IV. Energy & Mining Engineering

1 Engineering research hotspots and engineering research focus

1.1 Development trends of engineering research hotspots

The Top 10 engineering research hotspots (Table 1.1.1) involve a number of research directions in the field of energy and mining engineering[1], among which "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells," "Research and optimization of hybrid renewable energy system," "CO_2 fixation, storage, and utilization," "Solar thermochemical processes," "Wave energy and its potential assessment," and "High-efficiency battery thermal management system" are emerging hotspots, whereas "Flow, heat/mass transfer, and combustion under extreme conditions," "Regional industrial energy efficiency and CO_2 emission reduction," "Stirling engine," and "Structure, materials, and performance of the vertical-axis wind turbine" are developments in traditional research hotspots. The annual numbers of papers of each hotspot published in core journals from 2011 to 2016 are listed in Table 1.1.2.

(1) High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells

The photovoltaic (PV) industry mainly employs PV materials, solar cells and modules, PV inverters, and PV system integration; the key element is the solar cell. At present, commercial solar cells can largely be divided into crystalline silicon solar cells and thin-film solar cells. Scientists, technicians, and even the human kind face the pressing task of developing more efficient, economical,

Table 1.1.1 Top 10 engineering research hotspots in energy and mining engineering

No	Engineering research hotspots	Core papers	Citation frequency	Average citation frequency	Mean year	Proportion of consistently cited papers	Patent-cited publications
1	High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells	87	7724	88.78	2014.05	35.6%	1
2	Research and optimization of hybrid renewable energy systems	49	1395	28.47	2014.24	18.4%	1
3	Flow, heat/mass transfer, and combustion under extreme conditions	212	4888	23.06	2014.00	16.0%	2
4	Solar thermochemical processes	37	1574	42.54	2013.35	16.2%	0
5	CO_2 fixation, storage, and utilization	46	2230	48.48	2014.11	19.6%	0
6	Regional industrial energy efficiency and CO_2 emission reduction	47	1655	35.21	2013.64	6.4%	1
7	Wave energy and its potential assessment	44	1538	34.95	2013.48	11.4%	1
8	Stirling engine	31	919	29.65	2014.39	54.8%	0
9	High-efficiency battery thermal management system	41	1112	27.12	2014.24	9.8%	1
10	Structure, materials, and performance of the vertical-axis wind turbine	41	1068	26.05	2014.00	12.2%	2

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[1] The Standing Committee of the Department of Energy and Mining Engineering agreed, on January 15, 2017, that at the first stage of the project, the disciplines of energy and mining engineering should only involve the energy and electrical science, technology, and engineering (thermal power engineering, electrical engineering, hydropower engineering, energy new technology), the nuclear science, technology, and engineering (nuclear energy engineering, nuclear materials and nuclear fuels, nuclear safety, protection, and environment, and applications of nuclear science and technology), the geology resources science, technology, and engineering (oil and gas resources and exploration), and the mining science, technology, and engineering (coal exploration, oil and gas engineering).

Table 1.1.2 Annual number of core papers belonging to each of the top 10 engineering research hotspots in energy and mining engineering

No.	Engineering research hotspots	2011	2012	2013	2014	2015	2016
1	High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells	3	10	12	29	21	12
2	Research and optimization of hybrid renewable energy systems	1	3	6	16	19	4
3	Flow, heat/mass transfer, and combustion under extreme conditions	22	16	30	47	67	30
4	Solar thermochemical processes	5	7	9	5	8	3
5	CO_2 fixation, storage, and utilization	3	5	5	10	17	6
6	Regional industrial energy efficiency and CO_2 emission reduction	3	8	8	14	12	2
7	Wave energy and its potential assessment	6	6	9	9	12	2
8	Stirling engine	0	1	6	7	14	3
9	High-efficiency battery thermal management system	3	0	5	13	16	4
10	Structure, materials, and performance of the vertical axis wind turbine	5	5	6	4	11	10

and environmental-friendly solar cells. Up to present, owing to the flourishing development of the science and the technology of semiconductor materials—predominantly silicon—and because of the low cost and wide application of silicon, commercial solar cells based on silicon p-n junction still dominate the PV market (with a market share of over 90%). Nevertheless, silicon-based structures now have to face increasing competition from other materials, such as various semiconductor thin films and perovskite. The current trends in high-efficiency solar cells involve both the distinctive crystalline silicon (c-Si) solar cells, with an efficiency of higher than 22%, and the development of advanced thin-film solar cells. The high-efficiency crystalline silicon solar cells mainly include amorphous silicon/crystalline silicon heterojunction (a-Si/c-Si HJT) solar cells, back-contact solar cells, back-contact silicon heterojunction (BC-HJT) solar cells, bifacial solar cells, and broad-spectrum solar cells. The current research hotspots in advanced thin-film solar cells include the new perovskite solar cell, the copper–indium–gallium diselenide (CIGS) solar cell, and its substitute, the copper–zinc–tin sulfide (CZTS) solar cell. Focusing on these new PV technologies, scientists in universities and research institutions in America, Germany, Japan, and Switzerland are working together, and have already achieved remarkable breakthroughs.

(2) Research and optimization of hybrid renewable energy systems

Intermittence and fluctuation are intrinsic to renewable energies, such as solar and wind energies, and their outputs can be stabilized through a hybrid renewable energy system. Systems such as solar-wind hybrid power systems and renewable energy-gas turbine (or internal combustion engine) hybrid power systems can take full advantage of renewable energy sources as well as meet the needs of user loads. At present, there are two main categories of hybrid renewable energy systems. One category comprises the combination of different renewable energy sources—such as wind, solar, and water power—in a complementary manner to overcome the discontinuity and instability of a single energy source. The other category comprises hybrid power systems, in which a renewable energy source is combined with existing fossil fuels. Power generation in a hybrid manner can substantially improve energy efficiency, mitigate environmental pollution, and help promote a low-carbon economy and the optimization of the energy mix.

From the engineering perspective, the development of hybrid renewable energy systems calls for knowledge in disciplines such as power machinery, fluid machinery, material, power electronics, and control technologies. The current research hotspots mainly include the topological structures integration, the thermodynamic cycle analysis of hybrid energy systems, the establishment of a dynamic model of hybrid energy systems, the maximum utilization of renewable energy sources, the minimization of the utilization of natural gas, and the overall balance between the supply and demand of different energies.

(3) Flow, heat/mass transfer, and combustion under extreme conditions

Flow, heat/mass transfer, and combustion are closely related to numerous industrial applications in energy utilization systems. These applications entail various extreme conditions, such as high temperature, high pressure, and high heat flux. This engineering research focus contains mainly four branches, including evaporation and condensation, boiling heat transfer, heat transfer optimization, and combustion. Boiling, evaporation, and condensation are the main phenomena that take place in gas-liquid phase change processes, which are widely employed in the thermal management of electronic devices, the desalination of sea water, and the combustion process. Constrained by the fixed heat-transfer area of heat exchangers (heat sinks), heat transfer optimization is the maximization of heat transfer under conditions of high temperature, high pressure, ash and dust-laden settings, and high heat flux by changing the type of heat transfer (heat sink), structures, surfaces, and fluids. Combustion is a high-temperature exothermic redox chemical reaction between a fuel (the reductant) and an oxidant. Combustion devices—such as gas turbines, internal combustion engines, and industrial furnaces—are currently employed as the main method to generate power. The key technologies that are the research focus of contemporary engineering involve multi-phase, multi-component turbulent flows, chemical reactions, and multi-objective optimization; these require extensive study through theoretical analysis, high-precision numerical simulation, and advanced optical diagnostics. While developing basic theories, the theoretical guides and technologies for practical industrial production should not be neglected.

(4) Solar thermochemical processes

In solar thermochemical processes, the solar energy is converted into chemical energy that is stored in hydrocarbon fuels; therefore, the efficient conversion and high-density storage of solar energy becomes possible. This technology enables regions that are rich in solar resources to convert their resources into secondary fuels, which are then transported to different regions. This technology also serves as a solution to the instability and discontinuity of power systems that solely dependent on solar energy.

The applied research of thermochemical processes of solar energy includes fields such as hydrolysis reaction, methane reforming and coupling, coal gasification, and thermal decomposition of fossil fuels. Several advances have been accomplished in the design of high-temperature solar energy thermochemical reactors, the research and development of catalysts, the steam resistance array of complicated solar collector, and the material of high-temperature direct absorption vacuum pipe. In recent years, the utilization and fixation of CO_2 via solar thermochemical processes has attracted considerable attention. Metal oxides act as catalysts or redox mediators (oxygen carriers) to obtain CO or hydrocarbons by decomposing CO_2. The procedure mainly includes CO_2 decomposition and the two-step reaction of redox recycling via the thermochemical process. In that respect, researchers have focused on key technologies, such as the preparation of high-efficiency catalysts, the investigation of reaction dynamics and the mechanisms thereof, and the selectivity of target products.

(5) CO_2 fixation, storage, and utilization

CO_2 is the primary greenhouse gas. Carbon capture and storage (CCS) has been considered to be the predominant solution to the issue of reducing CO_2 emissions. The storage locations include geological structures (reservoirs of petroleum and methane, deep salt marshes, and unmineable reservoirs of coal) and oceans. CCS, deemed as a mature technology, has been put into practice in several regions around the world. Furthermore, attention has also been paid to the evaluation of the cost, the economic benefits, and the safety of CCS. In recent years, CO_2 fixation and utilization through chemical conversion has ignited the interest of the scientists who are committed to decreasing the emissions of CO_2.

CO_2 is put into both physical and chemical use. The physical properties of CO_2 are put into effect when it is used as an air-conditioner refrigerant, a curing hardener, and a food additive. Furthermore, CO_2 is applied in oil displacement technology as well; which also plays a role in CO_2 storage, owing to the fact that it can easily dissolve in crude oil, thus reducing its viscosity. The chemical use of CO_2 presents broader prospects. The activation of CO_2 molecules is a key technology, which is currently realized through biological methods, photochemical and electrochemical reduction, and heterogeneous and homogeneous catalytic reduction. Using CO_2 as a material, it may be realized by synthesizing small molecular compounds or the polymer materials as well (e.g., methane, formic acid, dimethyl carbonate, urea, salicylic acid, carbonate, carboxylic acid, and hydrocarbons). Much attention has been paid to the synthesis of gases and liquid fuels by CO_2 for the purpose of energy conversion and utilization. The preparation of catalysts with superior conversion efficiency, selectivity, and stability, and both the kinetics and the mechanisms of catalytic reactions have become research hotspots.

(6) Regional industrial energy efficiency and CO_2 emission reduction

The regional industrial energy efficiency measures the benefits produced from energy consumption in the industrial production process within a given area. It is a type of input-output ratio, and it refers to the ratio of the energy cost to the benefits obtained by a company; a lower energy cost indicates higher energy efficiency.

The low comprehensive efficiency of energy utilization (particularly the industrial energy utilization efficiency) is a widespread problem in developing countries. Owing to the rapidly growing economy of China, energy consumption has greatly increased, with the emission of CO_2 rising sharply. Faced with the dual challenge of economic development and CO_2 emission reduction, the regional industry should strictly control the total energy consumption, as well as adjust the industrial structure and transform the pattern of energy utilization from extensive to intensive, thus improving the energy utilization efficiency. The efficiency of coal utilization should be enhanced, and the utilization of renewable energy should be broadened based on the existing domestic energy structure. Moreover, the process of managing the pressures of energy demands while reducing the energy-supply constraints should be improved, in the process of alleviating environment pollution problems brought by energy production. The current research hotspots mainly include energy consumption analysis based on big data, real-time energy consumption measurements and statistics, high-efficiency industrial energy-conversion technology, and CCS technology.

(7) Wave energy and its potential assessment

Energy stored in wave is usually considered as a kind of ramification of solar radiation energy, and comes from wind energy. One of advantages of the wave energy is its high energy quality—mechanical energy of vibration. Furthermore, there is little power loss during wave energy transportation over a long distance. At present, the efforts of the utilization and exploitation of wave energy is mainly focused on the method of the assessing of wave energy deposit and optimization design of power generation devices.

Based on the advanced real-time monitoring system and abundant test data, the research on the assessing method is mainly concentrated on how to adopt a reasonable mathematic model and then precisely predict and estimate distribution of the wave energy deposit in a certain ocean area during a certain future period (short or long), which can provide a theoretical basis and support for feasibility analysis of wave energy exploitation programs.

In general, power generation devices for wave energy can be classified into several types according to extracting methods, such as oscillating water column type, raft-type, pendulum type, duck-like type, overtopping type, point absorber type, and so on. Among these types, oscillating water column power generation device is the earliest developed type. Nowadays, the study of the power generation device is focused on how to develop a kind of wave energy extracting equipment, which not only owns more efficient performance but also can be stably and long-term operated in oceanic environment. In addition, the effects of power generation devices on marine ecological environment and fishery industry development are also evaluated and analyzed in recent years.

(8) Stirling engine

The Stirling engine is an externally heated piston engine that operates with gas as the working medium in a closed regenerative cycle. A typical Stirling engine work cycle includes the following processes: the working medium is heated through the heat exchanger by an external heat source; then it expands and gives out effective power; after that, the working medium is cooled and compressed, and is then reused. The ideal Stirling engine consists of a cylinder with opposed pistons, a heater, a cooler, and a heat regenerator that is installed between two pistons. The pressure-swirl nozzle is typically used in Stirling engines, and it features a simple structure, reliable performance, good atomization performance, and low energy consumption. Up to now, the research on the Stirling engine has focused on the work cycle and the performance of key components.

A wide range of energy sources can be used to power Stirling engine. In addition to conventional diesel, a variety of alternative fuels, including methane, coal-bed methane, natural gas, and even straws and wood, can be used. Therefore, the performance of the Stirling engine using alternative fuels has become a research hotspot, which mainly focuses on applications in fields such as the combined cooling, heating, and power (CCHP) and standby power stations.

The Stirling engine can operate in environments that are entirely different from the atmosphere. The small vibrations and low noise levels during its operation render it ideal for power generation in submarines during their long voyages, without them leaving trails behind. At present, several countries are committed to the research and development of the Stirling engine used in submarines and submersibles. Therefore, the spray, combustion, and reliability of the Stirling engine under high back pressure are focal points of the research.

