

Article

The Evolutionary Path and Emerging Trends of Circulating Fluidized Bed Technology: An Integrated Analysis through Bibliometric Assessment and Data Visualization

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Abstract: Confronted with the significant challenges of global climate change and environmental deterioration, the pursuit of carbon emission peaks and the realization of carbon neutrality have become a collective goal for countries worldwide. As an exemplary combustion technology noted for its efficiency and environmental friendliness, the circulating fluidized bed (CFB) is instrumental in curbing the release of carbon dioxide alongside other deleterious gases. The technology is pivotal in promoting the clean and efficient use of coal, simultaneously expediting the global shift towards a sustainable, green, and low-carbon future. This study employs a bibliometric analysis, a social network analysis, and information visualization techniques to delve into the evolution of CFB technology, leveraging the Web of Science database (SCI-EXPANDED and CPCI-S) and the Derwent Innovations Index (DII). Through a meticulous examination of academic papers and patent literature related to CFB technology, this research unveils the developmental trajectory and trends of CFB technology, providing a scientific foundation and reference for strategic technology planning and focused research in key areas. The findings indicate that, while there is a downward trend in the global publication of academic papers on CFB technology, the number of patent applications continues to grow steadily. CFB technology has achieved significant advancements in enhancing combustion efficiency, environmental protection, energy utilization, and waste management, and is progressing towards a direction of diversification and greater efficiency. Moving forward, the development of CFB technology should concentrate on pivotal areas such as material science, fluid dynamics simulation, environmental impact assessment, system integration, and intelligentization, to foster ongoing innovation and a broad application of the technology.

Keywords: circulating fluidized bed; domain development trend; bibliometrics; knowledge mapping



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1. Introduction

In the context of global climate change and environmental deterioration, achieving carbon peak and carbon neutrality has become a shared goal of the international community. To address this challenge, countries are actively seeking green and low-carbon development pathways. Among these, CFB technology, recognized for its high efficiency and cleanliness, plays an indispensable role in the clean and efficient utilization of coal and in promoting a global shift towards green and low-carbon transformation [1]. The CFB boiler operates by combusting solid particulate materials (such as fuel, limestone, sand particles, and slag) within the furnace chamber in a gas–solid flow pattern (fluidization), with the particles leaving the furnace being separated and recycled back into the furnace for continuous combustion. The high concentration of solid particles within the CFB boiler chamber results in intense combustion, mass transfer, and heat transfer, with a uniform temperature

distribution, characterized by a high combustion efficiency [2], a wide range of load adjustment [3], minimal pollution, and broad fuel adaptability [4]. CFB technology can effectively reduce the emissions of carbon dioxide and various harmful gases [5], playing a crucial role in promoting the green and sustainable transformation of energy production and consumption.

Beyond traditional industrial fields such as chemical engineering, metallurgy, and energy, circulating fluidization technology has been extended to emerging areas including carbon dioxide adsorption and utilization, chemical chain combustion and gasification, and biomass pyrolysis [6–11]. The typical CFB main circulation loop features a “one in, two out” material balance characteristic [12]. The bed material entering the system originates from the ash content of the fuel, desulfurization agents, and desulfurization products, and sometimes includes additional inert bed materials. For larger-particle-sized bed materials, if the fluidization air velocity is less than their terminal settling velocity and they cannot be carried to the upper part of the furnace, these particles will move in the dense phase area at the bottom of the furnace until they are discharged through the slag outlet. Smaller-particle-sized bed materials are carried to the upper dilute phase area of the furnace, leave the furnace, and enter the separator for gas–solid separation. Some extremely fine particles are not successfully captured by the separator; they escape along with the flue gas, exiting through the upper part of the separator and, ultimately, entering the downstream convection flue in the form of fly ash; most of the particles leaving the furnace are separated by the separator and returned to the furnace through the return valve to continue the cycle [13]. The CFB system, categorized based on fuel properties and addition methods, includes key technical aspects such as the combustion side, hot ash side, flue gas side, and steam–water side, as well as production processes and control methods [3,14,15]. The technological characteristics of fuel include fuel substitution strategies, fuel modification, and coal feeding methods, as well as technologies related to oil and gas fuels [16–19]; combustion side features including air distribution systems, furnace, burners, air distribution devices, separators, external circulation units, and pressurized firing [20–25]; hot ash side features involving hot ash devices, ash concentration, and hot ash transportation methods [26–28]; flue gas side features including recirculated flue gas, denitrification methods and devices, SNCR, SCR, etc. [29–33]; steam–water side features including water-cooled walls, superheaters, economizers, reheaters, etc. [34–37]; and production process methods encompassing system structure, process flow, system control methods, and reaction operation conditions [8,38,39]. Therefore, CFB boilers have a broader fuel adaptability compared to pulverized coal furnaces, capable of utilizing fuels such as bituminous coal, anthracite, coal gangue, and biomass. CFB boilers feature lower NO_x emissions, with original NO_x emissions typically below 200 mg/Nm³, over 50% lower than those from pulverized coal furnaces. Additionally, CFBs exhibit high desulfurization efficiency within the furnace, achieving desulfurization efficiencies exceeding 90%. Through a meticulous analysis of patent filings and scholarly publications within the domain of circulating fluidized bed (CFB) technology, this study reveals the development of the field at a macro level, which helps researchers and decision makers to grasp the development of the technology comprehensively, and to assess the importance of the technology and the potential for its development on a more objective and accurate basis, which is of certain guiding significance for grasping the direction of future research, identifying the main breakthrough points, and rationally allocating resources.

2. Data Resources and Research Methodology

2.1. Data Resources

In this study, the thesis data is sourced from the Clarivate Analytics' Web of Science Core Collection database (SCI-EXPANDED and CPCI-S), which includes over 8000 influential academic journals across more than 170 disciplines in the fields of natural science, engineering technology, and clinical medicine, covering over 150 academic subject areas with data dating back to 1900. The search was conducted using core keywords related

to CFB technology, with document types limited to “articles”, “proceedings papers”, and “reviews”. As of March 2024, this paper identified 5707 SCI papers, collecting information such as keywords, abstracts, publication years, source journals, publishing countries, author institutions, and author details.

Patent data were obtained from Clarivate Analytics’ Derwent Innovations Index (DII), a comprehensive database of international patent information that includes unique value-added patent information from over 1963 patent-granting authorities since 1998. As of March 2024, this paper retrieved 7403 global patents, gathering details such as patent titles, abstracts, claims, application years, applying institutions, inventors, legal status, receiving countries, and patent classification numbers.

2.2. Research Methods

This paper adopts a bibliometric approach to conduct a preliminary quantitative analysis of the raw data, examining the fundamental characteristics of the literature, which include countries/regions, research and development institutions, researchers, technical fields, citation counts, and publication years. Furthermore, the paper utilizes VOSviewer 1.6.19 software to construct a network map that reveals the knowledge structure and developmental trajectory within the research field. The underlying algorithms of VOSviewer integrate various techniques, including text mining, co-occurrence analysis, network analysis, and iterative optimization, to facilitate the thematic clustering of scientific literature and provide an intuitive representation of research dynamics and trends in specific domains [40].

3. Overall Development Trend of CFB Technology

3.1. Analysis of Time Trend

Papers and patents represent the two primary types of scientific research output, and studying their development trends can aid in uncovering the latest technological research achievements and theoretical underpinnings within a field. As of March 2024, a total of 5707 papers related to CFB technology were retrieved from the SCI-EXPANDED and CPCI-S databases, and 7403 relevant patents were identified from the DII database, with the annual change trends depicted in Figure 1.

