Kruger, T., Henrich, O. [135]	Mesoscopic modelling and simulation of soft matter	1	1.00	Soft Matter

TC total citations, *TCY* total citations per year.

especially for the convection effect of liquid water to gaseous diffusion coefficient. Therefore, it was necessary to perform accurate 3D simulation on the cell and stack levels with convection effects, whence achieved better water-thermal management. Another exciting direction was that CL agglomerate model was added to the 3D multiphase models so as to better reflect the concentration loss in PEM fuel cell, and meanwhile optimized the CL structure in macroscopic scale [237], [242]. However, this model could only simulate cathode electrode, and was not suitable to anode electrode, for instance, the surface reaction was not a first order reaction relative to hydrogen. Therefore, more modified 3D LB models were needed to address the reactive multiphase flows and evaluate electrode properties.

Multiscale modeling was nearly described in all reviews (refer to Table 10) wherein seven papers performed profoundly investigated and discussed [92], [96], [213], [222], [227], [240], [244]. Andersson [96] and Xu [240] suggested that further development of LB method multiscale models was significant for solving the complex interaction between aspects of physics like multiphase flows, heat/mass transfer, and chemical reactions at various scales. In general, multiscale models were divided into two categories based on the physical length scale, i.e., representative elementary volume (REV)-scale models and pore-scale models [213], [222], [227]. Through the REV-scale LB model, the porous flow systems with large size could obtain the reasonable results, however, their accuracy seriously depended on empirical relation. On the contrast, the pore-scale LB method attracted extensive interest in predicting transport properties, such as permeability, effective thermal conductivity, and heat/mass transfer coefficient [240], [244]. In this aspect, one

TABLE 10. **Technical contents of the LB method related reviews.**

Year (No.)	Modeling	Simulation	Multiscale	Hydrodynamic	Multiphase	Heat transfer	Nanofluid	Transport	Soft matter	Phase change	Diffusion	Application
2009 (1)	✓	✓		✓					✓			
2009 (2)	✓	✓		✓			✓	✓				
2009 (3)	✓	✓		✓	✓			✓			✓	
2009 (4)	✓	✓		✓		✓						
2009 (5)	✓	✓	✓	✓								✓
2010 (1)	✓	✓		✓	✓			✓			✓	
2010 (2)	✓	✓	✓					✓	✓			✓
2010 (3)	✓	✓		✓				✓				✓
2010 (4)	✓	✓		✓			✓	✓	✓			
2010 (5)	✓	✓		✓	✓							✓
2011 (1)	✓	✓		✓				✓			✓	✓
2011 (2)	✓	✓						✓			✓	✓
2011 (3)	✓	✓		✓	✓	✓						✓
2011 (4)	✓	✓		✓	✓							
2011 (5)	✓	✓		✓								✓
2012 (1)	✓	✓		✓	✓							✓
2012 (2)	✓	✓		✓		✓	✓					
2012 (3)	✓	✓		✓	✓							
2012 (4)	✓	✓	✓			✓		✓				✓
2012 (5)	✓	✓		✓	✓							
20013 (1)	✓	✓	✓	✓					✓			✓
2013 (2)	✓	✓	✓	✓				✓				✓
2013 (3)	✓	✓	✓	✓			✓	✓	✓			✓
2013 (4)	✓	✓		✓								
2013 (5)	✓	✓	✓	✓								✓
2014 (1)	✓	✓		✓	✓			✓		✓	✓	✓
2014 (2)	✓	✓						✓			✓	✓
2014 (3)	✓	✓	✓	✓								
2014 (4)	✓	✓		✓	✓	✓			✓			
2014 (5)	✓	✓		✓					✓			
2015 (1)						✓	✓					✓
2015 (2)	✓	✓										✓
2015 (3)	✓	✓		✓		✓						
2015 (4)	✓	✓		✓		✓		✓				
2015(5)	✓	✓		✓				✓				

TABLE 10. ***(Continued.)*** **Technical contents of the LB method related reviews.**

2016 (1)	✓	✓		✓	✓	✓		✓		✓		✓
2016 (2)	✓	✓		✓		✓	✓					
2016 (3)	✓	✓		✓								
2016 (4)	✓	✓		✓		✓	✓					
2016 (5)	✓	✓		✓		✓		✓				✓
2017 (1)	✓	✓		✓		✓	✓			✓		
2017 (2)	✓	✓		✓				✓		✓	✓	
2017 (3)	✓	✓	✓	✓		✓						✓
2017 (4)	✓	✓		✓	✓	✓		✓				✓
2017 (5)	✓	✓		✓					✓			
2018 (1)	✓	✓		✓	✓	✓					✓	✓
2018 (2)	✓							✓			✓	✓
2018 (3)	✓	✓	✓	✓	✓	✓		✓				✓
2018 (4)	✓	✓		✓								
2018 (5)	✓	✓	✓	✓					✓			✓