(9) High-efficiency battery thermal management system

Battery thermal management, which affects the safety, life, and performance of a battery, ensures that batteries operate in an ideal thermal environment. The following key technical problems should be solved: battery heat generation mechanism and heat generation prediction model, heat transfer medium materials and devices, highly efficient heat management system model and its design method, temperature control of the battery system, temperature difference control between battery cells. Active or passive heat management is performed on the batteries by means of external cooling, heating (or electric heating), or by maintaining a stable temperature throughout the heat transfer medium, which may be air, liquid and phase change materials, or a composite medium. By establishing a coupled simulation model and a method for the thermo-mechanical-electric multi-physics field of the battery system considering the entire working condition and the entire environment temperature condition, the research on the thermal energy management system model and the multi-objective design optimization can help to maintain the temperature of the battery system at an ideal level, and to control the temperature difference between battery cells. A highly efficiency thermal management of the battery system can be achieved via technologies such as heat pipes, heat pumps, and micro-channel heat exchangers. Intelligent control of the battery system temperature can be achieved through temperature feedback from multiple points; this feedback represents the distribution of the temperature field in the battery system. It is expected that the following studies will be carried out: thermal energy management technology based on advanced phase change materials combined with fluid heat transfer; the predictive control of battery thermal management based on battery heat generation prediction; active lean thermal management for battery cell or battery system partition; internal temperature adjustment thermal management technology of the battery cell through the external current pulse excitation or built-in heating circuit using the battery's own energy.

(10) Structure, materials, and performance of the vertical-axis wind turbine

The vertical-axis wind turbine is a type of small- and medium-sized wind power equipment, which can be easily installed and maintained, and has low start-up wind speed. It features prominently in the use of wind energy. It can be classified into three types, namely the drag type, the lift type, and the lift-drag type, according to the operation principle of the wheel blade. Compared with the traditional wind turbine, the vertical-axis wind turbine presents the following advantages: ① efficient use of the wind field, smaller operation area, simple structure, low weight, convenient maintenance, good response to wind from all directions, and strong wind resistance; ② longer service life and less noise pollution; ③ no need for the tail and yaw system to drive the blades; and ④ the speed-increasing gear box and generator can be installed on the ground. This type of wind turbine can be combined with solar power, small hydropower, natural gas power generation, and geothermal power to build complementary power systems.

Wind power generation technology is a comprehensive and systemic engineering that involves disciplines such as aerodynamics, computational fluid dynamics, material mechanics, automatic control, and electromechanics. The main research hotspots are the aerodynamic analysis of the blades, the high-performance blade design technology, the structural dynamics optimization, and the connection of wind turbines to the grid and control techniques.

1.2 Understanding of engineering research focus

1.2.1 High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells

(1) Concept elaboration and development status

Fossil fuels help promote the development of human society; however, the excessive consumption of the fossil fuels leads to global warming and deterioration of the environment as well, thus posing an enormous threat to the survival of mankind. Most countries have expressed their willingness to change their energy consumption strategies and develop renewable energies. Among various renewable energy sources, solar energy has attracted considerable attention because it is an inexhaustible, clean, and safe energy that can be used in several regions. In recent decades, although renewable energies represented by solar PV power generation have been growing rapidly, solar PV accounted for only 1.2% of the global electricity generation capacity by the end of 2015. In addition, the PV-generated electricity in China was 66 200 GW·h in 2016, which only accounted for 1.1% of China's electricity consumption. It is anticipated that PV-generated electricity will account for more than 10% of the global energy supply in 2030, and will thus contribute substantially to the global energy supply and the adjustment of the global energy mix. Therefore, the solar PV industry has bright prospects both in China and in the rest of the world. The solar PV industry mainly includes PV materials, solar cells, PV modules, PV inverters, and PV system integration; the key element is the solar cell. At present, commercial solar cells can largely be divided into crystalline silicon solar cells and thin-film solar cells. It is a pressing task facing scientists, technicians and even the human kind to develop more efficient, economical and environmental-friendly solar cells.

Up to present, owing to the flourishing development of the science and the technology of semiconductor materials—which are predominantly silicon—and because of the low cost and wide application of silicon, commercial solar cells based on silicon p-n junction still dominate the PV market (with a market share of over 90%), Nevertheless, silicon-based structures now have to face increasing competition from other materials, such as various semiconductor thin films and perovskite. The current trends in high-efficiency solar cells involve both the distinctive c-Si solar cells, with an efficiency of higher than 22%, and the development of advanced thin-film solar cells. The high-efficiency crystalline silicon solar cells mainly include a-Si/c-Si HJT solar cells, back-contact solar cells, BC-HJT solar cells, bifacial solar cells, and broad-spectrum solar cells. The current research hotspots in advanced thin-film solar cells include the new perovskite solar cell, the CIGS solar cell, and its substitute, the CZTS solar cell. Crystalline silicon solar cells present great commerical potentials owing to their high efficiency, stable performance, and the abundance of silicon. Futhermore, several advanced industrial techniques are already available for c-Si solar cells. The present mainstream techniques, e.g., the passivated emitter and rear cell (PERC) and the bifacial solar cell, have both been industrialized in earnest (with efficiencies of 21.0%–21.5%). In addition, the industrial processes of a-Si/c-Si HJT solar cells, back-contact solar cells, and broad-spectrum solar cells are developing rapidly. The next-generation technology—the back-contact silicon heterojunction solar cell—is growing more and more mature. In contrast, there is room for improvement for the advanced thin-film solar cells to reach mass industrial production levels. At the present stage, the work on perovskite solar cells is mainly focused on improving the efficiency and long-term stability, increasing the cell area, and finding nontoxic substitutes, whereas the industrial process is only at the beginning. The work on CIGS solar cells technology is focused on narrowing the wide gap between the efficiency of industrial modules (~16%) and that of the small-area solar cells fabricated in laboratories, and on replacing CIGS with CZTS. It is expected that thin-film solar cells, with the flexible thin-film battery leading the way, will play an important role in the development of future PV technology as well, owing to their low material consumption, increased efficiency, and their flexibility. In fact, flexible solar cells, which use flexible materials such as plastic or metal as a substrate, have always been a subject of interest owing to their wide range of applications.

(2) Current situation in China

Since 2005, the China's PV industry has realized striking progress. Approximaely 75% of all PV modules produced in the last two years were made in China, which is expected to remain the largest PV producer in the following years. At present, the conversion efficiency of conventional single crystalline silicon solar cells has reached 20%–21%, and that of the multi-crystalline silicon solar cells has reached 18%–19%. Most China's PV companies focus on conventional crystalline silicon solar cells; therefore, the China's PV industry may obtain a leading position in this domain, establsihing the PV industry as one of the few emerging strategic industries of China with international competence**.** Certain important China's PV firms, universities, and research institutions are pursuing breakthroughs in the mass production of crystalline silicon solar cells that present an efficiency of over 22%. With the support of national projects—863 Program—and through international collaborations, the technologies of a-Si/c-Si HJT solar cells and back-contact solar cells have significantly progressed. However, the research on back-contact silicon heterojunction solar cells is only at its beginning, and falls behind compared to that of developed countries. In the past few years, there has been rapid progress in the research and industrialization of perovskite solar cells; China is already a competitive player in this technology. Although several universities and research institutions in China have started studying CIGS solar cells a long time ago, there is still great room for improvement to level with advanced players. In the past few years, certain key China's companies that focus on thin-film solar cells have been importing or even purchasing CIGS from PV companies with advanced fabrication techniques from Europe and the USA to improve China's CIGS technology. Consequently, China has become one of the leading players with its rapidly-growing CIGS technology. It should be pointed out that China still lacks a national PV laboratory similar to the Fraunhofer Institute for Solar Energy Systems (ISE) in Germany, the National Renewable Energy Laboratory (NREL) in America, the National Institute of Advanced Industrial Science and Technology (AIST) in Japan, and the Energy research Centre (ECN) in the Netherlands. The research on solar cells in China is mainly conducted in universities, research institutions, and key PV companies. Although the China's Ministry of Science and Technology established two national key laboratories several years ago, they were both inside PV companies; this affects the application and spread of advanced PV technologies.

Although China is a large PV manufacturer, it is still not a major PV technology innovation center. We should be aware of the severe situation faced by the PV industry. Currently, researchers in universities and research institutions in the USA, Germany, Japan, and Switzerland closely collaborate, and have made great progress in CIGS solar cells, perovskite solar cells, a-Si/c-Si HJT solar cells, back-contact solar cells, back-contact silicon heterojunction solar cells, perovskite/crystalline silicon tandem solar cells, bifacial solar cells, and broad-spectrum solar cells. When basic research on innovative PV techniques is conducted at the highest level around the world, what strategies should China's PV specialists follow? Should China be satisfied with only being a large PV manufacturer? Only through innovation at the source and through institutional reforms can China become an advanced and innovative industrial PV power.

(3) Major countries and research institutions

In the research on distinctive high-efficiency crystalline silicon solar cells, American and Japanese companies are frontrunners. The American company SunPower and the Japanese company Panasonic have manufactured solar cells with an efficiency topping 24%, and realized the industrialization of solar cells with average efficiencies of 22.5%–23.0% by using interdigitated back contact and a-Si/c-Si HJT, respectively. Recently, the Japanese firm Kaneka has produced a crystalline silicon solar cell with a record efficiency of 26.6% by adopting the back-contact Si HJT technique. Although China has been progressing in the development of the advanced thin-film solar cells, the best techniques have been mastered in Europe, Japan, and Korea. The European thin-film solar cell alliance "Solliance" and the Ulsan National Institute of Science and Technology of Korea have both developed millimeter-sized perovskite solar cells with an efficiency that reaches 22.1%. In addition, the École polytechnique fédérale de Lausanne (EPFL) in Switzerland and the University of Oxford in England are at the forefront of the research on perovskite solar cells. The Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) in Germany and the Solar Frontier of Japan have produced CIGS solar cells with an area of 0.5 cm^2 and efficiencies of 22.6% and 22.3%, respectively. Another recently developed field is the perovskite/silicon tandem solar cell. In 2017, Stanford University, collaborating with other universities and corporations, announced that its perovskite/crystalline silicon tandem solar cells (with an area of 1 cm^2) had reached an efficiency of 23.6%.

From Table 1.2.1, it may be seen that the major countries in which high-efficiency solar cells are studied are the USA, Germany, Japan, Switzerland, and Spain. Table 1.2.2 indicates that the research institutions that develop high-efficiency solar cells mainly include Ecole Polytech Fed Lausanne, IBM Corp., and the Fraunhofer Inst Solar Energy Syst.

Figure 1.2.1 shows the collaboration relationships between the major countries that contribute to the development of high-efficiency solar cells, which include thin-film, perovskite, silicon heterojunction, back-contact, and

Table 1.2.1 Major producing countries or regions of core papers on the engineering research focus “High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells”

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	USA	28	32.18%	4351	61.97%	155.39	8	1
2	Germany	16	18.39%	929	13.23%	58.06	3	0
3	Japan	14	16.09%	763	10.87%	54.50	2	0
4	Switzerland	13	14.94%	587	8.36%	45.15	3	0
5	Spain	7	8.05%	238	3.39%	34.00	1	0
6	Australia	5	5.75%	160	2.28%	32.00	0	0
7	China	5	5.75%	157	2.24%	31.40	0	0
8	Korea	4	4.60%	205	2.92%	51.25	0	0
9	England	4	4.60%	93	1.32%	23.25	1	0
10	France	3	3.45%	164	2.34%	54.67	1	0

Table 1.2.2 Major producing institutions of core papers on the engineering research focus “High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Ecole Polytech Fed Lausanne	9	10.34%	458	6.52%	50.89	2	0
2	IBM Corp	7	8.05%	1977	28.16%	282.43	3	1
3	Fraunhofer Inst Solar Energy Syst	7	8.05%	295	4.20%	42.14	1	0
4	Grad Univ	6	6.90%	196	2.79%	32.67	0	0
5	Okinawa Inst Sci & Technol	6	6.90%	196	2.79%	32.67	0	0
6	IREC	6	6.90%	167	2.38%	27.83	1	0
7	Catalonia Inst Energy Res	6	6.90%	167	2.38%	27.83	1	0
8	Univ Calif Los Angeles	5	5.75%	572	8.15%	114.40	0	0
9	Helmholtz Zentrum Berlin Mat & Energie	5	5.75%	389	5.54%	77.80	2	0
10	Purdue Univ	5	5.75%	238	3.39%	47.60	3	0

Note: IREC stands for the Interstate Renewable Energy Council.

back-contact silicon heterojunction structures. Figure 1.2.2 shows the collaboration networks among major research institutes that focus on the aforementioned research field.

Table 1.2.3 lists the major producing countries or regions of citing core papers on the engineering research focus “High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells.” It may be seen that the USA, Germany, and Switzerland are the top 3 countries. Table 1.2.4 lists the major producing institutions of citing core papers on the aforementioned engineering research focus. Ecole Polytech Fed Lausanne, the IREC, and the Catalonia Inst Energy Res are the top 3 institutions.

1.2.2 Research and optimization of hybrid renewable energy systems

Developing renewable resources is an important approach to solving the problems of energy utilization and environment pollution in the world; it is an inescapable option and an effective measure to maintain the sustainable development of energy utilization. In the past ten

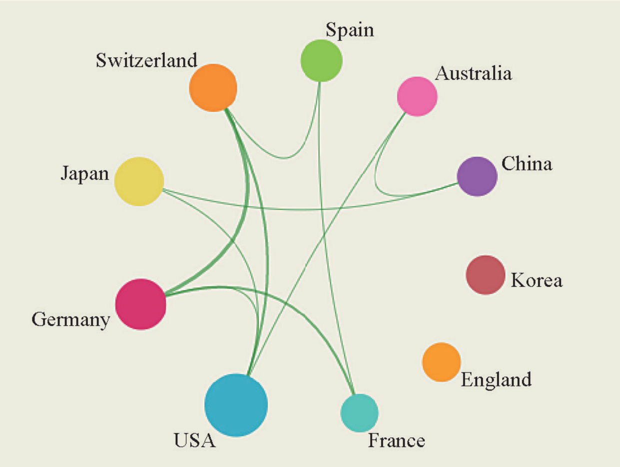

Figure 1.2.1 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"[1]

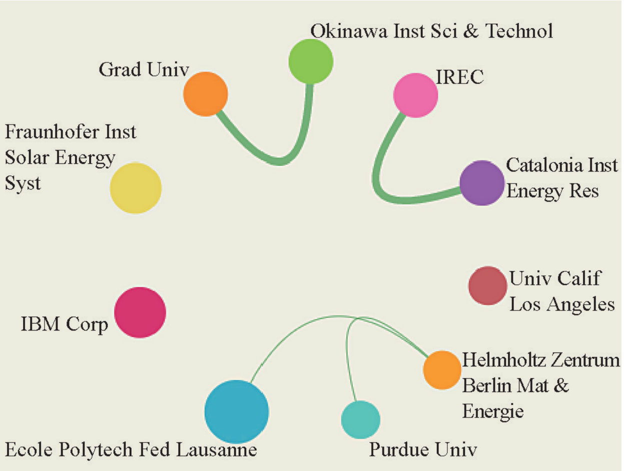

Figure 1.2.2 Collaboration network of the major producing institutions of core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

Table 1.2.3 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	USA	23	25.84%	2013.87
2	Germany	12	13.48%	2013.92
3	Switzerland	12	13.48%	2014.33
4	Japan	10	11.24%	2015.00
5	Spain	6	6.74%	2014.67
6	Australia	5	5.62%	2014.80
7	China	4	4.49%	2014.75
8	England	3	3.37%	2014.33
9	Korea	3	3.37%	2014.33
10	France	2	2.25%	2015.50

years, the hybrid renewable energy system has attracted more and more attention worldwide.