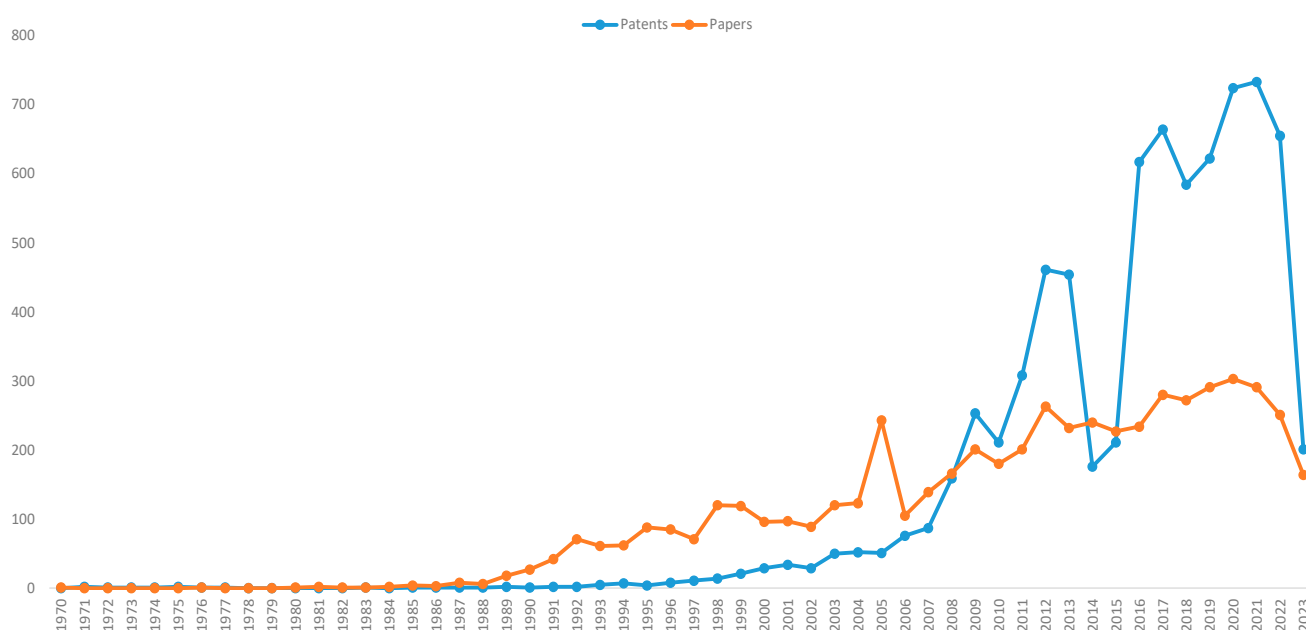


Figure 1. Annual output of papers and patents related to CFB technology.

The production trends of papers and patents in the CFB domain can be broadly divided into four phases: First, there was the incubation period from 1970 to 1988, during which the average annual output of papers and patents remained below 10. The growth period spanned from 1989 to 2008, characterized by a continuous increase in the number of papers and patents, with fundamental research experiencing rapid development. There was a significant surge in the number of papers in 2005, reaching the first small peak of 243. The Tenth Five-Year Plan period (2001–2005) was a time of significant economic expansion in China. During this phase, the country experienced a substantial increase in its economic output and energy consumption. The growing demand for energy spurred the widespread adoption of CFB boiler technologies in industrial applications, which, in turn, fueled an increase in both academic research and industrial application papers focusing on CFB technology. The rapid growth period from 2009 to 2020 saw a steady increase in paper production, peaking at 302 in 2020, while the patent output grew rapidly, surpassing the growth rate of papers, with the number of patents surpassing 600 in 2016, marking the entry into the development research phase. After 2020, as CFB technology matured, the output of papers declined annually, and the production of patents maintained a high growth, reaching a peak of 732 in 2021, indicating the technology's progression into the applied research phase (due to the 18-month confidentiality period for patents and the delay in database data collection, the data for 2023 and beyond are incomplete).

3.2. Technology Research and Diffusion Study

3.2.1. Layout of Research Areas

The distribution of disciplines involved in the CFB field spans 95 academic areas, including Engineering Chemical, Energy Fuels, Thermodynamics, and others. Due to the classification of disciplines in this paper being based on the field of the journal in which the papers are published, there are instances where a single journal may belong to two or more fields, consequently leading to a single paper potentially covering multiple disciplines.

Table 1 presents the top ten disciplines in terms of paper output and their respective counts. The field with the highest number of papers is Engineering Chemical, which accounts for nearly 60% of the papers within the overall domain. Following closely is the energy fuels field, with a total of 1988 papers, significantly leading the other disciplines. The calculated results show that the total number of papers under the 10 disciplines listed in Table 1 far exceeds the total number of papers retrieved, indicating a prevalence of papers that span multiple disciplines within the CFB field. This also confirms the characteristic of a pronounced interdisciplinary nature in this domain. Moreover, the high ranking of several engineering technology disciplines in terms of paper count fully reflects the CFB field's emphasis on guiding scientific research with engineering technology and aiming for practical applications.

Table 1. Subject distribution of research papers.

Rank	Subject	Number of Papers	Proportion of Total Papers/%
1	Engineering Chemical	3281	57.59
2	Energy Fuels	1988	34.83
3	Thermodynamics	594	10.41
4	Engineering Mechanical	563	9.87
5	Engineering Environmental	461	8.08
6	Materials Science	393	6.89
7	Multidisciplinary	374	6.55
8	Environmental Sciences	341	5.98
9	Mechanics	157	2.75
10	Chemistry Applied	156	2.73
	Engineering Electrical		
	Electronic		

3.2.2. Layout of Technology

Patents are a significant output of technological innovation, and the layout of patent technology reflects the scope of technological applications. The International Patent Classification (IPC) is a globally recognized system for categorizing patent documents, where different IPC classification codes represent different technological subjects.

Figure 2 illustrates the global layout of CFB technology, indicating that patents in the CFB field are concentrated in the F23C category. This suggests that combustion equipment, such as fluid fuel burners, combustion devices, furnaces, boilers, and related combustion methods and environmentally friendly combustion technologies, are the hotspots and focal points of innovation in this field. Following closely is the B01D category, covering various technologies and devices related to material separation and mixing, such as filtration, distillation, adsorption, centrifugal separation, precipitation, etc., for the separation and mixing of liquids, gases, and solid materials. Next is the F23J category, primarily involving improvements and control technologies related to combustion and gasification processes, as well as gas emission control and purification technologies. Overall, the development of CFB patent technology tends toward environmental protection and sustainable development, aiming to enhance combustion efficiency, reduce pollutant emissions, and develop more environmentally friendly combustion technologies.