should be cautious when selecting Bhatnagar-Gross-Krook with a single relaxation time (LBGK) collision operator. A nonphysical influence was formed when the permittivity calculated by this model depended on the relaxation time. However, multiple-relaxation time (MRT) LB method not only overcame the drawback of LBGK, but promoted the extension of the LB method, which would play more important effects in the future [96], [222], [227], [238], [244]. Nonetheless, the lack of viable experimental methods was a restraining factor to evaluate inherent structure-performance dependence for pore-scale modeling [34], [92], [234]. Meanwhile, achieving the morphology optimization of porous structure such as pore size, shape, and distribution that made all the species reach the maximize flow, would be a great challenge of the LB method. Another challenging problem for LB method research was achieving a theoretical breakthrough for simulating multicomponent multiphase flows with phase change heat transfer [50], [226], [237], [240], [242]. Mills [196], Fedosov [227], Ho [222] and Van den Akker [244] *et al.* believed that collaboration across multiple disciplines (chemistry, biology, medicine and energy engineering, etc.) would advance the LB method more than isolated work.

Apart from the classical fluid dynamics field, soft matter systems was seen as a very inspiring source of LB method research; it contained many complex fluid-like flows in porous media [34], [234], polymer solutions [209], colloidal suspension [196], [221], [229], foams [215], gels [135], and granular materials [228], [241]. This was a booming direction of LB method research, with applications nearly throughout every collaborative fields of fluid-thermal systems, including chemical engineering [74], [243], [244], biotechnology [196], material science [109], [195], [214], pharmaceutical engineering [231] and energy and combustion processes [60], [95], [236], [240]. However, some critical issues in turbulent channel flow, such as evaluating forces on a particle, fluid-solid boundary, and refilling of particle via lattice nodes, would affect the local Galilean invariance and further influenced the calculation accuracy and stability [135], [241]. Several recent studies, including moving boundary with smooth quadratic interpolation [50], [238], implement in the relaxation step for different relaxation times to different moments [34], [242], and a new momentum exchange method based on Galilean invariant [234], [241], had been used to address the force evaluations and refilling nodes in turbulent flows with higher-Reynolds number. It was worth noting that the mesoscale modelling method would continue to play a central role in bridging the length- and time-scale gaps inherent in soft matter systems, as well as dominating extreme-scale applications on future high-performance computing (HPC) systems, which were one of the greatest challenges for LB method research [135], [227], [229]. In addition, perhaps the most promising development direction of LB method research was the merging with the immersed boundary method (IBM) [34], [228], [241], [245] for deformable objects [135], [221], as well as settle phase change issues with complicated geometry boundaries or solid-structure interactions [34], [245]. Recently, Tang et al. presented a LB lattice-spring method with three-body forces to simulate the dynamic behaviors of lots of flexible fibers, and evaluated effects of fibers parameters to drainage rate [245]. However, the application range with this method still needed to extend rather than limit in a finite Reynolds number flow. These techniques would be expected to simulate of many kinds of complex flows—including deformable erythrocyte in bloods [227], [229], boiling flow in rod-bundle geometries [50], [60], water droplet dynamic behavior in fuel cells [217], [229]—on leading edge high-performance parallel computers. The combination of the LB method with IBM techniques will continue to demonstrate its enormous potential for many soft matter system applications in coming years.

Furthermore, some new advanced ideas or applications with the LB method, such as hybrid methods [34], [48], thermal phase change pseudopotential LB models [240], no-equilibrium property of soft colloid [135], [209], [229] and mesoscopic electrophoresis effect of polyelectrolytes [135], have been proposed for fuel cells, evaporation and condensation, droplet collision, and energy storage materials. Further investigation has been necessary to achieve accurate modeling of dense suspension flows with the LB method for suspension redox flow batteries [240]. Gu *et al.* [217] and Molaeimanesh *et al.* [237] believed that the formation and combining of droplets could be flexibly implemented and with high precision through active control approaches (e.g. electric signals transmitted via microelectrodes). That would be a novel trend, with extensive applications in fuel cells, micro heat exchangers and micro energy systems. Other inspiring information was that thermal pseudopotential and phase-field LB methods were successfully applied in boiling heat transfer and droplet evaporation [50], [60], [225], [242]. This is of great significance for many thermal systems and applications, such as microchannel heat sink, microelectronic cooling, liquid-fueled combustion and spray drying. Despite the undeniable success of the enthalpy-based LB method for energy store material, it still had certain limits because of neglect of the microscopic effects (surface tension, thermal fluctuation, and kinetic undercooling) [47], [60], [235]. Moreover, Haddad *et al.* [60] and Vanaki *et al.* [236] argued that there was much work needed on the heat transfer enhancement property of nanofluid on the turbulent flow using the LB method, with which Sheikholeslami and Rokni [63] concurred. The nanoparticles with higher heat conductivity, for instance, Al_2O_3 with a heat conductivity (about 40), could not always provide larger heat transfer rates. Sometimes, the nanoparticles with lower densities, such as SiO_2 with a heat conductivity (1.4W/mK), would produce larger heat transfer rates, which were relevant to their higher velocities. In other words, the velocities of nanoparticles played an important role on the heat transfer rates that could not be neglected. Another urgent work was developing the experiment and theory models so as to predict properties with new nanoparticles and shape factors, and then evaluate their potential of enhanced heat transfer in different fluid-thermal systems. Future research would be directed toward radiation performance or boiling heat transfer of nanofluid because of the lack of studies on that area.