From the perspective of availability of renewable energies and technology maturity, the hydropower, the wind power, and the solar power are the most realistic energy resources with broad prospects. A hybrid energy power system typically consists of two or more sets of distributed power supplies, an energy storage system, and various power electronic control devices. At present, there are two main categories of hybrid renewable energy systems. One category comprises different renewable energy sources—such as wind, solar, and water power—in a complementary manner to overcome the discontinuity and instability of a single energy source. The other category comprises hybrid power systems, in which a renewable energy source is combined with existing fossil fuels. Power generation

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[1] In the figure, the nodes refer to the countries or regions, the size of the nodes refers to number of papers, the connecting line between nodes refers to papers published based on research cooperation, and the thickness of the connecting line indicates the number of papers based on research cooperation. These are the same in full text.

Table 1.2.4 Major producing institutions of core papers that are cited by core papers on the engineering research focus "High-efficiency solar cells, including thin-film solar cells, perovskite solar cells, silicon heterojunction solar cells, back-contact solar cells, and back-contact silicon heterojunction solar cells"

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Ecole Polytech Fed Lausanne	8	5.33%	2014.50
2	IREC	6	4.00%	2014.67
3	Catalonia Inst Energy Res	6	4.00%	2014.67
4	IBM Corp	6	4.00%	2013.17
5	Univ Calif Los Angeles	5	3.33%	2013.20
6	Helmholtz Zentrum Berlin Mat & Energie	5	3.33%	2014.20
7	Grad Univ	4	2.67%	2015.50
8	Fraunhofer Inst Solar Energy Syst	4	2.67%	2013.75
9	Natl Renewable Energy Lab	4	2.67%	2013.50
10	Univ Barcelona	4	2.67%	2014.25

in a hybrid manner can substantially improve energy efficiency, mitigate environmental pollution, and help promote a low-carbon economy and the optimization of energy mix.

From the engineering perspective, the development of hybrid renewable energy systems calls for knowledge in disciplines such as power machinery, fluid machinery, material, power electronics, and control technologies.

Renewable energy sources, such as wind power and solar power, are naturally complementary, and the hydropower has the ability to adjust quickly. From the perspective of time, solar energy is abundant during daytime, whereas the wind is quite weak. However, this situation is reversed during nighttime. During sunny days, sunlight is strong, whereas wind is weak; on the other hand, this situation is reversed during rainy days. The time limitation in solar power generation and the instability of wind power generation are the inherent defects of these energy sources. Wind-solar power generation can become a reliable groundwork for the development of national economy only if they are combined with the standby powers with considerable scale and better adjustment abilities. The hydropower is a type of large-scale power supply with good adjustment performance. It can be utilized to overcome the intermittence and instability of photovoltaic and wind power generation. The wind-solar-water power system can ensure the quality of the power supply. Therefore, it is critical to ensure that the power supply of the hybrid renewable energy system is continuous and stable.

Regarding the instability of renewable energies, such as wind and photovoltaic power, China utilizes thermal power and hydropower for the peak regulation of the power system. The combined power system of renewable energies and natural gas can be used in the peak regulation of the power system; this may improve the adaptability of the power grid to the changing load, while being more environment-friendly as well. The low emission of gas turbines offers great environmental benefits; they can substitute the coal-powered engine, and can contribute to peak regulation, particularly in well-developed cities that suffer from continuously increasing pollution.

To date, domestic and foreign institutions and researchers have conducted extensive research in the field of hybrid power generation technology. The latest research trends that are related to hybrid power generation, including wind-solar systems and renewable energy-fossil fuel systems, will be introduced in the following sections.

(1) Development status of wind and solar hybrid power systems

In terms of research and development on optimization software, the US Renewable Energy Laboratory has developed the HYBRID2 and HOMER systems to simulate and optimize wind-solar hybrid power systems. Based on a genetic algorithm, the University of Zaragoza developed an optimization software package that can be applied in complementary hybrid power systems, such as wind-solar and solar-diesel engine hybrid systems. In addition, the hybrid power system of the solar-diesel engine was improved and optimized.

In terms of practical applications, a skyscraper was built in 2007 in Dubai (United Arab Emirates), the power of which is supplied by both solar photovoltaic power equipment and wind turbines. This project is the first combination of urban buildings and solar-wind hybrid power systems, which carved a new path in the application of hybrid power systems. In 2009, China built the first national wind & solar & storage demonstration project at the wind farm located in the Shangyi and Zhangbei County in Zhangjiakou City of the Hebei Province. There are 500 MW of wind power and 100 MW of photovoltaic power generation systems, and energy storage systems with a storage capacity of 75 MW.

In recent years in China, various forms and sizes of hybrid renewable energy systems have been widely applied to street lights, remote oil well equipment, highway appliances, navigation stations, oil and gas delivery and heating devices, natural reserves, residential areas, industrial parks etc.

(2) Development status of other forms of hybrid power systems

Domestic and foreign scholars have conducted studies and analyses on hybrid power generation technologies, such as wind-hydrogen-biomass-solar hybrid power systems, wind and diesel hybrid power systems, underground coal gasification and high-temperature fuel cell hybrid power systems, solar and fuel cell hybrid power systems, and solar and geothermal flash hybrid power systems.

The first wind-hydrogen-biomass-solar hybrid power plant in Germany was officially put into operation in 2010; this power plant uses wind and solar power to generate electricity. The electricity is partly connected to the grid, and the remaining part is used to electrolyze water in order to produce hydrogen power. The total installed capacity is 6 MW, and when the wind and solar power cannot meet the demand, the hydrogen and biomass energy can be utilized as a supplementary energy-generation capacity. Norway has built a new type of wind and diesel hybrid power plant with an installed capacity of 2000 kW, which conserves more than 50% of fuels. In the Sequoia National Park of the USA, Schatz Energy Research Center of Germany and the Yurok Tribe built together a solar-cell and fuel-cell hybrid power system, which provides electricity mainly for wireless communication relay stations in remote areas, with a total efficiency of up to 64% and a net efficiency of over 48%.

In Europe, to meet the objectives of the European Commission project entitled "Photovoltaic fuel-cell hybrid system for electricity and heat production for remote sites (PVFC-SYS)", a solar-cell and fuel-cell hybrid power system was built in France, the net efficiency of which reaches up to 50%. As geothermal energy has the advantage of stability, a solar–geothermal hybrid energy pilot plant was built in Aydin, Turkey, in 2014.

(3) Future trends

Hybrid renewable systems, a systematic engineering, utilize a variety of renewable energy resources to complement each other in accordance with the conditions of different energy resources and the applications of the generated power. Through intelligent coordination control and optimal dispatch, comprehensive energy efficiency is improved, renewable energy accommodation is promoted, and the benign cycle of ecological environment becomes facilitated. At present, there are two main models.

Terminal integrated power supply system: it mainly focuses on electricity, heating, cooling, gas, and other demands of end users. As an integrated energy supply infrastructure, it is operated in line with local conditions, and uses traditional energy and new energy in a complementary manner. This type of system could meet the objectives of coordinated supply of multiple energies and comprehensive cascade utilization of energy, typically through the use of various of modes, such as the combined heating, cooling, and electricity (CHCP) system that is fueled by natural gas, the distributed renewable energy, and smart micro-grid systems.

Wind & solar & hydropower & gas & storage multi-energy complementary system: this system mainly presents the advantage of utilizing a comprehensive energy base, where wind power, solar power, hydropower, coal, and natural gas are combined to generate electricity. Moreover, it utilizes the ability of regulating the peak electricity load of cascade hydropower stations and thermal power plants that have flexible adjustment abilities. The integrated operation can enhance the stability of the power output, promote the accommodation of intermittent renewable energies, including wind and solar power, and enhance the overall benefits.

According to Table 1.2.5, countries that produce the highest number of core papers in "Research and optimization of hybrid renewable energy systems" are India, China, Iran, Greece, and Malaysia; the proportion of core papers in India, China, and Iran are more than 10%. From Table 1.2.6, it may be observed that the institutions with the highest number of core papers in this research field are the Hong Kong Polytech Univ, Univ Tehran, and the Univ Malaya, where the proportion of core papers in the Hong Kong Polytech Univ and the Univ Tehran is over 10%.

In Figure 1.2.3, it may be observed that Iran, Malaysia, Indonesia, and the US have placed greater focus on the collaboration with other countries and regions in this research field. Iran has a cooperative relationship with three countries, and has co-published several papers. China has large number of published papers as well, many of which are works that have been produced in collaboration with the USA. India has the highest number of published papers; however, scarce are in collaboration with other countries and regions.

According to Figure 1.2.4, Institutions that actively cooperate with other institutions are the Univ Tehran, the Univ Malaya, and the Univ Tenaga Nas, all of which have a cooperative relationship with each other; their respective number of published papers rank in the top 5 positions. Two Indian institutions maintain a cooperative relationship with each other. The Hong Kong Polytech Univ in Hong Kong of China, is the institution that has published the highest number of papers; however, it has not collaborated with other organizations.

In July, 2016, in order to accelerate the multi-energy complementary integrated optimization demonstration project, the National Development and Reform Commission and the National Energy Administration issued *Implementation suggestions on the promotion of the multi-energy complementary integrated optimization demonstration project*. This document aims to accelerate the construction of multi-energy complementary integrated optimization demonstration projects of renewable energy, so as to improve energy system efficiency, increase effective energy supply, meet reasonable demands, drive efficient investment, and promote stable economic growth.

There are two modes of integrated demonstration projects defined in the document: one is the terminal integrated system that is based on the electricity, heating, cooling, gas, and other energy needs of users; the other one is the wind & solar & hydropower & gas & storage multi-energy complementary system that has the advantage of utilizing a comprehensive energy base, where wind power, solar power, hydropower, coal, and natural gas are combined to generate electricity. The National Energy Administration announced as many as 23 first demonstration projects, including 17 projects of the first mode, and 6 projects of the second mode.

The development of the hybrid renewable energy system is important in the construction of the intelligent energy system of "Internet Plus", which is conducive to the improvement of the coordination ability of the renewable energy supply by promoting the utilization of renewable energies, reducing the waste of solar, wind, and hydropower owing to shortage in the accommodation ability of the power grid, and by enhancing the comprehensive

Table 1.2.5 Major producing countries or regions of core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	India	9	18.37%	119	9.92%	13.22	0	0
2	China	8	16.33%	329	27.42%	41.13	2	0
3	Iran	7	14.29%	175	14.58%	25.00	0	0
4	Greece	4	8.16%	124	10.33%	31.00	0	0
5	Malaysia	4	8.16%	123	10.25%	30.75	0	0
6	USA	4	8.16%	116	9.67%	29.00	1	0
7	Algeria	3	6.12%	81	6.75%	27.00	1	1
8	Canada	3	6.12%	79	6.58%	26.33	0	0
9	Indonesia	3	6.12%	75	6.25%	25.00	0	0
10	Korea	3	6.12%	46	3.83%	15.33	1	0

Table 1.2.6 Major producing institutions of core papers on the engineering research focus “Research and optimization of hybrid renewable energy systems”

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Hong Kong Polytech Univ	5	10.20%	221	18.42%	44.20	1	0
2	Univ Tehran	5	10.20%	136	11.33%	27.20	0	0
3	Univ Malaya	4	8.16%	123	10.25%	30.75	0	0
4	Indian Inst Technol	4	8.16%	35	2.92%	8.75	0	0
5	Univ Tenaga Nas	3	6.12%	110	9.17%	36.67	0	0
6	Natl Tech Univ Athens	3	6.12%	95	7.92%	31.67	0	0
7	Univ Washington	3	6.12%	60	5.00%	20.00	0	0
8	Indian Inst Technol Roorkee	3	6.12%	29	2.42%	9.67	0	0
9	Technol Educ Inst Crete	2	4.08%	60	5.00%	30.00	0	0
10	Norwegian Univ Life Sci	2	4.08%	56	4.67%	28.00	0	0

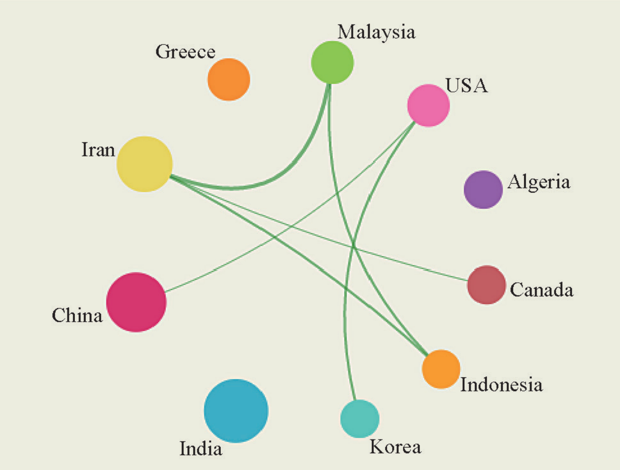

Figure 1.2.3 Collaboration network of the major producing countries or regions of core papers on the engineering research focus “Research and optimization of hybrid renewable energy systems”

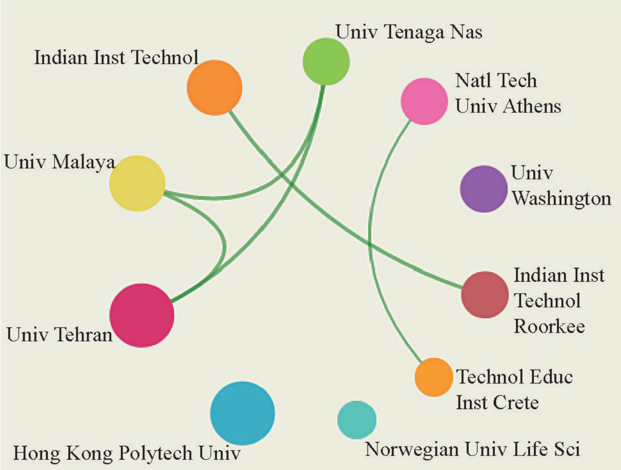

Figure 1.2.4 Collaboration network of the major producing institutions of core papers on the engineering research focus “Research and optimization of hybrid renewable energy systems”

efficiency of the energy system, which is of great significance in terms of facilitating the shift of the energy mix and the construction of a low-carbon and high-efficiency energy system. From the perspective of technological prowess and development trend, China is leveling with or advancing with the same pace as other players; however, its development is quicker than that of the vast majority of countries.