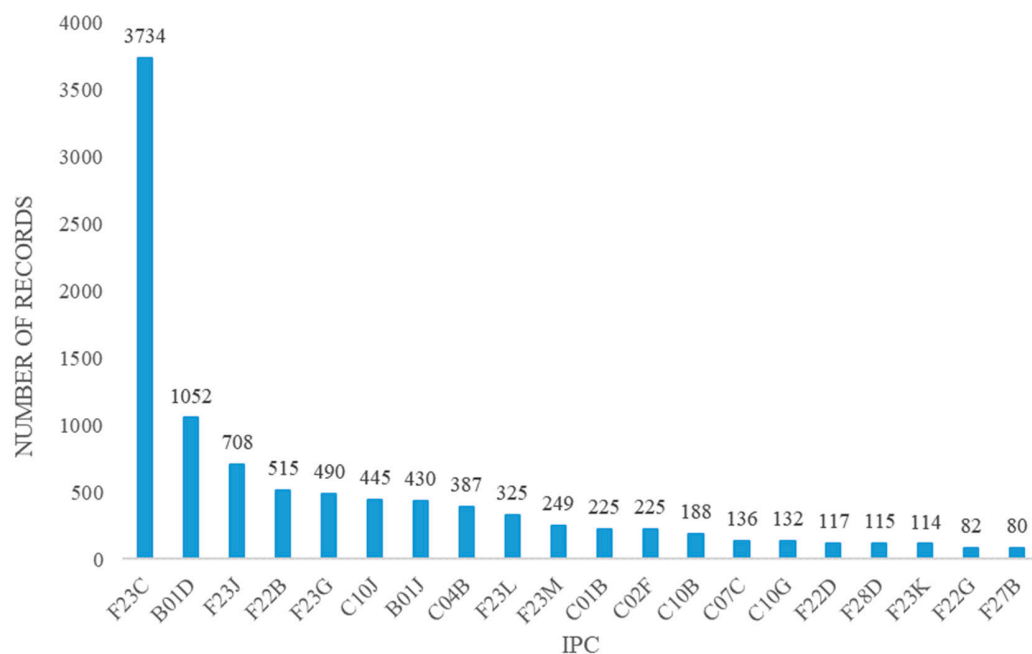


Figure 2. International patent class of CFB technology (more than 100 patents).

Table 2 describes the relationship between the overall IPC classification quantity and the ratio over the past three years in CFB technology. In the past three years, patents in the F23J category have the highest application ratio, reaching 21%, indicating the increased activity in this category, possibly due to the heightened requirements for treating combustion by-products in response to global climate change. On the other hand, patents in the F22B and C10J categories have relatively low activity over the past three years, possibly due to technological saturation or greater research and development challenges. Additionally, it is noteworthy that, while the overall quantity of patents in the C04B and F23L categories is relatively low, there has been a significant increase over the past three years, possibly reflecting recent research hotspots, including boiler combustion methods and efficiency, as well as emissions and safety issues.

Table 2. International patent class of CFB technology (top 10).

IPC	Number of Patents	Ratio over the Past Three Years
F23C (Methods or Apparatus for Combustion Using Fluid Fuel or Solid Fuel Suspended in Air)	3734	16%
B01D (Separation)	1052	14%
F23J (Removal or Treatment of Combustion Products or Combustion Residues; Flues)	708	21%
F22B (Methods of Steam Generation; Steam Boilers)	515	11%
F23G (Cremation Furnaces; Consuming Waste or Low-Grade Fuels by Combustion)	490	14%
C10J (Production of Gases Containing Carbon Monoxide and Hydrogen from Solid Carbonaceous Materials by Partial Oxidation Processes Involving Oxygen or Steam)	445	11%
B01J (Chemical or Physical Processes, E.G. Catalysis or Colloid Chemistry; Their Relevant Apparatus)	430	14%
C04B (Lime; Magnesia; Slag; Cements; Compositions Thereof, e.g., Mortars, Concrete or Similar Building Materials; Artificial Stone; Ceramics; Refractories; Treatment of Natural Stone)	387	18%
F23L (Supplying Air or Non-Combustible Liquids or Gases to Combustion Apparatus in General; Valves or Dampers Specially Adapted for Controlling Air Supply or Draught in Combustion Apparatus; Inducing Draught in Combustion Apparatus; Tops for Chimneys or Ventilating Shafts; Terminals for Flues)	325	17%
F23M (Casings, Linings, Walls or Doors Specially Adapted for Combustion Chambers, e.g., Firebridges; Devices for Deflecting Air, Flames or Combustion Products in Combustion Chambers; Safety Arrangements Specially Adapted for Combustion Apparatus; Details of Combustion Chambers, Not Otherwise Provided for)	249	14%

3.2.3. Highly Cited Papers Analysis

Table 3 shows the top ten CFB papers in order of citations. The most cited paper was a paper by Gómez-Barea, A and Leckner, B published in 2010 on modelling biomass gasification in fluidized beds, which provides an overview of gasification modelling in bubbling and circulating fluidized bed gasifiers, outlining the relevant elements to be considered in modelling. The second most cited paper is related to gasification in circulating fluidized beds, where a non-stoichiometric equilibrium model is developed to predict the performance of the gasifier by comparing experimental and model prediction results. The third most cited paper is about the exploration of new methods to improve the efficiency of biomass gasification, and it was found that more efficient biomass gasification can be achieved by roasting. From the research content of the ten highly cited papers, coal gasification and kinetic simulation/numerical modelling are the research directions in which CFB has attracted much attention in the basic science field.

Table 3. Analysis of highly cited papers in CFB technology.

Title	Year	Cited
Modeling of biomass gasification in fluidized bed	2010	645
Biomass gasification in a circulating fluidized bed	2004	584
More efficient biomass gasification via torrefaction	2006	497
CFD simulation of concurrent-up gas–solid flow in circulating fluidized beds with structure-dependent drag coefficient	2003	474
Eulerian two-phase flow theory applied to fluidization	1996	457
Chemical looping combustion of solid fuels	2018	418
A review on bio-oil production from biomass by using pyrolysis method	2012	404
Characterization of fluidization regimes by time-series analysis of pressure fluctuations	2000	368
Filtered two-fluid models for fluidized gas–particle suspensions	2008	365
State of the art of applied fast pyrolysis of lignocellulosic materials—a review	1999	317

3.2.4. Highly Cited Patents Analysis

Patent citations can be an important indicator for assessing the value and innovativeness of a technology. If a patent is cited by many other patents, it indicates that the patent has high technical value and influence. Table 4 shows the top ten CFB patents in order

of citations. The most cited patent is WO200224614-A1 [41] for the production of olefins (e.g., ethylene or propylene) from lower alkanes (e.g., methane or ethane). The technology focus is on the use of a CFB reaction system in which the lower alkane feed is contacted with an oxidation catalyst in a riser reactor to form a reduction catalyst, which is then re-oxidized in a fluidized bed generator using air or oxygen. The second most cited patent is US6505567-B1 [42], a technology for a CFB steam generator that improves the heat output of a fossil fuel power generation system. It cools and compresses the flue gas end product to produce liquid carbon dioxide. The third most cited patent (US2009227823-A1 [43]) is directed to the production of a fluid hydrocarbon product from a solid hydrocarbon material in a process that includes supplying a hydrocarbon material from a first reactor of a CFB reactor or a turbulent fluidized bed reactor. From the ten highly cited patents, CFB technology is applied in chemical production, energy production, environmental protection, and other fields.

Table 4. Analysis of highly cited patents in CFB technology.