The past three decades have witnessed the great development of fluid systems and fundamental thermal processes using the LB method. The enormous potential of the LB method for resolving various changeling problems—such as multiphase flow, heat/mass transfer, coupled flow and various complex transport phenomena in porous media, phase change material and colloidal suspension flow—have attracted great attention and interest in the fluid dynamic and fundamental thermal research communities. However, research work for the LB method not only requires a profound foundation of mathematics, but emphasize a thorough theoretical understanding. As an ever-developing methodology, there is still a long way to arrive maturity, with theoretical researches and new applications continuously emerging. This new discipline is still faced with great challenges and requires a number of scholars with a variety of scientific backgrounds, including physics, chemistry, computer science, biomedicine, mathematics and energy science. Moreover, they will need to enhance their collaboration and communication each other, and make substantial achievements in theoretical and applied research.

V. CONCLUSION

The LB method has witnessed astonishing growth in fundamental thermal research and fluid engineering applications over the past 30 years, with supported from emerging publications, new related journals, and general interest. In this review, based on bibliometric analysis, we have provided an unusual comprehensive overview for fluid systems and thermal processes with the LB method in terms of leading countries, institutes, keywords, research trend and hotspots. The outlook for the LB method's application in fluid-thermal systems is also highlighted. There is no doubt that handling complex fluid dynamics and fundamental thermal processes with the LB method has become a very hot research topic. This area is experiencing rapid growth across institutions in the USA, Europe and Asia, which contribute most of the original research, developing infrastructure and consolidating the academic community. The USA leads the list of total citations and average citations per publications (ACPP), and is the most active country in collaborative relationships, which are full illustrated that the USA has higher academic influence. However, China has a relatively low ACPP and collaborative relationship, and needs more efforts to bridge the gap.

The progress and development of the LB method requires the intersection and collaboration of differing disciplines such as physics, mathematics, chemistry, engineering and energy science. This is reflected in the number and prominence of papers, as well as journals that discuss gas-liquid coupling transport in fuel cells, interface wettability and instability, nanofluids complex hydrothermal treatment, multiscale modeling in porous media, water drop dynamics, soft matter systems and phase change heat transfer; these appear in the top list of LB method publications.

In reference to journals, *Physical Review E* ranked first among the top 20, followed by *International Journal of Heat and Mass Transfer* and *Computers and Fluids*. As for the leading authors, Succi Sauro, Shu Chang, and Guo Zhaoli are the three most productive authors assessed by total publication number. Sheikholeslami Mohsen, Krafczyk M. and Yeomans Julia M. rank in the top three positions for ACPP, indicating their powerful influence in the global LB method community. Apart from the top 20 authors, a large number of researchers are working in this field and have contributed 82.49% of the publications.