Certain suggestions for the development of the hybrid renewable energy system of China are the following. First, policy support should be enhanced, and efforts should be made to ensure that the implementation of the introduced policy is effective. Second, the energy pricing mechanism should be improved in a manner that reflects the technical advantages and comprehensive benefits of the multi-energy complementary integrated optimization project. Third, a corresponding power dispatch and a market trading mechanism should be established to support the operation of the multi- energy complementary system. Fourth, the standardization system should be improved, and the multi-energy complementary technology and the access to the electricity (gas) network should be standardized. Fifth, the supervision of the planning and the implementation of the major multi-energy integrated optimization demonstration projects should be strengthened. Sixth, a sector corresponding to the "Information Management System of Renewable Energy Power Project" should be set up to facilitate the project information entry, the project management, and the electricity subsidy declaration.

Table 1.2.7 shows that the countries with the largest output of citing core papers are India, Iran, and China; the proportion of citations for all three countries tops 10%. In Table 1.2.8, it may be observed that the institutions with the most output of citing core papers are the Hong Kong Polytech Univ, the Univ Tehran, and the India Inst Technol, among which the proportion of citing core papers of the Hong Kong Polytech Univ and the Univ Tehran exceeds 5%. It can be inferred that the research output and the citations of the core papers of China in this particular research field are at the forefront compared with other countries; however, most of the research output is produced from institutions located in Hong Kong, China. There is still a gap between the institutions of China's mainland and those of Hong Kong of China and foreign institutions in terms of the number of papers.

1.2.3 Flow, heat/mass transfer, and combustion under extreme conditions

(1) Concept elaboration

This engineering research focus contains four main branches, namely the evaporation and condensation, the boiling heat transfer, the heat transfer optimization, and the combustion. Harsh extreme conditions are involved in their practical applications, such as high temperature, high pressure, and high heat flux. Boiling, evaporation, and condensation are the main phenomena that take place in gas-liquid phase change processes, which can be observed in our daily life. Evaporation and condensation play a very important role in the thermal management of electronic devices, the desalination, and the combustion process. When the fuel droplets are injected into extreme environments—such as the internal combustion engines, where the temperature is high, and wall contact takes place —the phase transition processes could directly affect the efficiency of combustion. Boiling heat transfer demonstrates great potential in the fields of heat dissipation in electronic devices and spacecraft, with very high heat flux. Under the constraints of fixed heat exchange areas of heat exchangers (or heat sinks), heat transfer optimization aims to maximize heat transfer under conditions of high temperature, high pressure, ash and dust-laden settings, and high heat flux by changing types, structures, surfaces, and fluids of the heat exchanger (or heat sink). Heat transfer optimization has been widely used in the design of heat exchangers and the system optimization of industrial processes, such as waste heat utilization. As the major means to generate power at present, combustion is widely used in several applications, such as gas turbines, internal combustion engines, and industrial furnaces. As combustion processes directly determine the power output, stability, emission, and fuel conversion efficiency of the equipment, the primary goal of the research teams in this field is to

Table 1.2.7 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus "Research and optimization of hybrid renewable energy systems"

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	India	8	17.39%	2015.38
2	Iran	6	13.04%	2014.33
3	China	5	10.87%	2014.40
4	Indonesia	3	6.52%	2014.00
5	Malaysia	3	6.52%	2014.00
6	USA	2	4.35%	2014.50
7	Canada	2	4.35%	2014.00
8	Greece	2	4.35%	2013.00
9	Korea	2	4.35%	2014.50
10	Algeria	2	4.35%	2014.50

Table 1.2.8 Major producing institutions of core papers that are cited by core papers on the engineering research focus “Research and optimization of hybrid renewable energy systems”

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Hong Kong Polytech Univ	4	6.56%	2014.25
2	Univ Tehran	4	6.56%	2014.25
3	Indian Inst Technol	3	4.92%	2016.00
4	Univ Malaya	3	4.92%	2014.00
5	Grad Univ Adv Technol	2	3.28%	2015.00
6	Indian Inst Technol Roorkee	2	3.28%	2016.00
7	Natl Inst Technol	2	3.28%	2015.00
8	Syiah Kuala Univ	2	3.28%	2013.50
9	Univ Ontario	2	3.28%	2014.00
10	Univ Tenaga Nas	2	3.28%	2013.50

find a series of techniques to achieve a highly efficient, stable, and clean combustion process for a wide range of working conditions. As the basic unit affecting the macroscopic characteristics of combustion, micro-combustion is attracting growing attention.

(2) Key technologies to be explored, and developments in different countries

Evaporation and condensation are the processes of liquid vaporization and gas liquefaction, respectively. Understanding the mechanism of evaporation and condensation has become a research hotspot because these two phenomena are closely related to the combustion process. One of the main issues in this research subject is the experimental measurement and theoretical modeling of the evaporation rate under various operating conditions. The challenges arise from multi-component fluids, droplet deformation, the geometrical shape of the droplet, droplet-to-wall interaction, and temperature differences between the liquid and the gas. The research methods include the integration of theoretical models based on physical processes with computational fluid dynamics (CFD) calculations, as well as obtaining measurements through visualization methods, such as particle image velocimetry (PIV) and high-speed cameras. Future research fields may include the study of the condensation mechanism of droplets on the nano-surface, and the determination of the evaporation coefficient through molecular simulations and statistical mechanics. International research on evaporation and condensation is concentrated in Europe and Asia. European teams, including several teams in Russia and the UK as well, have conducted some research on the evaporation of droplets. Asian researchers, such as China’s and Pakistani scholars, focus on the direct contact condensation.

Boiling heat transfer refers to the heat transfer between the liquid and the heating surface, when the temperature of solid wall exceeds the liquid saturation temperature; it is highly efficient because the generated bubbles remove a significant amount of heat through vaporization. By changing the morphologies and wettability of the solid heat transfer surface, and by changing the liquid properties via the addition of nanoparticles and surfactant, the heat transfer coefficient and critical heat flux can be increased, thus meeting the heat dissipation needs of high heat flux electronic devices and spacecraft, which has become a trend in the research on boiling heat transfer. In China, the studies on boiling heat transfer are mainly conducted experimentally, and numerical simulations are conducted as well. Experimental studies in China focus on changing fluid properties (adding nanoparticles and surfactant) and the morphology of the heat transfer surface, whereas numerical simulations place emphasis on the simulation of bubble growth and spatial distribution by means of lattice Boltzmann method (LBM). In China, Tsinghua University, Shanghai Jiao Tong University, Xi’an Jiao Tong University, the North China Electric Power University, and the Institute of Engineering Thermophysics (Chinese Academy of Sciences) are the major institutions where studies on boiling heat transfer have been conducted. In South Korea, the studies on boiling heat transfer focus on understanding the mechanism of boiling heat transfer through experimental methods. In Japan, Kyoto University and Tokyo University have conducted extensive studies on boiling heat transfer. In the USA, the studies on boiling heat transfer focus on pool boiling and boiling in narrow gaps. Purdue University, the Massachusetts Institute of Technology (MIT), and Stanford University have made significant contributions.

In terms of heat transfer optimization, several basic theories have been proposed in recent decades: finite-time thermodynamics, entropy generation minimization theory, constructal theory, entransy theory, and the field synergy principle. Because there are numerous fin structures on the surface of heat exchangers, and because convective heat transfer is involved, the development of related basic theories to guide the heat transfer optimization under extreme conditions is the focus of contemporary research. The aforementioned heat transfer optimization methods have been widely used in applications in the iron and steel industry, in waste heat recovery, in heat-work conversion, and in the optimization of heat exchangers. In China, studies are focused on the development of the entransy dissipation extremum theory and the field synergy principle, as well as the combination of the entransy dissipation theory and the constructal theory. In USA and Europe, the main focus is on the entropy generation minimization theory and the constructal theory.

Combustion is a complex process, with a series of chain reactions combined on a series of microscale levels. Even slight changes in the physical or chemical process would accumulate and influence the macro characteristics of combustion. The study of the differences in combustion characteristics under various conditions, and revealing the mechanism of micro-combustion have become one of the focal interests in engineering studies both at home and abroad. In recent decades, the studies on the characteristics and mechanisms of microscale combustion have been enhanced owing to the rapid development of non-contact optical methods and to advances in CFD simulation. Meanwhile, the theoretical system of microscale combustion has been improved based on experimental and simulation studies. At present, research subjects include micro-droplets (representing the liquid fuel), coal particles (representing the solid fuel), and the coal water slurry (representing the liquid-solid fuel). The research process includes droplet breakup of secondary atomization of liquid fuel, evaporation of suspended or surface droplets, the mixture with surrounding air, the ignition, and the combustion process. The experimental methods include high-speed imaging, PIV, and laser induced fluorescence (LIF), whereas simulation studies establish accurate models of different processes based on self-developed software. Up to present, papers related to micro-combustion mainly originate from Asia and Europe. China and Russia have significantly contributed to experimental research, whereas the UK, Finland, and Iran focus on simulation studies.

(3) Current development status and future trends

Form the viewpoint of evaporation and condensation, different research teams have studied specific problems due to a number of factors involved in these phenomena, including gas-liquid temperature difference, gas flow, droplet deformation, and droplet-to-wall interaction. At present, the main research methods include visual experiments and numerical calculations. In the visual experiments, high-speed cameras, which directly observes the phase change processes, is widely used; this satisfies the need to study the mass transfer process from the macroscopic angle. Furthermore, the fluid motion inside the particles can be measured using PIV techniques. The thermogravity and thermocapillary convection during the process of droplet settling to the surface was investigated through a laser shade technique. The thermal phenomenon of the droplets was measured using a noncontact far-infrared thermal imaging technique. In the numerical calculations, one challenge is to consider a two-phase flow. The Euler two-phase, Euler-Lagrangian, and other methods are usually employed. For multicomponent fluids, the discrete multicomponent model is used when the number of components is small, while the distillation curve model and continuous thermodynamics method are used for cases in which a large number of components are involved. Future research directions include the precise determination of the evaporation/condensation rate, which directly affects the basic combustion mechanisms. In terms of theoretical modeling, possible approaches include molecular dynamics calculations and statistical mechanics modeling. In the measurement, change in the mass flux could be obtained by measuring the movement of the contact line through PIV. With all this information, the local evaporation/condensation rate can be obtained. Moreover, the local evaporation coefficient of the local heat flux can be measured using an infrared camera. In addition, it is desirable to allow the prompt removal of the droplets from the wall to enhance heat transfer in droplet condensation. Researchers have prepared nanostructured super-hydrophobic surfaces, where the adhesion is low and droplets are more likely to bounce. Such surfaces could enhance heat transfer to some extent. However, the further optimization of the wall performance still remains a long-term topic for discussion.

In the field of boiling heat transfer, the main focus is on bubble dynamics in liquid and porous media, and the effects of wettability and morphology on bubble departure and heat transfer coefficient. Experiments in this field usually employ infrared thermal imaging instruments and a high-speed camera to reveal the temperature and flow-field information, while LBM is commonly used in numerical studies. Most of the current research is experimental rather than theoretical. With the development of aerospace and electronics industries, the heat flux values of spacecraft and electronic devices are increasing, and there has been a shift from the study of macro heat/mass transfer to that of microscale boiling heat transfer mechanisms, which are attracting increasing attention. Furthermore, the application of boiling heat transfer to industrial practices and development of highly efficient heat exchanger products are considered as an important trend.

In terms of heat transfer optimization, several theories have been developed to satisfy the requirements of practical engineering applications. Finite time thermodynamics combines thermodynamics, heat transfer, and fluid dynamics to optimize the practical processes and devices in limited time and size. Constructal theory, regarded as the thermodynamics for nonequilibrium constructal problems in thermal science, provides the theoretical basis of the explanation of the generation and design of flow structures. The entropy-generation minimization theory is applied in the analysis and optimization of heat exchanger performances. However, an entropy production paradox indicates that results obtained from the entropy-generation minimization method are not optimal. In this regard, various modified objectives were defined to address the entropy production paradox. To reveal the nature of heat transfer, Guo et al. proposed a new physical quantity called entransy, which describes the total heat transfer ability. Based on the entransy concept, the principle of entransy dissipation extremum has been established, which not only provides a new direction for heat transfer optimization, but also successfully addresses the limitations and uncertainty of thermal resistance analysis and entropy-generation minimization theory. The combination of the various heat-transfer optimization methods is a trend for future research.

In terms of microcombustion, there are plenty of influencing factors, including the physical properties of fuel, fuel components, ambient pressure/temperature, air flow, droplet structure, and droplet-wall interaction. Here, visualization experiments and numerical simulations are the primary research methods. High-speed photomicrography is widely applied to observe and analyze the variation in droplets on a microscale process. The influence of flow field and the concentration and mixing characteristics on microscale combustion could be investigated based on PIV and LIF techniques, respectively. For the viewpoint of simulating actual working conditions, various self-developed simulation methods have been employed and detailed simulation models have been used to predict the characteristics of microcombustion, including evaporation and combustion. Moreover, the comparisons between experimental and numerical results have been conducted to improve the accuracy of simulation models. Researchers from China and Russia have made outstanding contributions in experimental research, among which China's Xi'an Jiao Tong Univ and Russia's Tomsk Polytech Univ played a leading role. In addition, Europe and Asia achieved a remarkable progress in simulation studies, among which the England's University Brighton, Finland's Lappeenranta Univ Technol, and Iran Univ Sci & Technol played a vital role; until now, they have preliminarily established the evaporation and combustion model of droplets on the microscale level.

(4) Comparisons of major research countries or regions and institutions and their collaborations

Table 1.2.9 shows that China, Iran, and USA rank as the top 3 in terms of the number and proportion of core papers, citation frequency, proportion of citation frequency, and number of consistently cited papers. The statistical data indicate that these three countries have greater research prowess and input; the demand in this research field is also very strong. Note that the average citation frequency for the papers from China is only 16.08, pushing it behind the top 10 countries, among which Japan, USA, and Singapore are the top 3. This indicates that although China has conducted a large amount of research, the quality should be improved further. Figure 1.2.5

shows that USA has collaborated with many countries, including China, Iran, Malaysia, Korea, England, Japan, and India. China also shows strong collaborations with other countries, especially with Singapore. Strong connections also exist between Iran and Malaysia.