Patent Number	Title	Priority Application Date	Cited
WO200224614-A1	Production of olefins (e.g., ethylene and/or propylene) from lower alkane (e.g., ethane) involves converting lower alkane by oxidative dehydrogenation, and recovering olefin product by complexation separation	18 September 2000	131
US6505567-B1	Operating method for circulating fluidized bed steam generator involves separating flue gas into end product and recycling portion to be directed to steam generator for combustion process	26 November 2001	120
US2009227823-A1	Producing fluid hydrocarbon products comprises providing solid catalyst in a reactor and feeding solid hydrocarbonaceous material, pyrolyzing the reactor, and catalytically reacting obtained pyrolysis products with the catalyst	3 March 2009	101
WO2006087083-A2 [44]	Manufacturing acrolein, useful as intermediate for synthesis of methionine and acrylic acid, by dehydration of glycerol in the presence of molecular oxygen at outside the flammability range	10 June 2005	89
WO2003076051-A1 [45]	Removal of mercury from flue gas containing mercury and particulate solids, comprises contacting mercury in flue gas with solution containing chloride-containing salt	12 March 2002	86
WO2010014938-A2 [46]	System for hot solids combustion and gasification, has chemical looping system, including endothermic reducer reactor and oxidizer reactor, which is in fluid communication with at least portion of existing power generation system	19 September 2008	82
US2002037246-A1 [47]	Simultaneous reduction in carbon dioxide and sulfur dioxide emissions by injecting calcium-based agent into hearth, subjecting flue gases to intermediate cooling, carbonizing, and extracting solids contained in the flue gases	27 September 2000	70
WO2006031011-A1 [48]	Apparatus for catalytic gasification of refined biomass fuel comprises catalytic circulating fluidized bed gasifier; dust collector to collect fly ash; catalytic reformer; heat exchanger; and tar scrubber	5 August 2004	67
WO2004027220-A1 [49]	Power generation system has pipe to conduct portion of compressed exhaust gas of gas turbine to gasifier, to control gasifier temperature, provide carbon dioxide, and steam for gasification, and reduce oxygen demand of gasifier	17 September 2002	67
WO2006087084-A2 [50]	Production of acrolein by gas-phase dehydration of glycerol in the presence of strongly acidic solid catalyst with specified Hammett acidity	10 Jun 2005	66

3.3. Country and Regional Analysis

3.3.1. Main Countries of SCI Paper Publication

The distribution of research output across different countries and regions can, to a certain extent, represent the development status of the field in those areas, aiding in the identification of the leading research nations and regions.

According to statistical data, researchers from over 70 countries and regions have actively explored the field of CFB technology. China stands out as the country with the highest number of publications, with 2333 relevant papers, surpassing the combined total of the countries ranked second to eighth, and accounting for over 40% of the global paper count. Canada and USA follow, with 540 and 517 publications, respectively, maintaining a significant lead over the subsequent countries despite having a gap compared to China (Figure 3). Among the top publishing countries, most are developed nations or developing countries with higher levels of economic development. These countries have recognized the potential of CFB technology to address various energy and environmental issues currently facing the globe and, as a result, have placed great emphasis on research and development in this field.

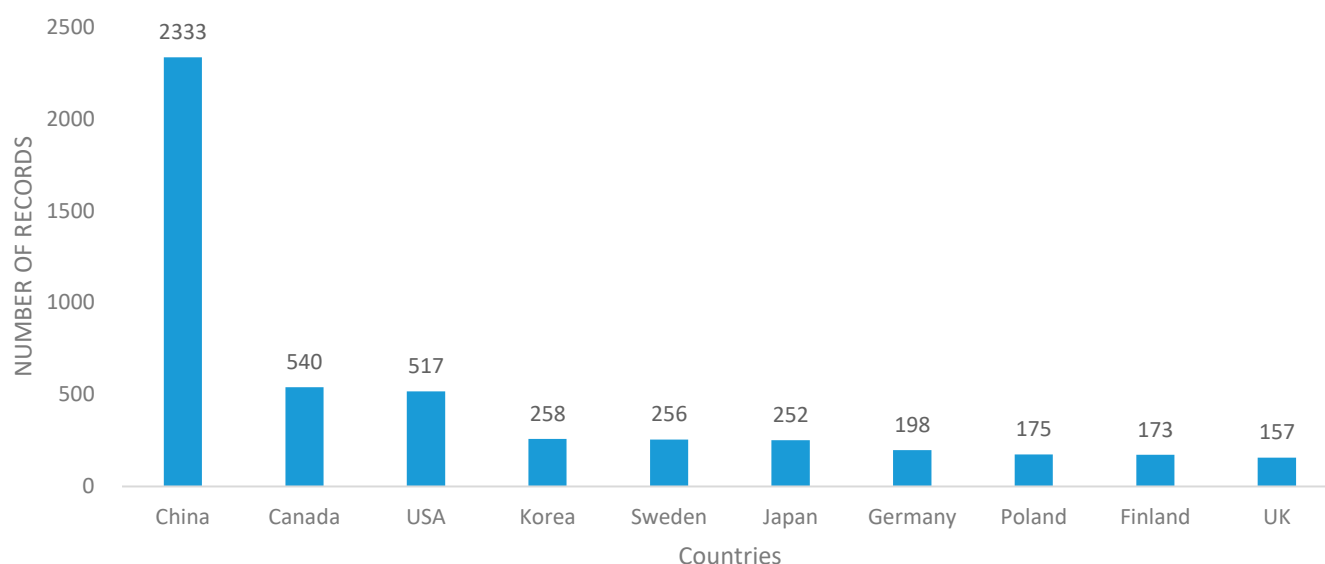


Figure 3. Top 10 countries in the field of CFB technology.

Figure 4 illustrates the annual publication trends of the major contributing countries in the CFB field. Prior to 1989, only a few countries produced relevant papers sporadically, such as Swedish researchers who conducted studies on the application of chemical and physical operations in CFB systems in 1980. After 1989, the field gradually gained increased attention, with scholars from countries like South Korea and Finland joining the research efforts. Overall, before 2002, the annual publication output of the leading countries in this field showed little variation, with countries like China, Canada, and USA maintaining an average annual publication rate of 10 to 20 papers. Sweden and Germany also occasionally exceeded ten publications in some years, while the remaining countries generally maintained an average of fewer than ten papers per year. After 2002, Chinese researchers intensified their efforts in CFB research, with the annual publication share growing from 17% to 59% by 2020, while other countries maintained a stable development trend. This is because, following 2002, China had abundant low-grade fuels, and issues inherent to CFB industrial applications became increasingly apparent, such as wear, high energy consumption, and the need to further reduce pollutant emissions, particularly NO_x, in response to heightened environmental standards. These factors stimulated a considerable amount of research. In contrast, countries abroad primarily rely on natural gas for their energy needs, which has limited the application of CFB technology. Instead, the focus

overseas has been on developing CFB systems with higher parameters and larger capacities. Notably, the publication output of the main contributing countries reached a historically high level in 2005, with China showing the most significant increase of 29 additional papers compared to the previous year. The year 2005 represents a significant turning point in the development of China's CFB technology, transitioning from the conventional power boiler era to the more advanced supercritical era. During this pivotal period, the team led by Academician Yue Guangxi at Tsinghua University diligently addressed the critical needs in the engineering design of CFB, successfully establishing a unique and internationally leading theoretical system for coal combustion in CFB that originated from China [51].