Throughout an analysis of reviews on the LB method research, we believe that the following aspects may be most attractive to researchers: multiscale, hydrodynamic, modeling, multiphase simulation, heat transfer, nanofluid, magnetic field, turbulence, soft matter, transport, permeability, particle, and application. The nanofluid hydrothermal treatment in magnetic fields is a hot topic at present. However, current models are often based on the homogeneous fluids and no-slip boundaries. To acquire more accurate single phase or two phase thermal models, extensive nanoparticles considering shape factor should be needed so as to evaluate their heat transfer rates. A non-negligible critical factor for nanoparticle is its velocity that has important effects on the heat transfer rate. Meanwhile, in view of the natural convection or forced convection in complex porous structures, optimizing combination between nanoparticle loads and external factors, such as constant or variable magnetic fields, thermal radiation, microchannel boundary slip condition, and conduction model, have important application prospects. Further investigation for is necessary to develop more accurate multiphase transport modeling technology to tackle complex multiscale and multiphysics phenomena, especially considering important thermal effects such as evaporation and condensation. Some modified satisfying 3D multicomponent models, such as consider different matters slipping, high-density ratio, Knudsen diffusion effect, CL agglomerate model, will better address phase change phenomena in porous structures of CL and MPL layers and evaluate the electrode performance. However, the lack of viable experimental methods and morphology optimization—including porous size, shape and distribution so as to reach the maximize flow, would be great challenges of the LB method. Moreover, a novel trend for fuels cells is the active control of formation and the merging of droplets through electric signals transmitted via microelectrodes. Achieving a theoretical breakthrough with the phase change heat transfer of multicomponent multiphase is still a great challenge, as is its application in radiation performance or the boiling heat transfer of nanofluid. Furthermore, some reviewers believe that the mesoscale modeling method and hybrid method may be the most promising development directions of the LB method. These are expected to resolve the challenges in fluid dynamic and thermodynamic communities, such as boiling flows in complex geometries, water droplet dynamic behavior, energy storage with phase change materials, and no-equilibrium property of soft colloid. There is no doubt that the LB method has achieved considerable success in fluid systems and thermal processes with various LB-based methods—such as thermal pseudopotential LB method, enthalpy-based LB method, and phase-field LB method—applied in fuel cells, micro heat exchangers and energy systems. Further development directions can concentrate on the improvement of numerical stability and applications of these models in boiling heat transfer, droplet evaporation and condensation, and energy storage material, as well as the theoretical breakthrough considering the microscopic effects.

According to the gasps derived from the present review, some further directions and potential applications of the LB method are suggested as follows:

1) Further develop the multiscale models for fuel cells, and achieve coupling of different physical models. For instance, the pore-scale models are adopted to describe transport phenomena of anode, and the REV-scale models are applied to show the whole fuel cell.

2) Although most promising researches for CL and MPL layers transport has been conducted, their transport properties are still vague that neglect the Knudsen diffusion effect. More multicomponent LB models, including consider different species slipping, high-density ratio, Knudsen effect and evaporation and condensation, should be developed to address the porous structure flows.

3) Feasible experiment methods that are used to achieve the optimization morphology with porous parameter so as to evaluate the structure-performance dependence, will face great challenge.

4) In nanoparticles, the shapes with sphere and cylinder are most common used. For the Platelet shaped nanoparticle or other new nanoparticles, their application ranges and interactions with based fluids still need more experiment and theory models to evaluate potential of enhanced heat transfer.

5) In view of the mixing nanoparticles, nonuniform property of nanoparticles, such as shape, size and density, may be a challenge. Meanwhile, more researches on the force contribution should be performed, and evaluate the common forces (e.g., Brown force and thermophoresis force) and forces between particles (e.g., Van der Waals' force).

6) In practical applications, nanoparticle flows are usually transition state or turbulent state. New or modified turbulent models are developed to accurate illustrate vortex flow attenuation and higher heat transfer, which need further researches.

7) For the concentrated suspensions, resolved simulations of particle forces (e.g., lubrication forces, contact forces, and granular friction) in turbulent flows remain challenging. A critical issue is to ensure that the particle motion does not fluctuate with an underlying numerical mesh.

8) A most promising direction is that mixing method, including the combination of the LB method with IBM,

the LB lattice-spring method with three-body forces, and other combination with LB method. However, these technology should not be limited specific applications.

9) Currently, the researches on the 3D simulations of bubble dynamic in nanofluid boiling pool are little. Radiation performance or boiling heat transfer of nanofluid in 3D simulation will attract scholars' interests.

10) Some new applications, such as phase change of metal foam, erosion and corrosion induced by nanaofluid, anode circulating, 3D modeling in thermal systems with vibration, and magnetohydrodynamics microfluid devices, could be of interest going forward.

As a powerful mesoscopic methodology and numerical strategy, the LB method has been found in a series of fluid-thermal engineering fields, but it still faces many challenges. This review can help potential researchers to quickly understand the LB method area globally; it can provide useful information for identifying research trends and potential collaborators. We expect that more researchers will join this exciting research field and that more high-quality papers will be published out of international collaboration between different research groups; these will continue to have great influences on both academia and industry.

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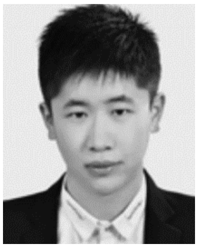

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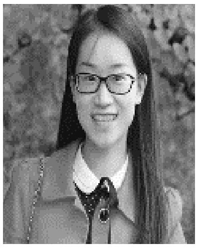

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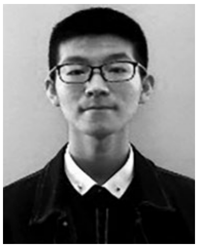

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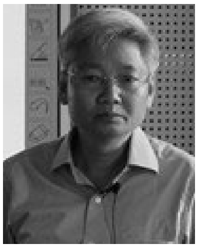

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