Table 1.2.10 shows that Univ Malaya, Nanyang Technol Univ in Singapore, Ferdowsi Univ Mashhad in Iran, PLA Naval Univ Engn in China, and Huazhong Univ Sci & Technol in China are very close in terms of the number of core papers. Nanyang Technol Univ in Singapore shows better performance in the number, proportion, and average citation frequency. In terms of the number of consistently cited papers, the PLA Naval Univ Engn and Huazhong Univ Sci & Technol in Wuhan, China stand out. These two universities and Xi'an Jiao Tong Univ in China account for 67% of the number of consistently cited papers; this shows their strong ability in the research field. Figure 1.2.6 shows that intensive collaborations have been established among Ferdowsi Univ Mashhad of Iran, Univ Malaya, and Islamic Azad Univ. Strong connections can also be observed between Shanghai Jiao Tong Univ and Nanyang Technol Univ, as well as between Tomsk Polytech Univ and Natl Res Tomsk Polytech Univ.

The main researchers for condensation and evaporation hail from Russia, UK, China, and some other countries. In addition, intensive collaborations exist between Russian

Table 1.2.9 Major producing countries or regions of core papers on the engineering research focus "Flow, heat/mass transfer, and combustion under extreme conditions"

No.	Country/Region	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	China	83	39.15%	1335	31.21%	16.08	14	0
2	Iran	37	17.45%	808	18.89%	21.84	7	0
3	USA	36	16.98%	1076	25.15%	29.89	5	1
4	Singapore	20	9.43%	458	10.71%	22.90	2	0
5	Malaysia	20	9.43%	347	8.11%	17.35	0	0
6	Korea	16	7.55%	282	6.59%	17.63	1	0
7	Russia	16	7.55%	262	6.12%	16.38	1	1
8	England	8	3.77%	170	3.97%	21.25	0	1
9	Japan	7	3.30%	385	9.00%	55.00	1	0
10	India	7	3.30%	160	3.74%	22.86	2	0

Table 1.2.10 Major producing institutions of core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

No.	Institution	Core papers	Proportion of core papers	Citation frequency	Proportion of citation frequency	Average citation frequency	Number of consistently cited papers	Patent-cited publications
1	Univ Malaya	17	8.02%	296	6.92%	17.41	0	0
2	Nanyang Technol Univ	16	7.55%	322	7.53%	20.13	1	0
3	Ferdowsi Univ Mashhad	16	7.55%	257	6.01%	16.06	1	0
4	Naval Univ Engn	16	7.55%	214	5.00%	13.38	3	0
5	Huazhong Univ Sci & Technol	14	6.60%	262	6.12%	18.71	4	0
6	Islamic Azad Univ	12	5.66%	285	6.66%	23.75	2	0
7	Shanghai Jiao Tong Univ	12	5.66%	228	5.33%	19.00	1	0
8	Xi'an Jiaotong Univ	10	4.72%	167	3.90%	16.70	3	0
9	Tomsk Polytech Univ	10	4.72%	139	3.25%	13.90	0	0
10	Natl Res Tomsk Polytech Univ	9	4.25%	133	3.11%	14.78	0	0

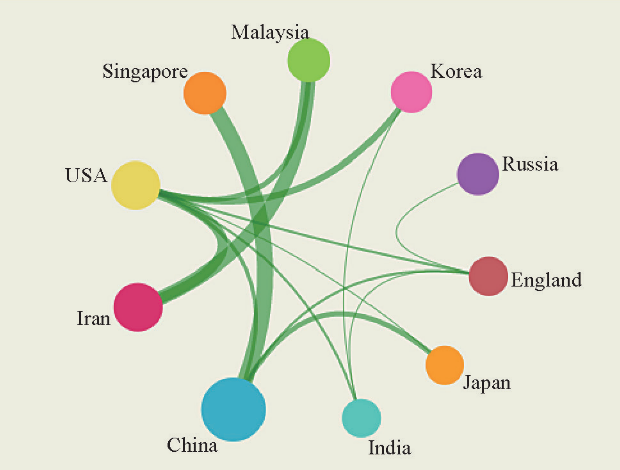

Figure 1.2.5 Collaboration network of the major producing countries or regions of core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

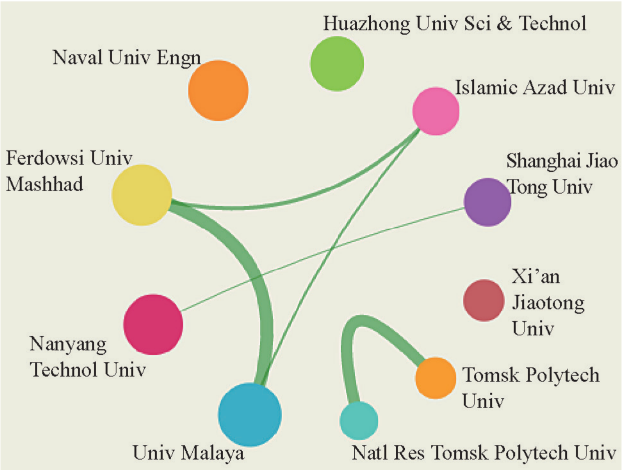

Figure 1.2.6 Collaboration network of the major producing institutions of core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions"

scholars and those from other European countries. However, researchers from USA are not active in this branch. In the field of boiling heat transfer, China, Japan, Korea, and USA comprise many scholars, while Malaysia and India do not have as many. Moreover, extensive collaborations exist between Korea and USA. In the field of heat transfer optimization, constructal theory was proposed by Professor Bejan from Duke University. This theory has been widely employed in USA, Europe, and Iran. Entransy dissipation theory was proposed by Professor Guo from Tsinghua University; it is mostly studied in China and has recently gained attention in other counties. In terms of combustion, Europe still leads in the number of studies on liquid fuel at the microscale level; nevertheless, several research teams in China have also conducted in-depth study in this field in recent years. In addition, China, Iran, and Russia are the major countries studying liquid–solid fuels, such as coal–water fuel, at the microscale level. Most of the international collaborations are in Asia, where China has a strong cooperative relationship with Singapore.

In the study of evaporation and condensation, China's scholars, such as those from Xi'an Jiao Tong University and Beijing University of Chemical Technology, have conducted several experimental and theoretical research on direct condensation, which is at the leading level. However, research on droplet evaporation is rare and requires more attention. Study on the branch of boiling heat transfer is mainly focused upon at the experimental level in China, seeking the enhancement of the coefficient of heat transfer. In recent years, some scholars in Tsinghua University, Shanghai Jiao Tong University, Xi'an Jiao Tong University, and the Institute of Engineering Thermophysics (Chinese Academy of Sciences) have made great progresses in this field. They adopted the LBM method to build liquid-vapor phase change models and explored the mechanism of phase-change heat transfer from the theoretical perspective. China's scholars play the leading role in this field, and have suggested further theoretical studies. In the field of heat transfer optimization, some optimization concepts, such as entropy, were introduced from overseas. By contrast, entransy dissipation theory proposed by Professor Guo is at the cutting edge of this field. The entransy dissipation and construtal theories form the basis of the new optimization theory for heat transfer. In terms of combustion, China has many years of an intellectual convention of solid and liquid-solid fuels at the microscale level; and the extensive research results prove that China belongs in the leading team in this area. From the viewpoint of liquid fuels, China lags the leading countries; however, it is catching up and seeking to become a leader in this field as well.

The statistical data in Table 1.2.11 shows that China, Iran, and USA rank the top 3 in citing the core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme conditions." Furthermore, as shown in Table 1.2.12, the top 3 institutions citing the core papers on the engineering research focus "Flow, heat/mass transfer and combustion under extreme condi-

Table 1.2.11 Major producing countries or regions of core papers that are cited by core papers on the engineering research focus “Flow, heat/mass transfer and combustion under extreme conditions”

No.	Country/Region	Number of core papers cited by core papers	Proportion	Mean year
1	China	62	30.69%	2014.90
2	Iran	33	16.34%	2014.61
3	USA	22	10.89%	2014.23
4	Malaysia	22	10.89%	2014.73
5	Singapore	17	8.42%	2014.59
6	Russia	10	4.95%	2014.90
7	Korea	8	3.96%	2014.00
8	England	4	1.98%	2014.00
9	Finland	3	1.49%	2014.00
10	Japan	3	1.49%	2012.67

Table 1.2.12 Major producing institutions of core papers that are cited by core papers on the engineering research focus “Flow, heat/mass transfer and combustion under extreme conditions”

No.	Institution	Number of core papers cited by core papers	Proportion	Mean year
1	Univ Malaya	19	7.17%	2014.79
2	Nanyang Technol Univ	15	5.66%	2014.67
3	Huazhong Univ Sci & Technol	14	5.28%	2014.64
4	Ferdowsi Univ Mashhad	14	5.28%	2015.07
5	Islamic Azad Univ	12	4.53%	2014.33
6	Naval Univ Engn	10	3.77%	2015.30
7	Amirkabir Univ Technol	8	3.02%	2013.75
8	Shanghai Jiao Tong Univ	8	3.02%	2014.38
9	Xi’an Jiaotong Univ	8	3.02%	2014.88
10	Natl Res Tomsk Polytech Univ	7	2.64%	2015.43

tions” include Univ Malaya, Nanyang Technol Univ, and Huazhong Univ Science & Technol.

2 Engineering development hotspots and engineering development focus

2.1 Development trends of engineering development hotspots

The top 12 engineering development hotspots in energy and mining engineering research are listed in Table 2.1.1. These 12 hotspots include a number of research directions in energy and electrical (science, technology, and engineering), geological resources (science, technology, and engineering), mining (science, technology, and engineering), and nuclear (science, technology, and engineering). Among them are five emerging hotspots: “Electric vehicle battery (structure, material, efficiency, and thermal management system),” “New fracturing methods, fluids, proppants, and additives,” “Geological modeling and simulation based on fracturing and rock characteristic parameters,” “Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application),” and “Biomass conversion and biofuel preparation.” At the same time, some traditional research directions have been further expanded, including “Equipment and technology for deepwater oil and gas development,” “Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment,” and “Transfor-

Table 2.1.1 Top 12 engineering development hotspots in energy and mining engineering

No.	Engineering development hotspots	Published patents	Citation frequency	Average citation frequency	Mean year
1	Electric vehicle battery (structure, material, efficiency, and thermal management system)	696	12 707	18.26	2011.89
2	Equipment and technology for deepwater oil and gas development	162	1 382	8.53	2012.25
3	New fracturing methods, fluids, proppants, and additives	481	4 348	9.04	2012.49
4	Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment	304	780	2.57	2012.43
5	Transformation and utilization of non-traditional fossil and carbon resources	397	4 348	10.95	2012.07
6	Exploitation of symbiosis/associated energy and technology of smart drilling equipment kits	1 036	8 379	8.09	2012.44
7	Research and development of key technologies for advanced hybrid vehicle engines	427	6 097	14.28	2012.07
8	Geological modeling and simulation based on fracturing and rock characteristic parameters	56	326	5.82	2012.61
9	Research on polymers used in the cable sheath layer in extreme conditions	110	1 570	14.27	2012.89
10	Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)	240	4 322	18.01	2012.00
11	Biomass conversion and biofuel preparation	254	4 656	18.33	2012.15
12	Assembly, monitoring, and control of wind turbines	106	1 561	14.73	2011.55

Table 2.1.2 Annual number of published core patents belong to each of the top 12 engineering development hotspots in energy and mining engineering

No.	Engineering development hotspots	2011	2012	2013	2014	2015	2016
1	Electric vehicle battery (structure, material, efficiency, and thermal management system)	329	196	116	34	14	7
2	Equipment and technology for deepwater oil and gas development	50	58	31	13	6	4
3	New fracturing methods, fluids, proppants, and additives	114	151	118	70	19	9
4	Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment	81	77	93	41	10	2
5	Transformation and utilization of non-traditional fossil and carbon resources	151	127	84	22	3	10
6	Exploitation of symbiosis/associated energy and technology of smart drilling equipment kits	278	300	265	125	52	16
7	Research and development of key technologies for advanced hybrid vehicle engines	187	116	56	48	17	3
8	Geological modeling and simulation based on fracturing and rock characteristic parameters	11	16	15	12	2	0
9	Research on polymers used in the cable sheath layer in extreme conditions	21	26	22	27	13	1
10	Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)	106	61	49	16	6	2
11	Biomass conversion and biofuel preparation	98	70	40	42	3	1
12	Assembly, monitoring, and control of wind turbines	69	21	12	3	1	0

mation and utilization of non-traditional fossil and carbon resources." Table 2.1.2 shows the number of published patents related to each hotspot from 2011 to 2016.

(1) Electric vehicle battery (structure, material, efficiency, and thermal management system)

As the central part of an electric vehicle (EV), batteries would significantly influence the mileage, safety, and cost of the vehicle. It is necessary to focus on the key technical problems of electric vehicle batteries: energy density, safety, environment adaptability under low and high temperature, durability, charging speed, and development of low-cost advanced rechargeable batteries, battery pack and its management. A new generation of rechargeable batteries may be developed including by nano lithium battery, lithium-air battery, lithium-sulfur battery, graphene-assisted Li-ion battery, multielement lithium-ion battery, solid-state battery, and flow battery. Battery packs with high efficiency and performance can be produced by the development of several methods and technologies, including the design optimization of thermo-mechanical-electric multi-field coupling structures, the smart evaluation and testing of multi-target dynamic/static consistency, the application of light but hard materials and lightweight structures, battery modularization, intelligent manufacturing, and robot disassembly and assembly. Concerning thermal management, active or passive thermal management of external cooling, heating (also by electric heating) or constant temperature control can be realized through diverse methods: heat transfer by a single medium such as air, liquid, and phase-change materials or composite media, heating by external current pulse excitation or built-in heating circuits, internal thermal management of the battery cell using the battery's own heat, as well as an integral thermal-management system that involves both the battery and vehicle. Finally, safety, efficiency, reliability, and durability of the batteries in the application of electric vehicles can be improved through battery condition estimation, service life prediction, fault diagnosis and prediction, charging optimization management, intelligent balancing control, and vehicle-battery dynamic coordination control by modeling, and control-oriented electrochemical modeling in particular.