The development and application of CFB technology have played an indispensable role in optimizing and upgrading China's energy structure and reducing the reliance on fossil fuels. Currently, China has the largest installed capacity and the greatest number of CFB boilers in the world, conducting extensive research and applications ranging from theory to practice. CFB combustion technology, recognized as an efficient and clean coal combustion technology, has garnered widespread research and application globally in recent years, particularly in China. Since the 1990s, Chinese engineers and researchers have made significant improvements to CFB boiler technology, developing a new CFB boiler design theory [52] and successfully applying it to the manufacturing of CFB boilers of various capacities. China has become the world's largest supplier and consumer of CFB boilers [13]. In 2007, China successfully developed low-energy-consuming CFB technology, redefining the fluidization state, reducing the energy consumption of forced draft fans, and addressing potential erosion issues of water-cooled walls. In 2013, the commercial operation of China's first 600 MW supercritical CFB (SCCFB) boiler marked a step towards higher efficiency in power generation [53]. Moreover, Chinese scientists and engineers are developing more advanced ultra-supercritical CFB (USC-CFB) technology, and China is now leading the world in the development of ultra-supercritical 1000 MW units, with the fastest growth, the largest number, the greatest capacity, and the most advanced operational performance [6].

Figure 5 presents the collaboration landscape among countries active in the CFB research field. The figure indicates the following: (1) Globally, CFB research has formed multiple collaborative groups based on geographical locations. For instance, Europe has established a co-operation network centered around Sweden and Germany, while the USA and Canada are the primary publishing countries in the Americas. In the Asia-Pacific region, a collaboration group has emerged with China as the central publishing country, and several Asian countries have formed partnerships with South Korea as the core. (2) The collaboration among European countries is primarily driven by initiatives such as the EU 2020 plan, the European Regional Development Fund, and the European Commission's Coal and Steel Research Fund (RFCS). Additionally, the European Community's Future Energy Plan has included CFB technology, leading to extensive co-operation and the formation of stable collaborative relationships within the region. (3) The United States and Canada in the Americas have a significant publication output and focus more on research areas such as fluid mechanics and numerical simulation. (4) In the Asia-Pacific region, the collaboration network is centered on China and also includes countries like Japan, Singapore, and Australia, which collectively hold certain research advantages in the field of traditional coal chemical engineering. Specifically, Japan and Australia place greater emphasis on gasification technology, Singapore is more focused on high-temperature pyrolysis technology, and China has conducted research in coal combustion, pyrolysis, and gasification. However, these countries have some gaps in the research of dynamic simulation. (5) Another co-operation network formed by Asian countries mainly includes South Korea, India, Saudi Arabia, Iran, and Vietnam, with South Korea, as a core publishing country, paying more attention to fuel combustion research.

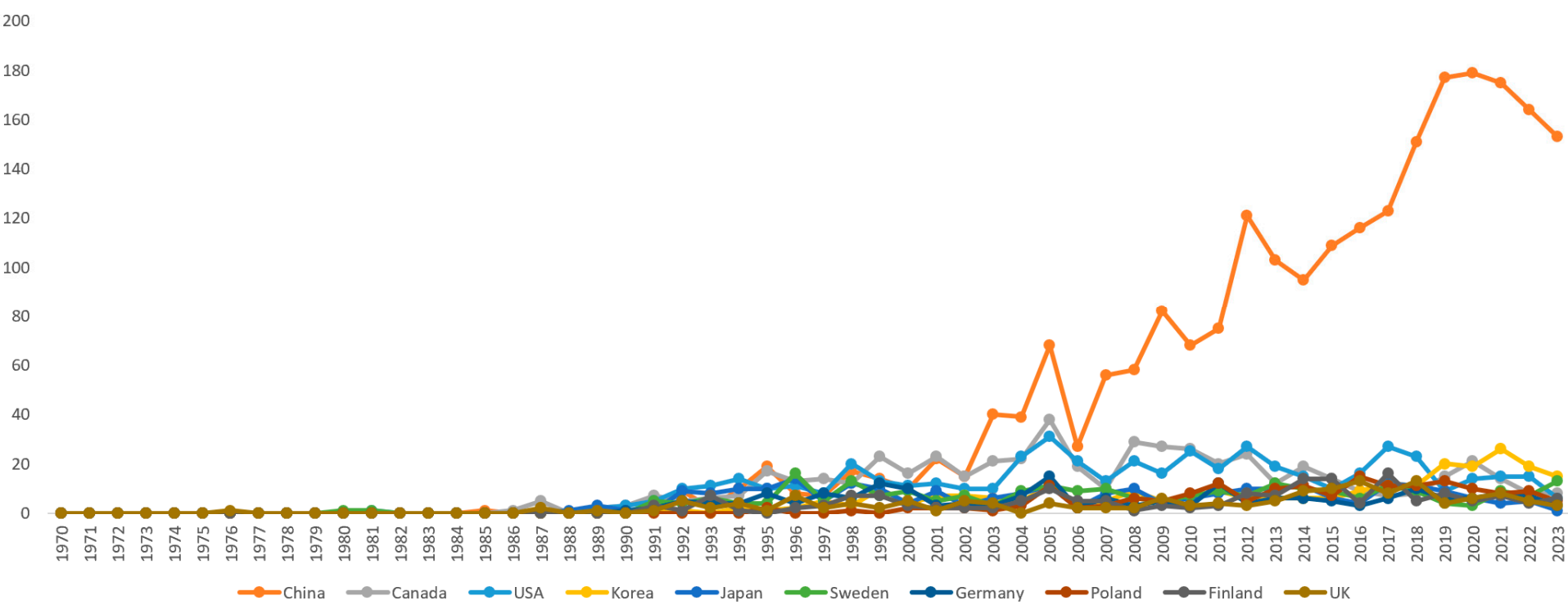


Figure 4. Annual output of CFB papers in the world.

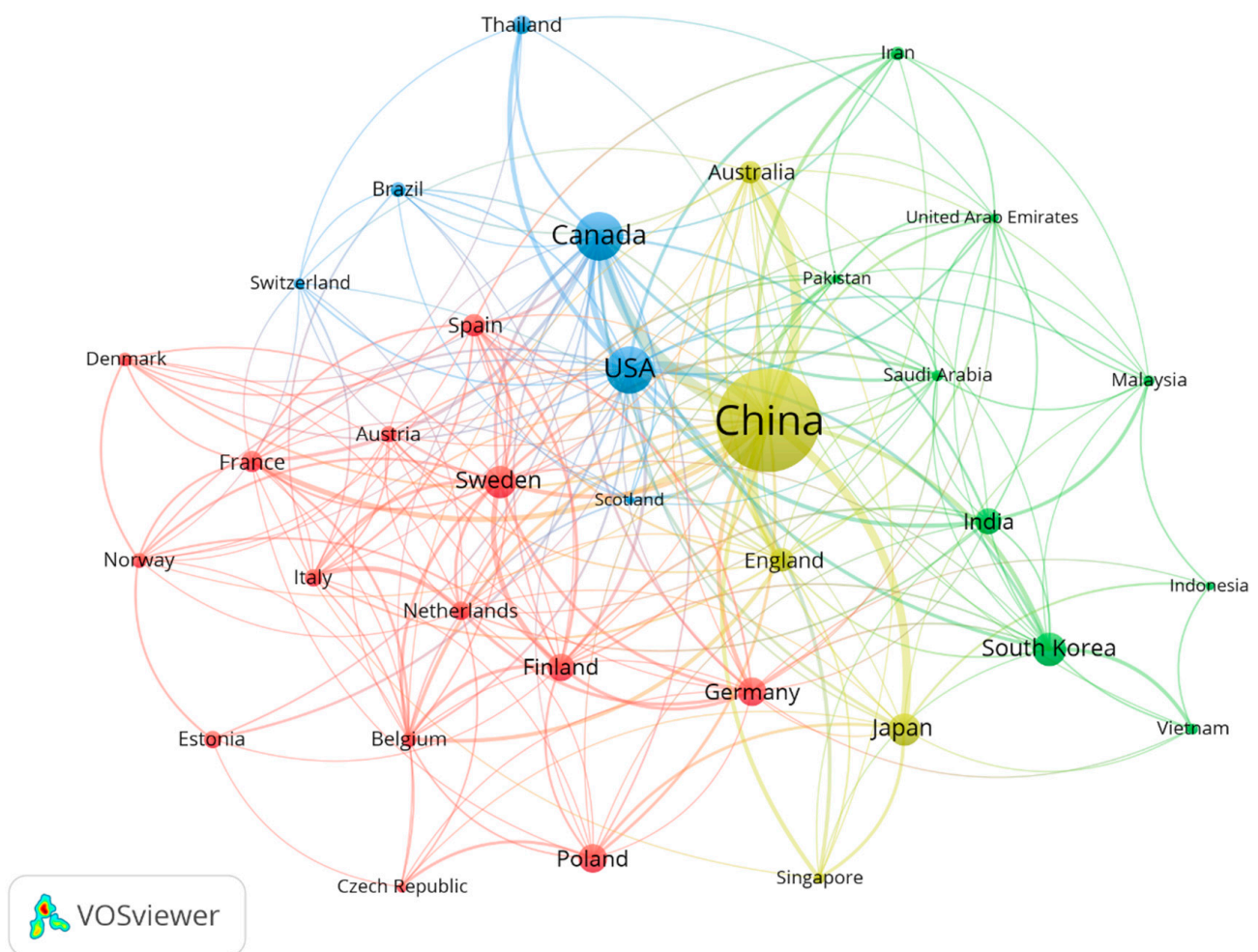


Figure 5. National co-operative network.

3.3.2. Main Countries and Regions of Patents

By examining the number of patents granted in various countries/regions within a certain technological field, one can gauge the level of activity of that technology across different locales. Table 5 presents the primary countries and regions for patent filings in CFB technology, with China leading by a significant margin with 6215 patents granted, far surpassing the second-ranking country, South Korea, with 290 patents. This discrepancy underscores China's substantial investment in research and innovation within the CFB technology domain. Moreover, the proportion of patents granted in China over the past three years accounts for 24% of the total, indicating frequent technological innovation activities in this field during this period. The broad market demand and application scope are evident, with the majority of global R&D efforts concentrated in China, to a certain extent, reflecting China's leading position in CFB technology patents. South Korea, the United States, and Japan all have more than 200 patents granted in CFB technology. However, South Korea and Japan have a higher proportion of patents granted in the past three years compared to the United States, indicating that the East Asian region is a vibrant hub for CFB technology research and development, likely influenced by China's dominant role in R&D within this field.

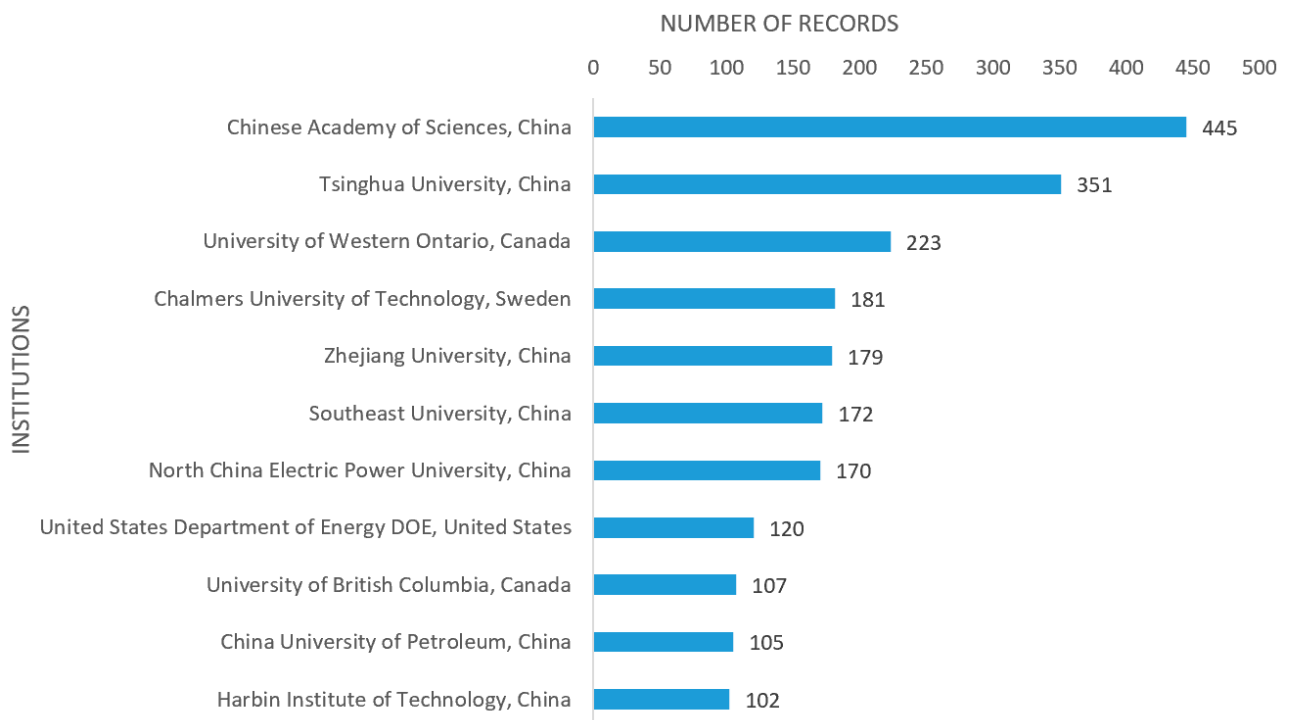
Table 5. Main countries and regions of CFB technology (top 10).

Countries/Regions	Number of Patents Issued	Ratio over the Past Three Years
China	6215	24%
South Korea	290	13%
United States	237	4%
Japan	209	9%
Canada	75	7%
European	71	6%
Finland	71	8%
Germany	40	5%
France	37	3%
India	36	0%

3.4. Analysis of Organizations

3.4.1. Main Organizations Producing CFB Papers

In the CFB field, there are 11 institutions that have published over 100 papers (see Figure 6); with the exception of the United States Department of Energy, all are universities and research institutes. These include Tsinghua University, a pioneer in the development of fluidized bed combustion technology in China; the Institute of Engineering Thermophysics of the Chinese Academy of Sciences, which proposed the technology of preheated combustion in CFB; Zhejiang University, which innovated composite CFB combustion technology; and the University of British Columbia, Canada, which studies the gasification process of biomass in external CFBs, among others. Among all publishing institutions, there are seven from China, two from Canada, and one each from Sweden and the USA. The Chinese Academy of Sciences, with the highest publication count, has published 445 relevant papers, accounting for over 7.80% of the total number of papers.

**Figure 6.** Main organizations producing CFB papers.

3.4.2. Main Organizations Applying for CFB Patents

Analyzing the main patent applicants in a technological field helps to understand the leading innovators, technological trends, and market competition, thereby guiding strategic decisions and innovation investments.