(2) Equipment and technology for deepwater oil and gas development

China has rich marine oil and gas resources to be explored and exploited. Statistics have shown that South China Sea has 23 billion–30 billion tons of geological oil reserves, and 16 trillion cubic meters of natural gas reserves, of which 70% is located in deepwater. In this sense, it is essential to develop China's deepwater oil and gas resources fully. Deepwater oil and gas development has several features: expensive investment cost, complicated technologies, high risks, and high returns. The exploitation difficulty and investment cost will also increase exponentially as the depth increases. Having focused on promoting deepwater oil and gas exploitation, China has benefited from the dual modes of independent research and development and international collaboration, and has made great achievements in the equipment and technology of deepwater oil and gas development, including deepwater oil and gas development floating structures, underwater intelligent robots, deepwater drilling blowout preventers (BOP), seabed isolation valves and safety valves, vertical single-channel production tree systems, and underwater pressurization and processing equipment. At the same time, various technologies have been applied in deepwater oil and gas exploitation, such as intelligent automation, remote control, underground monitoring, pipe design, and control. Among them, the intelligent and fully automatic underwater production system, submarine remote control through radio frequency identification, multi-functional monitoring technology, and robotic deepwater monitoring technology are good examples.

(3) New fracturing methods, fluids, proppants, and additives

There are also rich non-traditional oil and gas resources in China, such as shale gas coal bed methane (CBM), and tight gas, and the exploration and development potential is huge. For example, China's shale gas resources amount to 36.1 trillion cubic meters, ranking the first in the world. However, non-traditional oil and gas reservoirs have the characteristics of low pressure, low porosity, low permeability, and low production yield. Therefore, the reservoir fracturing technology plays a critical role in the commercialization of non-traditional oil and gas development. However, traditional hydraulic fracturing is not applicable to the development of non-traditional oil and gas owing to its high cost and poor technological adaptability. In this context, infinite-stage fracturing, directional hydraulic perforation fracturing technology, steering fracturing, repetitive fracturing, and other new fracturing technologies came into being. Anhydrous, clean, and efficient fracturing technologies as represented by CO_2, N_2, and liquefied petroleum gas (LPG) have also been developed rapidly. For example, the technology of CO_2 (or supercritical CO_2) fracturing, if integrated with CO_2 capture, reservoir displacement, CO_2 storage, and other technologies, can achieve the comprehensive utilization of the greenhouse gas CO_2. These new fracturing technologies play a significant role in the control of fracture trends, the scale of fracture, as well as efficiency. In addition, technologies of new fracturing fluids, proppants, and related additives are developing rapidly, and a large number of new materials have been developed, applicable for different reservoirs. For example, in recent years, the popular nanomaterials have been widely used in the development of fracturing fluids, proppants and additives, such as drag-reduction agents and controllable electrolytic metal (CEM) fracturing balls.

(4) Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment

Reactor fuel assembly is an important component of the reactor core, and the major place for chain fission reaction and radioactive fission products. The working condition of fuel assembly is very harsh, for it stays in the strong neutron field and withstands high temperature, high pressure, the rapid scouring of coolant, as well as the chemical reactions of fission products and complicated mechanical load. Also, the development of advanced fuel components would contribute to the development of advanced reactor technologies. The most popular hotspots in current research include cladding materials for fuel elements, defect monitoring of fuel assemblies, corrosion, thermal margin improvement, and the use of combustible toxicants.

Nuclear power plants have mainly three categories of equipment: nuclear island equipment, conventional island equipment, and auxiliary system. Nuclear island equipment, the main location for thermonuclear reaction, is technically complicated and has the highest requirement for safety design, especially the primary-circuit pressure boundary equipment that includes the pressure vessel, evaporator, voltage regulator, nuclear-grade pump, nuclear-grade valve, nuclear-grade container, and pipelines. Current research focuses on the nuclear power equipment's reliability, security, integrity, etc., and involves many aspects of the problem including fatigue, creep, corrosion, earthquake, shock tests, radiation, lost of coolant accident (LOCA), and standardization.

(5) Transformation and utilization of non-traditional fossil and carbon resources

Traditional fossil and carbon resources (including coal, petroleum, and natural gas) are the raw materials for energy and manufacturing, thus serving as the fundamental driving force of a society. However, such resources not only brings severe environmental problems, but will also be depleted someday. As supplements to such resources, non-traditional fossil and carbon resources can help in relieving the problem of environmental pollution and achieve development sustainability. Such non-traditional resources include biomass, shale oil, shale gas, oil sands, flammable ice, crop, household waste, and CO_2, etc. It is possible to obtain products such as syngas, methane, biodiesel, and oxygenated chemicals through pyrolysis, gasification, hydrolysis, combustion, and other transformation methods, in which catalysis, thermochemical and biochemical mechanisms, and engineering issues are involved.

(6) Exploitation of symbiosis/associated energy and technology of smart drilling equipment kits

Smart drilling equipment can significantly reduce drilling costs, speed up drilling, and reduce the number of accidents. With the assistance of underground smart drilling tools, smart drilling can acquire real-time information on downhole fluid, rock condition, tool features, and other parameters through the underground closed-loop system to calculate the well path, tool azimuth angle, reservoir location, calculate results, and then report the results for real-time parameter adjustment. Representative technologies include rotary steering drilling system, geosteering drilling system, and automated vertical drilling system. Besides, smart drill bits, pipe drilling, and other underground tools and technologies can also further improve the drilling accuracy and reduce drilling costs.

(7) Research and development of key technologies for advanced hybrid vehicle engines

Hybrid vehicles can be divided into three categories according to their power transmission routes: tandem vehicle, parallel vehicle, and mixed vehicle. Among them, parallel and mixed vehicles are both equipped with two sets of power systems (engine drive system and electric motor system) which apply a specific power coupling strategy to power the vehicle. At the same time, the electric motor system can achieve the following functions: prevent the engine from idle speed, reduce or avoid operating in conditions of low load and low efficiency by adjusting the engine working status, and recycle braking energy to improve the power system's fuel utilization rate. A hybrid engine can not only drive the vehicle but also charge the battery so that the vehicle's driving distance will not be limited by the battery capacity. To promote the R&D of engines exclusively for hybrid vehicles, it is important to develop the Atkinson cycle regenerative combustion system, engine control strategy, optimization of engine operation with multiple parameters and objectives, vehicle matching, power battery and its management system, and to reduce the energy loss in accessory systems.

(8) Geological modeling and simulation based on fracturing and rock characteristic parameters

Geological modeling can be used to give a general assessment of the oil reservoirs. When applying the geological model for accurate oil production, it is necessary to make full use of geological parameters. At present, various modeling methods have been employed, including facies-controlled modeling based on geo-statistical inversion and reservoir classification, 3D geological modeling based on multi-dimensional geological information, quantitative reservoir description based on multiple geophysical technologies, etc. Furthermore, new geological modeling based on fracturing and rock characteristic parameters has also played a positive role, for example, advanced 3D geological modeling based on 3D laser scanning technology and terrain and geological modeling based on HPIM technology.

(9) Research on polymers used in the cable sheath layer in extreme conditions

Concerning "Cable, Layer, Conductor" (as frequently mentioned in patent publications), current research has paid close attention to the composite materials used in cable sheath layers. Such cables are mainly used in extreme conditions, e.g., power cable on ships or marine platforms, DC transmission cables that require higher insulativity, cables in aircraft and spaceship, cables for artificial lifting equipment and drilling equipment, and cables used for vehicle control. Ten properties of such cables have been improved: waterproofness, heat resistance, insulativity, fire retardance, damp proofing and corrosion protection, thermoplasticity, low volatility, weatherproofness, freezing resistance, and high stretchability. Materials for cable coating are mainly polymers, but aluminum, cuprum, and resin have also been employed for this purpose.

(10) Crystalline silicon solar cells (including limiting light, passivation, new structure, PV module installation, and its application)

Crystalline silicon solar cells have been and will be the mainstream product in the PV market in the next decade (their market share was 93% in 2015 and 95% in 2016). Focus points in the current PV industry are the application of limiting light and passivation technology in silicon solar cells, and the development of novel structures, including back-contact and heterojunction. For PV modules, research has focused on developing new cleansing methods, installation technologies, as well as the development of large-scale PV power stations.

(11) Biomass conversion and biofuel production

Biomass is widely distributed, storable, and transportable, and it is the only renewable carbon resource. Biomass conversion refers to the biochemical and thermochemical processes in which biomass materials are transformed into solid, liquid, or gaseous fuels and chemical products. Biofuels are high quality energy and can be widely applied. Biofuels production is a hot research topic nowadays, in which a variety of hotspots have been discussed, e.g., the improvement of the reaction mechanism through the reaction process, atmosphere, catalyst, and other factors, and the development of clean and efficient production technologies such as biodegradation, torrefaction, pyrolysis, gasification, and refinery.

(12) Assembly, monitoring, and control of wind turbines

Increasing number of wind turbines are being built with the rapid development of new energies. The assembly of wind turbines remains a frequently discussed issue, and hotspots include rotor blades' tip, the lifting tower of lifting and falling devices, the joining parts of tower bases, transporting component, and automatic sensing system. For offshore wind turbines, research is mainly focused on the offshore/submarine operating platform, and on how to reduce water oscillation. To achieve the optimal operation, real-time data should be used to control the output power of wind turbines and to measure the wind speed, blade revolving speed, and other factors. In future studies, hybrid power systems may attract more attention, e.g., a power generation system that combines wind turbines and solar cells.

2.2 Understanding of engineering development focus

2.2.1 Electric vehicle battery (structure, material, efficiency, and thermal management system)

(1) Background of electric vehicle batteries

For their features of “zero pollutants emission” and “battery-driven”, EVs have been seen as a promising alternative to traditional internal combustion engine vehicles, and a major solution to the exhaust pollution problem caused by gasoline-powered automobiles. To date, hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV), and fuel cell electric vehicle (FCEV) have been the four most well-developed types of EVs. To promote the development and application of EVs, it is important to solve three problems: to accelerate the development of electric vehicle batteries that are affordable and perform well, to build up sufficient number of battery swap stations and/or hydrogen refueling stations, and to establish a supply chain of adequate raw materials.

Electric vehicle batteries are exclusively used in new energy vehicles, and have two categories in general—advanced secondary batteries and fuel cells. Fuel cells are beyond the scope of the discussion here since they are closely related to the utilization of hydrogen energy. Thus, in this chapter, electric vehicle batteries refer specifically to advanced secondary batteries or power batteries.

In this chapter, we focus on engineering technologies of the electric vehicle battery, including materials development, structural design and production, battery measurement, battery pack, battery management system, and power system integration.

(2) Structure and material of advanced secondary batteries

Advanced secondary batteries can be charged or discharged via redox reactions at their anodes and cathodes. According to the chemical components, there are several different types of secondary batteries, e.g., nickel-metal hydride (NiMH) battery, lithium-ion battery (LIB), lithium-sulfur battery, etc. In the 1990s, NiMH battery, an environment-friendly battery, drew much attention internationally, and numerous studies have been conducted on it since then. Japan’s Toyota Motor Corporation has developed the technology for NiMH battery to a mature level, and applied it to their non-plug-in hybrid electrical vehicle, as represented by their PRIUS automobile whose market sales have exceeded one million.

LIB has become the most promising research direction for EV battery development mainly for its safety, durability, high energy density, and affordability. The cathode of the LIB is made of graphite, while lithium manganese oxide, lithium iron phosphate, and $LiNi_xMn_yCo_{1-x-y}O_2$ (NMC) are the most commonly used anode materials. At present, lithium iron phosphate and NMC account for over 90% of the EV batteries market. In particular, lithium iron phosphate has dominated the EV batteries market of China, USA, and Germany for its safety, durability, and affordability, while NMC has started to attract people’s attention for its high energy density. In China, USA, and Japan, automobile manufacturers have promoted the NMC application in their production. However, the widespread commercialization of NMC may be limited due to its potential safety risk, as well as the high cost and availability of Co as one of its raw material. For HEVs, batteries that could provide high power will be preferred, while for BEVs, batteries with high energy densities will be preferred. Nowadays, China, Japan, and Korea are the three major countries manufacturing LIBs for EVs.

The pressing problem with lithium-iron-phosphate batteries is the realization of higher energy densities in them. One possible solution would be to use manganese-lithium-iron-phosphate as the cathode and silicon as the anode, and to add a proper electrolyte so that its energy density can reach up to 180 $\mathrm{Wh \cdot kg^{-1}}$, making it possible for EVs to go for a longer endurance mileage. In light of NMC batteries, the problems of safety and system stability are more urgent to deal with.

It is the goal of future studies to further increase energy densities of single batteries and battery packs to 300 and 260 $\mathrm{Wh \cdot kg^{-1}}$, respectively. Besides, it is important to conduct research on and develop nickel NMC materials or high-voltage cathode materials, silicon anode materials with high energy density, as well as their matching electrolytes. At the same time, all solid-state LIB, lithium-sulfur battery, and lithium-air battery remain alternatives for EVs.

(3) Power battery measurement and powerplant management information system (PMIS)

Current researches have also focused on the technology of accurate battery measurement and battery management system (BMS). The technology of accurate battery measurement includes state of charge (SOC), state of health

(SOH), state of power (SOP), battery internal resistance, and other parameters. In order to achieve this and to further promote the development of BMS and power control systems, it is critical to build an estimation model for SOC and SOH and to develop its matching computational methods, which have been the focus of many international EV battery patents.

Other critical technologies for the application of EVs are battery packing and system integration, including battery selection, battery packing, system electric and thermal management etc. Battery packing and system integration have been widely recognized among EV manufacturers as the core technologies for the combustion engines of traditional fossil fuel vehicles. Furthermore, automotive electronic technology related to system integration is crucial to realize the automatic and intelligent operation and control of EVs.

Tables 2.2.1 and 2.2.2 show that the majority of core patents on EV batteries have originated from USA, Japan, China, Korea, and Germany, and, among all the institutions, automobile manufacturers have accounted for most of the patents. Among the manufacturers, Toyota, Ford, and GM have obtained the most number of patents, followed by Tesla, Mazda, and Mitsubishi. With regard to

Table 2.2.1 Major producing countries or regions of core patents on the engineering development focus “Electric vehicle battery (structure, material, efficiency, and thermal management system)”

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	273	39.22%	6575	51.74%	24.08
2	Japan	203	29.17%	2815	22.15%	13.87
3	China	79	11.35%	1420	11.17%	17.97
4	Korea	70	10.06%	778	6.12%	11.11
5	Germany	56	8.05%	839	6.60%	14.98
6	France	8	1.15%	63	0.50%	7.88
7	Switzerland	6	0.86%	140	1.10%	23.33
8	Taiwan of China	6	0.86%	115	0.91%	19.17
9	Canada	5	0.72%	40	0.31%	8.00
10	Israel	5	0.72%	131	1.03%	26.20

Table 2.2.2 Major producing institutions of core patents on the engineering development focus “Electric vehicle battery (structure, material, efficiency, and thermal management system)”

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	TOYT	45	6.47%	600	4.72%	13.33
2	FORD	40	5.75%	801	6.30%	20.02
3	GENK	35	5.03%	472	3.71%	13.49
4	SAOL	35	5.03%	503	3.96%	14.37
5	SMSU	34	4.89%	429	3.38%	12.62
6	BOSC	26	3.74%	590	4.64%	22.69
7	GLDS	20	2.87%	138	1.09%	6.90
8	NPDE	19	2.73%	255	2.01%	13.42
9	SBLI	18	2.59%	248	1.95%	13.78
10	MATU	17	2.44%	278	2.19%	16.35

Note: TOYT stands for Toyota Motor Corp.; FORD stands for Ford Global Tech LLC; GENK stands for GM Global Technology Operations Inc.; SAOL stands for Sanyo Electric Co., Ltd.; SMSU stands for Samsung Electronics Co., Ltd.; BOSC stands for Robert Bosch GmbH; GLDS stands for LG Electronics; NPDE stands for Nippondenso Co., Ltd.; SBLI stands for SB Limotive; MATU stands for Matsushita Co., Ltd.

BMS and electronic control, SONY, Panasonic, Samsung, LG, and Bosch have all obtained related patents.

With more than 20 years of experience in the research and development of EV batteries, the China's government has implemented the best policy for the development of new energy vehicles. The "Energy Saving and New Energy Vehicle" and "Electric Vehicle" projects backed by the "National High-tech R&D Program of China (863 Program)" and the "National Basic Research Program of China (973 Program)" have fostered many influential EV enterprises in China. Among them, BYD is a pioneer in filing related patents. In 2016, BYD became the world's largest seller of new energy vehicles. The BYD electric bus K9 has been widely promoted in USA, Japan, UK, and many other developed countries, and the lithium iron phosphate battery equipped in K9 has passed internationally recognized strict safety tests. The German company Mercedes-Benz has adopted the BMS and power system assembly developed by BYD, and two companies are collaborating on the development of DENZA EV. Together with CATL, the LIB supplier for Bayerische-Motoren Werke, BYD has become the leading supplier of LIBs for EVs with international impact.

The integration of industry, education, and research is a major characteristic of China's new energy vehicle industry. A number of China's universities, including Tsinghua University, Shanghai Jiao Tong University, Tongji University, Beijing Institute of Technology, the Chinese Academy of Sciences etc., have vigorously collaborated with automobile and battery enterprises and contributed to the development of the industry. Consequently, there has been a significant increase in the number of related patent filings in China. In the last five years, China has filed more patents on EV batteries than any other country in the world. In particular, more than 2000 patents have been obtained by BYD, out of which more than 200 patents are international patents. The development of EVs in China is so rapid that China is no longer a follower in international competition, but even a pioneer in some areas.

During the 13th Five-Year Plan period and under the nanomaterial project of the national research program, the China's government has proposed a new strategy for the development of EV batteries and BMS, highlighting the development of an EV management system and EV batteries with good safety and durability. By reviewing the 12th Five-Year Plan period, wherein lithium battery with long endurance mileage was considered as one of the major concerns by the Chinese Academy of Sciences, we can observe that remarkable advancements have been achieved in the research and development of lithium-sulfur batteries and solid-state lithium ion batteries, and China has assumed the leading position in the engineering applications and system integration in this area.

Since 2012, the emerging new energy cars have further promoted the development of EV battery engineering to a stage where central and local governments have begun to pay significant attention to it. Consequently, the number of battery material (cathode, anode, electrolyte, and separator) suppliers and power battery manufacturers in China increased dramatically, causing the problem of excess capacity, unnecessary investment, and waste of resources. Accordingly, strengthening the layout of EV industry has been suggested, with a focus on battery materials, manufacturing, and BMS to develop EV batteries with good performance, safety, and durability, such that China can continue to assume the leading position in the research and development of EV batteries for the next generation.

Table 2.2.1 and Table 2.2.2 demonstrate that the patents related to "electric vehicle" and "battery" mainly cover the following research directions: battery performance measurement, BMS, battery pack, EV power system assembly, and technologies of battery swap stations. These patents are mainly obtained by the automobile manufacturers from USA, Japan, Korea, and Germany, whereas, in China, only BYD and Tsinghua University have obtained many related patents. In contrast, China's four traditional automobile manufacturers have obtained few patents—a sign of their insufficient investment in new energy vehicles.

Figure 2.2.1 shows the international collaboration network between countries or regions for the development of EV batteries (structure, material, efficiency, and thermal management system); Figure 2.2.2 shows the collaboration network between the institutions.

2.2.2 Equipment and technology for deepwater oil and gas development

(1) Concept elaboration

The abundant global oil and gas resources account for 34% of the total resources, but only 30% of them have been discovered so far, indicating that we are still in the early stages of exploration, and there are immense prospects in

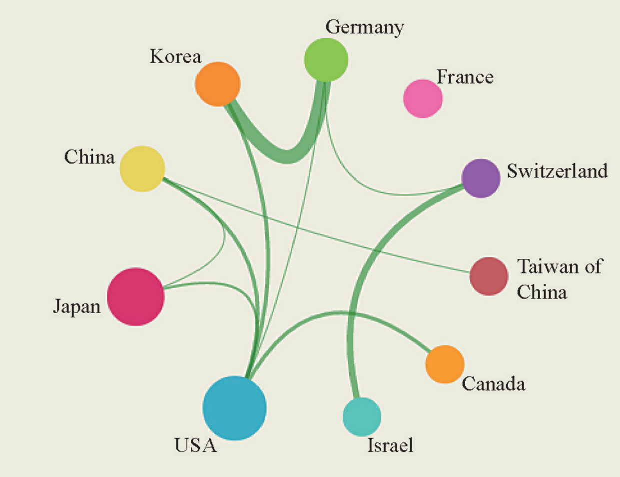

Figure 2.2.1 Collaboration network of the major producing countries or regions of core patents on the engineering development focus "Electric vehicle battery (structure, material, efficiency, and thermal management system)"

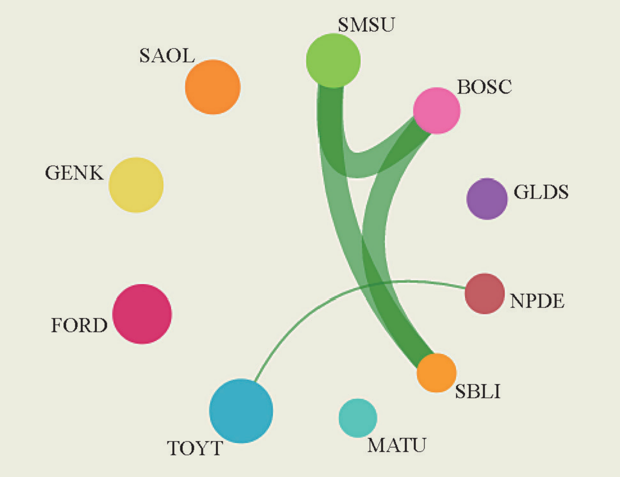

Figure 2.2.2 Collaboration network of the major producing institutions of core patents on the engineering development focus "Electric vehicle battery (structure, material, efficiency, and thermal management system)"

their exploration.

China has rich marine oil and gas resources. According to the geological survey data of the China's Ministry of Land and Resources, in China's South Sea, the geological oil reserves of the whole basin group amount to 23 billion–30 billion tons, and natural gas amounts to 16 trillion cubic meters. According to preliminary statistics, the total geological resources of the total oil and gas in the South China Sea account for one-third of China's total oil and gas resources, of which 70% are in the deep sea region. Generally, the deepwater depth is greater than 500 m, and the ultra-deepwater depth is greater than 1500 m. As we go deeper into the water, it becomes increasingly difficult to perform geophysical exploration, drilling, and resource exploitation. First, natural and weather conditions such as wind, wave, flow, and ice are significantly more complicated at such depths. Moreover, the window between pore pressure and fracture pressure narrows as the depth increases, rendering it increasingly difficult to control the drilling. Finally, as the water temperature decreases in the deep water, drilling fluid has poorer rheology, and the flow of oil and gas is more difficult to control.

Therefore, the equipment and technology of deepwater oil and gas development are important in the field of oil and gas technology innovation around the world. Deepwater oil and gas exploration involves information technology, new materials technology, new energy, and other disciplines, and is a complex systematic engineering that requires advanced technology, technological integration, high security, and reliability. Although China started relatively late in deepwater oil and gas development, we have proposed a major oceanic strategy to develop oceanic technology and improve the ability of marine resource exploitation. We feel confident that China will make rapid progress in the future in this aspect, in order to improve the safety level of energy production and contribute to China's rapid economic growth.

(2) Concept elaboration, key technologies to be resolved, future trends for the concerned engineering branches, and an overview of the development priorities in different countries.

The major engineering technology of deepwater oil and gas exploration includes drilling floating structure, underwater vehicle, deepwater riser system, underwater production system, deepwater BOP stack control system, water isolation valve system, downhole overflow monitoring technology, technologies to ensure the safety of deepwater flow, exploration technology, measurement and analysis of long cable seismic signal, and exploration technology of subtle hydrocarbon reservoirs.

• Deepwater oil and gas drilling floating structure

Deepwater oil and gas drilling floating structure mainly refers to drilling ships and a semi-submersible drilling platform. The components of drilling ships are hull, mooring or dynamic positioning system, and navigation system. Drilling ships have good flexibility, self-navigation ability, flexibility, and are easy to anchor. The main structure of a semi-submersible drilling platform is the upper propping component, which connects a column with a rounded or square section and the lower floating box. A semi-submersible drilling platform, which is seakeeping and flexible, occupies only a small water-plane area but has a large deck area and variable load. It helps to solve the problems occurring in regional drilling when the depth is greater than 3000 m.

During the installation phase, floating structures used for deepwater oil and gas development are mainly deep water pipeline layer, deep water multi-purpose vehicle (MPV) etc. A deepwater pipeline layer is composed of a hull, pipeline welding system, pipe laying system, lifting system, power system, and positioning system. It is responsible for installing a floating platform, and laying sea pipes and standpipes. It is composed of a multifunctional robotic manipulator and a winch system with the function of heave compensation, and thus it can undertake and execute a task on its own. MPV is commonly used for underwater tasks at a depth of more than 3000 m under complex sea conditions, including hoisting large deepwater structures (oil tree, water pipe etc.), conducting submarine installation, laying flexible pipes, supporting remote-operated vehicles (ROV) and saturation diving task, examining and repairing oceanic engineering, deepwater anchor operating and anchoring etc.

During the production stage of deepwater oil and gas development, a tension leg platform (TLP), spar platform (SPAR), floating production storage and offloading (FPSO), and semi-submersible platform are the floating structures responsible for oil and gas production, storage, transportation etc. The floating structure sheds light on key technologies including concept design, prediction of dynamic properties, design and construction, service, durability, maintainability, accident load and risk assessment, and environmental and ecological impact assessment. The development trend of floating structure lies in a new FPSO with TrussSpar as its main composite structure, the light tension leg platform (miniTLP) suitable for deepwater conditions, very large floating structures (VLFS) etc. Recent related researches have started to pay attention to the modernization of floating structures and their operational ability in deeper waters.

- Underwater vehicle

Underwater vehicles mainly include human-occupied vehicles (HOV), ROV, autonomous underwater vehicles (AUV), deep sea drag system (DT), underwater glider, and bionic submersible. Underwater vehicles can quickly carry personnel and equipment to a deepwater environment, and efficiently conduct exploration and operation tasks.

A HOV can dive to a depth of more than 10 000 m, but it does not have a strong power system, and suffers from high costs and risks during operation and maintenance. In contrast, an unmanned underwater vehicle, such as ROV and AUV, can be connected to the mother ship through an umbilical cable to transmit power and information. Ship operators on the mother ship can provide commands to the manipulator in a ROV to conduct underwater operation through the umbilical cable, whereas an AUV, equipped with an independent power system, can execute operations using its pre-set program instructions, and thus can operate for a longer time and have stronger operation abilities.

The key technical challenges in underwater vehicles are a powerful driving source, accurate positioning technology, high resolution monitoring technology, and ultra-deep water operation technology. The development trend of underwater vehicles includes lowering the cost of a HOV and making it more comfortable for humans to live in it, in order to establish a mutually reinforcing and coordinative system that connects the manned and unmanned facilities.

- Deepwater riser system

The deepwater riser system includes three types of tubing systems: pipes, drilling risers, and landing strings. Drilling risers connect the drilling platform and underwater wellhead, thus playing an important role in providing a circulation channel for drilling fluid, supporting auxiliary lines, guiding drilling tools, and carrying and retrieving BOPs. When in service, a series of complex mechanical phenomena occur in deepwater drilling risers owing to the dynamic effect from the combined forces of waves and flows, including axial tension, transverse bending, coupling vibration etc., resulting in significant challenges to the safe operation of deepwater drilling. The key technical challenges include the mechanics and design control of deepwater drilling risers, out of which the primary problems are to ensure the stability and safety of the underwater wellhead, design a proper operation window for the installation of deepwater risers, assess the vortex-induced vibration and fatigue life of deepwater risers, evaluate and control the integrity of deepwater shafts, and design the mechanical simulation of the deepwater tubing systems. In the future, deepwater risers are expected to become lighter, safer, stronger, and easier to install.

- Underwater production system

In addition to the construction of additional surface oil and gas production platforms, underwater production system has also become an important component of deepwater oceanic engineering technology in the process of deep sea oil and gas development. Underwater production systems can be categorized based on their functions: production tree system, manifold and connection system, and underwater control and umbilical cable system. The main function of the underwater production system is to guarantee that all the production fluids are properly handled under water.

Underwater production systems reduce the occurrence of sea accidents since they are not influenced by sea surface winds, waves, streams, ice, and other natural and weather conditions, thus making offshore oil and gas production safer and more reliable. The major technical challenges in this field mainly lie in underwater flow assurance technology, underwater power transmission and all-electric control technology, underwater installation technology, underwater production system reliability and integrity management technology, underwater production technology applicable for polar regions etc. The recent development trend in this area mainly focuses on improving the intelligent and automation level of the underwater production systems.

- Deepwater drilling BOP system

Deepwater drilling BOP stack is generally composed of a lower marine riser package (LMRP system), connector, lower BOP stack, and BOP frame composition. The deepwater drilling BOP system mainly includes a BOP stack and control unit, wherein the BOP control system employs a number of control technologies and is suitable for electricity, liquid, and gas. It possesses a large number of control points and a complex structure system, requiring high stability of the system and sensitivity of control units. The major technical challenges in this field include the BOP material, highly redundant modular integration technology of the control units in the deepwater drilling BOP system, and the design, production, and testing technology of the deepwater BOP control system. China's research institutions have carried out many studies on the structure of a BOP stack, its control system, and the system as a whole, e.g., theoretical analyses and researches, standardization, collection and report of the real-time feedback information from the system etc. Future studies will focus on the applicability of deepwater drilling BOP systems under high system pressure and triple redundancies, and the improvement of their reliability, intelligence, and environmental friendliness.