Figure 7 presents the primary patent applicants in CFB technology. The institution with the highest number of applications is China Huaneng Clean Energy Research Institute (188 items), with notably active research activities in recent years (23%). The institution's research focuses on various technology areas, including near-zero emission coal-fired power generation; coal gasification and clean conversion; and CO₂ capture, utilization, and storage; as well as large-scale CFB boilers. Following closely is Tsinghua University (145 items), which first proposed the concept of “steady-state design” for CFB boilers, enabling the determination of the design fluidization state of all circulating bed technology genres worldwide on a single flow pattern spectrum. Next is China Shenhua Energy Company Limited, primarily engaged in coal production and sales, railway and port transportation of coal-related materials, power generation, and sales. The remaining seven institutions have patent application volumes below 100 items, all originating from China, with four being enterprises and three being universities or research institutes. In summary, the patents in CFB technology are distributed relatively evenly among enterprises, universities, and research institutes in China, reflecting the close collaboration and effectiveness of industry–academia–research co-operation.

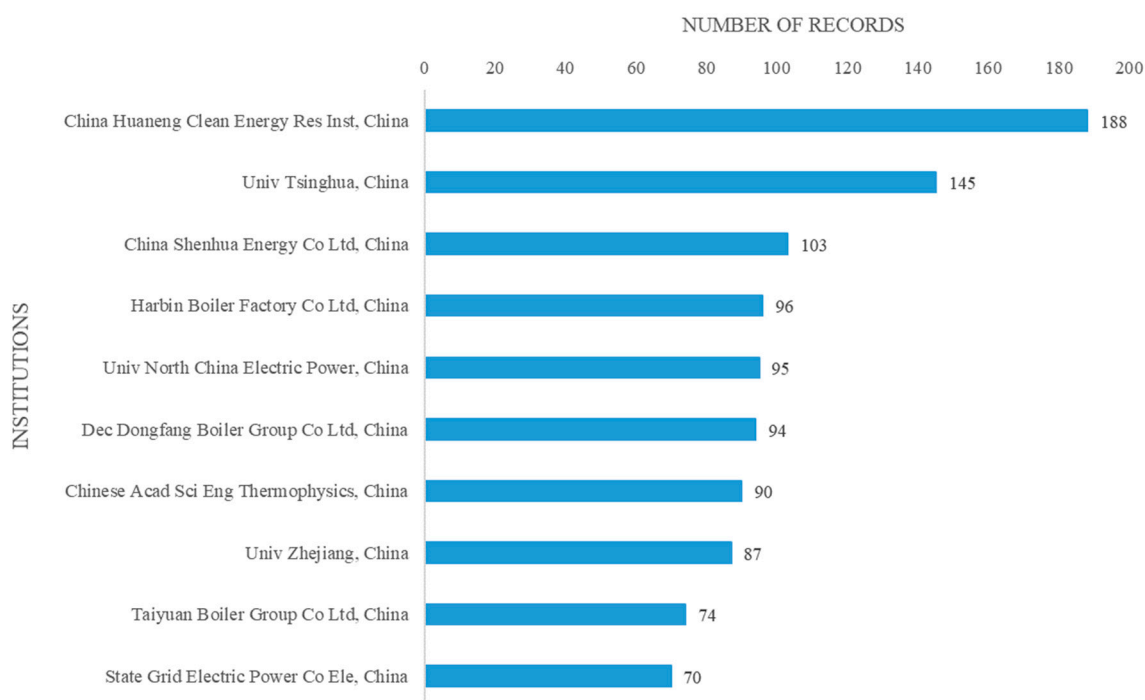


Figure 7. Main CFB patent applicants.

According to the data presented in Table 6, China Huaneng Clean Energy Research Institute is not only the leader in CFB technology research and development, but also has maintained continuous R&D investment and output in the past three years, and China Shenhua Energy Company Limited's total amount of CFB patents is relatively large, but the number of patents in the past three years accounts for only 1%, indicating that the agency may no longer focus on CFB technology in its development strategy, but instead turn to other fields. It is worth noting that State Grid Electric Power Co., Ele has a small number of patent applications, but it has been active in the past three years, so it may be a new competitor in the CFB technology field.

Table 6. Main organizations applying for CFB technology.

Organizations	Number of Patents	Ratio over the Past Three Years
China Huaneng Clean Energy Research Institute, Beijing, China	188	23%
Tsinghua University, Beijing, China	145	20%
China Shenhua Energy Company Limited, Shanghai, China	103	1%
Harbin Boiler Factory Company Limited, Harbin, China	96	20%
North China Electric Power University, Beijing, China	95	17%
Dongfang Boiler Group Company Limited, Zigong, China	94	9%
Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing, China	90	11%
Zhejiang University, Hangzhou, China	87	13%
Taiyuan Boiler Group Company Limited, Taiyuan, China	74	9%
The State Grid Corporation of China, Beijing, China	70	19%

3.5. Technology Trend Analysis

Utilizing the knowledge-mapping visualization tool VOSviewer, an analysis of the retrieved SCI papers was conducted, resulting in a keyword co-occurrence map (as shown in Figure 8). The distinct nodes within the map represent different keywords, while the lines connecting these nodes signify the co-occurrence relationships between the keywords. The size of the nodes is proportional to the frequency with which the keywords appear, the thickness of the lines corresponds to the number of times the keywords co-occur, and the length of the lines is inversely related to the similarity between the keywords. Nodes and lines of different colors represent various research themes.

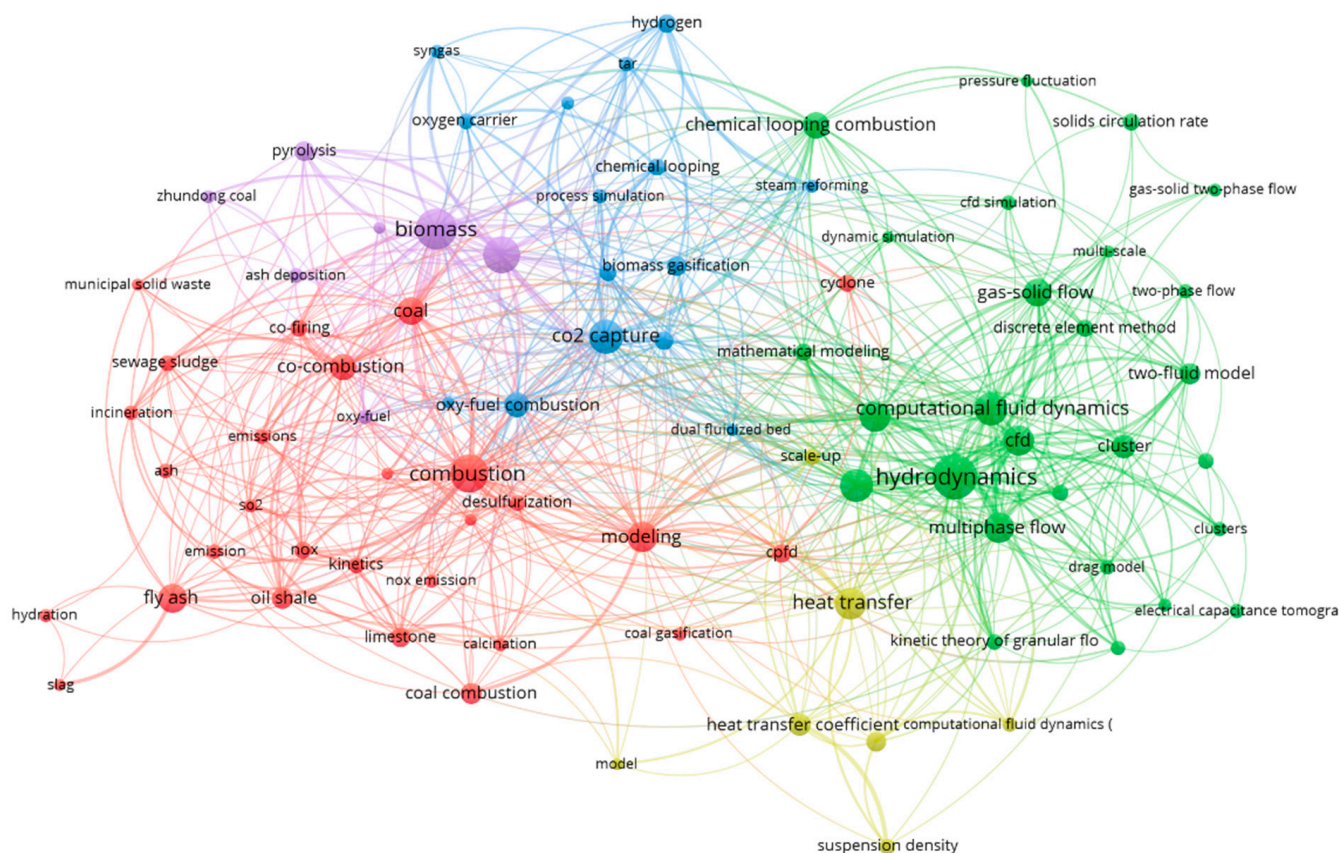


Figure 8. Research topics of CFB papers.

The keyword co-occurrence analysis of SCI papers in the CFB domain reveals that research related to CFB technology can be primarily categorized into five major areas

(Table 7): Combustion and Pollutant Emissions, Pyrolysis, Gasification, Dynamics simulation/Numerical simulation, and Low-Carbon/Zero-Carbon. Among these, technologies related to combustion and gasification have reached a more mature stage in industrial applications. Pyrolysis technologies are still in the laboratory development phase with limited industrial adoption. Numerical simulation emphasizes the development of new models from a computational perspective, providing a theoretical foundation for the research and development of new technologies. Low-carbon/zero-carbon represents an emerging research direction in the industry under the “dual carbon” background, aligning with the new trend of synergistic development for pollution reduction and carbon emission decrease.

Table 7. Research topics of CFB papers.

Clustering Number	Research Topic	Keywords
#1	Combustion and Pollutant Emissions	ash, calcination, co-combustion, co-firing, CO ₂ , coal, coal combustion, coal gasification, combustion, CPFD, cyclone, desulfurization, emission, fly ash, hydration, incineration, kinetics, limestone, modeling, municipal solid waste, NO _x , NO _x emission, oil shale, oxy-combustion, sewage sludge, slag, SO ₂
#2	Pyrolysis	heat transfer, heat transfer coefficient, scale-up, solid circulation rate, suspension density, computational fluid dynamics (CFD), model
#3	Gasification	ash deposition, biomass, gasification, lignite, oxy-fuel, pyrolysis, zhundong coal
#4	Dynamics simulation/Numerical simulation	CFD simulation, chemical looping combustion, cluster, computational fluid dynamics, discrete element method, drag model, dynamic simulation, electrical capacitance tomography, fast fluidization, gas–solid flow, gas–solid two-phase flow, gas–solids flow, hydrodynamics, kinetic theory, kinetic theory of granular flow, mass transfer, mathematical modeling, multi-scale, multiphase flow, numerical simulation, pressure fluctuation, simulation, solids circulation rate, two-fluid model, two-phase flow
#5	Low-Carbon/Zero-Carbon	biomass combustion, biomass gasification, carbon capture, chemical looping, chemical looping combustion, CO ₂ capture, dual fluidized bed, hydrogen, modelling, oxy-fuel combustion, oxygen carrier, process simulation, steam reforming, syngas, tar

The knowledge map indicates that the current CFB technology research is mainly focused on combustion and pollutant emissions, pyrolysis, and gasification. The research on combustion and pollutant emissions concentrates on low-cost pollution control for low-quality coal, with keywords including ash, co-combustion, calcination, desulfurization, limestone, and nitrogen oxides. Pyrolysis technology research primarily focuses on how to efficiently utilize the circulating ash from CFB boilers for coal pyrolysis and the in-furnace combustion of char produced after pyrolysis, as well as how to enhance heat transfer efficiency [54], with keywords such as heat transfer, heat transfer coefficient, scale-up, and hot ash recirculation. Gasification research mainly covers keywords like gasification, lignite, and zhundong coal. With the advancement in theoretical calculations, model-based CFB research has gradually become an important branch in this field, focusing on computational fluid dynamics and related kinetic theories, and employing dynamic simulation and numerical computation technologies to develop models such as the two-fluid model and drag model. Moreover, the introduction of “dual carbon goals” has drawn increasing attention from scholars to low-carbon energy sources like biomass and hydrogen, and the development of low-cost carbon capture technologies represented by chemical looping combustion has become a hot topic in the industry, with a growing number of research outcomes.

4. Conclusions and Prospects

Based on the analysis of research papers and patents, the research investigates the development of the CFB field from a global perspective:

- (1) From the perspective of annual production trends, the CFB field has reached a mature stage, with a decrease in fundamental research and a greater emphasis on application

development. Consequently, the number of related research papers has declined over the past three years, while the patent output remains consistently high.

- (2) From the distribution of subjects, the CFB field encompasses a wide range of disciplines and exhibits significant interdisciplinarity, with a focus on engineering applications.
- (3) From the perspective of major contributors to the literature, China has emerged as a major and core publishing country in this field, while developed countries such as Canada, the United States, and South Korea, and economically advanced developing countries also play significant roles in the field of CFB.

CFB technology, as an efficient combustion and gas–solid reaction process, has been widely applied globally, particularly in power generation and chemical processes. By conducting a thematic clustering analysis on the research papers and patent technologies associated with CFB technology, third-party observers can identify emerging trends in the research and development of CFB technology:

- (1) The core of CFB technology lies in its unique fluid dynamic characteristics, which enable fuel particles to exist in a fluidized state within the bed, facilitating efficient energy conversion and mass transfer. In recent years, with increasing demands for environmental protection, CFB technology has gained attention due to its lower pollutant emissions and good fuel adaptability. By optimizing operational parameters and improving designs, such as enhancing material circulation systems, increasing fuel adaptability, and improving heat exchange efficiency, efforts have been made to further enhance the combustion efficiency of CFB boilers and reduce harmful gas emissions.
- (2) In the field of materials science, researchers are developing new high-temperature and corrosion-resistant materials and manufacturing technologies to improve the durability and reliability of CFB systems. The development of these materials not only contributes to extending the equipment's service life and reducing wear and maintenance costs but also helps maintain a stable performance under more extreme operating conditions.
- (3) Computational fluid dynamics (CFD) simulation has become an important tool in CFB technology research. Through CFD simulation, researchers can predict and analyze the flow characteristics and chemical reaction processes within the fluidized bed without conducting actual experiments. This is of great significance for optimizing design and operation.
- (4) In terms of energy utilization, CFB technology is advancing towards diversification and high efficiency. For example, by integrating gasification and combustion processes, the effective utilization of biomass and other renewable energy sources can be achieved, reducing the reliance on fossil fuels and lowering greenhouse gas emissions. With the growing global demand for sustainable development and clean energy, the application of CFB technology in waste treatment and resource recovery is also expanding.

In summary, CFB technology has made significant progress in combustion efficiency, environmental protection, energy utilization, and waste treatment. However, to achieve broader applications and higher performance, further research is needed in materials science, computational fluid dynamics simulation, environmental impact assessment, system integration, and intelligentization.

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