- Subsea isolation valve system

Subsea isolation valve (SSIV) is designed to isolate the near-end riser and submarine pipelines in order to reduce the risks of fire and explosion caused by overflow. However, SSIV requires a high investment cost; thus, it is a major challenge in current engineering projects to determine whether SSIV is necessary. Moreover, there is no proven quantitative SSIV assessment system. Since the initial cost of SSIV is too high, it becomes highly important to accurately quantify the consequences of a potential accident, and to assess the profits contributed by SSIV. Based on the historical overflow rate of offshore risers and submarine pipelines, China has successfully built an SSIV benefit evaluation system to accurately assess the benefits of employing an SSIV.

- Downhole overflow monitoring technology

According to the different features of offshore drilling and the location of the installed sensor, overflow monitoring methods for deepwater drilling can be divided into platform (wellhead) monitoring method, seawater section (near the mud line) monitoring method, and measurements while drilling (MWD) method. Downhole overflow monitoring technology for deepwater drilling is mainly used to detect the downhole overflow, but can also be used for the comprehensive monitoring of underground well pressure and wellbore pressure to provide technical support for deepwater drilling. The platform (wellhead) monitoring method mainly compares certain parameters of the drill hole returns with those measured in the wellhead, and can be further classified into conventional monitoring method, unconventional monitoring method, and wellhead comprehensive monitoring method. Seawater monitoring method is an exclusive method for offshore drilling, wherein the best place for overflow monitoring is the sea-bed mud line. The timely detection of underground overflow plays a critical role in well control and gas cut, in particular. The downhole monitoring method includes annular pressure while drilling (APWD), logging while drilling (LWD), formation testing while drilling (FTWD), downhole micro-flow measurement, ultrasonic flow measurement etc. The key technical challenge in this field lies in the timely updating of monitoring results, and the key technologies are acoustic monitoring technology, riser ultrasonic monitoring technology, pressure monitoring technology, robotic underwater monitoring technology etc. Furthermore, the recent development trend of overflow monitoring technology for deepwater drilling is to shorten the reaction time by improving the technology of overflow monitoring and detection, and to develop an early warning mechanism, which monitors the wellbore pressure to ensure its safety.

- Technologies to ensure the safety of deepwater flow

The technology of safe deepwater flow mainly aims to solve the problems occurring in the flow of deepwater oil and gas, including submarine pipeline blockage, leakage, and other safety issues. It serves to control the flow of oil and gas within a proper range, and to reduce the costs of oil and gas transmission to guarantee an economic and safe transmission. The major technical challenges in this field are described as follows. The first challenge is the technology of multiphase flow mixing, whose primary concern lies in the determination of flow pattern of multiphase flow and the flow regularity in a mixed pipeline. The second challenge is the generation and control of the solid-state product, wherein the synergistic effect of gas hydrate, paraffin, and gas hydrate should be studied. The third challenge is the prediction and control technology of slug flows. The recent development of technologies in this field have focused on the heating technology of oil and water pipelines, which helps to ensure that the temperature of the fluid in the pipeline remains higher than the wax precipitation temperature of crude oil and the hydrate formation temperature. Thus, it can effectively prevent the deposition of paraffin in the pipeline and the formation of hydrate in order to achieve the purpose of flow safety and security. Moreover, underwater multi-phase separation technology is also significant. It separates the liquid product around the subsea wellhead, thus reducing the riser pressure and lifting energy loss, and raising the utilization rate. Moreover, the separation technology not only eliminates severe slug flows from the root, but also effectively inhibits the hydrate generation since it reduces the water content in the oil and gas mixture, thus enabling a more distant transmission.

- Deepwater oil and gas exploration technology

A frontier topic of the oil industry, the exploration and development of deep-sea oil and gas resources is riskier than petroleum exploration and drilling on land or continental shelves, since it is constrained by the present technologies for deepwater exploration, oil platform construction, and natural disaster forecasting and prevention. Moreover, many other factors contribute to its operational difficulty and complexity, e.g., the particularity of oceanic environment, complex storage conditions, and lack of reliable supporting equipment and logistical support etc. Some key technical problems remain to be solved, including the berth port of fixed offshore platform or deep-sea floating platform as a supportive structure for deep-sea drilling, unstable geological environment, floating well control in deep waters, deep-sea environment protection etc. The major challenges in these technologies include the determination of the precise location of a reservoir and the integration of high technologies involved in deepwater drilling; further, progress in the aspects of offshore drilling equipment and related logistical units is desired. Future deep-sea exploration vessels are expected to fully utilize semi-submersible drilling platforms equipped with more automated and efficient drilling equipment and improved deep drilling technology. New light materials with high strength will also be extensively employed in this industry.

- Measurement and analysis of long cable seismic signal

The measurement and analysis of a long cable seismic signal is different from that of a conventional seismic signal in its seismic offset and record length. It has a long cable and involves large amount of data processing, broad working area, significant changes in water depth, and multiple wave development. Influenced by currents and waves, a cable deviates from its set position as its length increases, rendering it difficult to fix the accurate reflection point position and offset migration during two-dimensional seismic data processing. Consequently, the best reflection imaging profile is often unavailable, leading to the problems of tensile distortion and lost Amplitude variation with offset (AVO) phenomenon. There are many key technical difficulties to overcome, e.g., a four-order dynamic correction technology of anomalous seismic offset in a long cable signal, and AVO technology, which monitors the amplitude of seismic reflection waves to perform lithological judgments and to explore oil and gas reservoirs. Currently, efforts are being made to develop a positioning technology applicable for ultra-deep waters, long cables, seismic merging, high-order correction technology, a variety of denoising technologies etc.

- Deepwater exploration technology of subtle hydrocarbon reservoirs

According to geological science, subtle hydrocarbon reservoir refers to the nonstructural lithological reservoirs that originated during the process of deposition. Subtle hydrocarbon reservoirs are often closely linked with the nature of sedimentary rocks and stratigraphic overlap. Constrained by the tectonic environment, paleo-geomorphology, and paleo-current conditions, the distribution of deposited materials typically exhibits fast lateral changes, while with horizontal bedding it remains flat. Therefore, such reservoirs are not easy to be detected from its geophysical information. Key technical difficulties in this area are the exploration technologies of underwater alluvial fan reservoirs, turbidity sandstone lens reservoirs, and reservoirs with seismic unconformity. Currently, researchers are focusing on a novel method that uses seismic reflection amplitude information for predicting the thickness of a reservoir, measuring seismic wavelets to increase the resolution of seismic data, and developing technologies on synthetic acoustic logging and seismic modeling.

- Development priorities for different countries:

China: Considering the development in the equipment and technology of deepwater oil and gas research, China has been focusing on the design of deepwater floating structures (e.g., the design of drilling vessels, semi-submersible platforms, and FPSO with large oil storage capacity), lifting pipe laying vessels, deepwater standpipes, and risers; deepwater drilling BOP lifting devices, subsea BOP stack and its control system, as well as an intelligent well control monitoring system.

European countries: European countries have paid close attention toward the exploration technology of geo-microbiological oil and gas resources (Germany), BOP and IWOC technology, submarine electronic systems, submarine mobile control modules, underwater transformers, and a piezoelectric structure monitoring system for composite risers.

UK: UK OHM corporation has developed four generations of electromagnetic signal emitter, entitled as deep-sea active field source equipment (DASI Ⅳ), to prevent underwater oil and gas overflows; other research hotspots include the BOP power accumulator system, the underwater riser hydraulic control system, the underwater workover control system, soft landing system and technology, the installation of annular safety valve, oil and gas gathering units equipped with float valve, underwater oil and gas gathering units, and a dynamic positioning system for vessels.

Norway: Norway has conducted related research on the technologies to extend the service life of the oil production tree, the floating structures for deepwater oil and gas development, the positioning anchor winch driven by hydraulic pressure, and a dynamic positioning system for vessels.

USA: US has been pioneering in the development of marine equipment and technology for its extensive research directions and advanced technology. In addition to exploration technology, the US has also devoted to underwater production safety, e.g., deepwater BOP devices and a wellhead pressure control system. Besides, a number of novel technologies have been developed, including the 4D seismic technology that can detect leakage and determine dead oil areas, small-sized all-optical sensors that can reliably be applied for seismic exploration and resources production, marine controlled-source electromagnetic survey, subsea BOP system technology that could enhance the strength and fatigue resistance of the wellhead and prime conductor, the design of plugging devices for oil well blowout, the emergency control system for subsea BOP, submarine test tree control system, deepwater container system and its operations, deployment of submarine stacking system, protective device for submarine oil leakage and its operations, the transportation and management of BOP devices, the subsea wellhead pressure control system, laser-assisted system for deepwater drilling emergencies, wellhead pressure testing devices and methods, subsea operating valves connected low pressure receivers, interface equipment connection systems applicable for submarine fluids, laser-assisted BOP devices, BOP devices for spare wellhead, well control system that decreases its mechanical energy, the integration and monitoring technology of BOP devices, submarine laser modules and its transformation technology, and design of subsea BOP seals.

Internationally: Hotspots in the research of related fields include submarine pipelines system, wellhead BOP system, offshore oil well sealing system, submarine disperse spraying system, deepwater mixed risers system, submarine pumping method and equipment, subsea BOP control system, submarine noise control system, anti-blowout component in BOP and its operations, floating drilling ship, BOP monitoring system, the dual-gradient drilling enhancement system, and cable design.

(3) Current development status and future trends

Deepwater oil and gas development is a systematic engineering topic, as well as a cross-disciplinary technological innovation project that requires the coordinative collaboration of different institutions and units. Nowadays, all countries around the world are participating in this competition to enhance their exploration, drilling, and development technologies of deepwater/ultra-deepwater oil and gas resources. On May 9, 2012, China officially launched its "Submarine Oil 981" project in the South China Sea, thereby demonstrating that China has taken its first step in the implementation of its "deep-sea strategy" in the offshore oil industry. By far, China has accumulated rich experiences in the exploration and development in deepwater oil and gas, and is capable of executing tasks at a maximum water depth of 3000 m. However, compared with the other countries that have made considerable achievements in this research area, e.g., USA, the Netherlands, Norway, and Canada, we might be aware that there is still room for improvement. Some major challenges for current developments include the poor marine environment (low temperature area in Arctic), the difficulty of drilling well control in deep waters, the geological disaster caused by mudline shallow hydrates, and the safety risk in system operations. Future studies are expected to focus on the abovementioned issues and strive to make breakthroughs in aspects of the deepwater floating drilling platform, robotic drilling system, non-riser drilling rig, intelligent gathering, and transportation system in deep waters. The ultimate goal for us is to realize industrialization in submarine resources exploration and development (i.e., submarine automatic drilling, oil and gas processing, power supply and its automatic control, production and its automatic control, maintenance and expansion, etc.), and try to overcome the negative influences caused by ocean climate changes. Furthermore, we should face the fact that in addition to independent innovation, China still needs to learn from the west in terms of advanced technologies. Only in this manner, we can continuously enhance our development in deepwater oil and gas exploration and production, and strive to reach the international advanced level in the future.

(4) The development status of different countries and the collaboration among major research countries and institutions

Table 2.2.3 demonstrates that the USA, UK, and the Netherlands are the top 3 countries that have obtained the most core patents on technologies and equipment for

Table 2.2.3 Major producing countries or regions of core patents on the engineering development focus "Equipment and technology for deepwater oil and gas development"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	121	74.69%	1168	84.52%	9.65
2	UK	12	7.41%	43	3.11%	3.58
3	The Netherlands	7	4.32%	14	1.01%	2.00
4	Norway	7	4.32%	64	4.63%	9.14
5	China	6	3.70%	20	1.45%	3.33
6	France	5	3.09%	4	0.29%	0.80
7	Canada	3	1.85%	2	0.14%	0.67
8	Germany	3	1.85%	25	1.81%	8.33
9	Singapore	3	1.85%	16	1.16%	5.33
10	Denmark	2	1.23%	7	0.51%	3.50

deepwater oil and gas development. Patents from USA account for 74.69% of the total patents in the world, while China has only obtained 3.70%. It indicates that the USA is taking the leading role in deepwater oil and gas development while China is following the mainstream research of others, and remains at the early stage with respect to equipment and technologies of deepwater oil and gas development.

Table 2.2.4 shows that nine out of ten institutions are American research institutions that have obtained the most core patents on technologies and equipment for deepwater oil and gas development in the world. UK has one seat, while China has zero seat. This indicates that American institutions have mastered the core technologies of deepwater oil and gas development, e.g., Schlumberger, Halliburton, Baker Hughes, and other large oilfield technological companies.

Figure 2.2.3 illustrates that the Netherlands, France, UK, Canada, and the USA have conducted extensive collaborations for promoting the integration of the industry, education, and research in deepwater oil and gas development. Among them, the USA and the UK have made the most frequent contacts and collaborations, which are followed by the USA and the Netherlands. This indicates that the USA not only takes the lead in research and technology development, but also pioneers in initiating academic exchanges and industrial collaborations in the area of deepwater oil and gas development.

Figure 2.2.4 shows that there were extensive academic exchanges and industrial collaborations between American institutions, e.g., between SLMB and PRAD, and HYDL and VETC. Furthermore, SLMB and PRAD are the two institutions that have obtained the most patents in this area. This indicates that the USA has established an enabling environment for institutions and businesses to develop contacts and collaborations with each other, and has laid a great foundation for the full fledgling of business collaboration on the technology of deepwater oil and gas development. In contrast, only a few China's institutions have obtained core technologies in this area, and they should strengthen the integration of the industry, education, and research, and develop more contacts and collaborations with each other.

(5) Current situation and dominant trends in China

With the exploitation of deepwater oil and gas resources under progress, research in China on the relevant equipment and technologies are based primarily on three stages: well drilling, underwater installation, and commissioning. Meanwhile, constant upgrading has been witnessed in all types of equipment, including drilling apparatus, construction vessels, and underwater vehicles. Currently, research focuses particularly in four areas: floating drillships, underwater vehicles, deep water riser systems, and underwater production system. Future technological innovations in deepwater applications will continue to be vibrant and dynamic. In general, the

Table 2.2.4 Major producing institutions of core patents on the engineering development focus “Equipment and technology for deepwater oil and gas development”

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	HYDL	15	9.26%	44	3.18%	2.93
2	VETC	14	8.64%	59	4.27%	4.21
3	COOI	11	6.79%	43	3.11%	3.91
4	BRPE	8	4.94%	86	6.22%	10.75
5	SLMB	8	4.94%	58	4.20%	7.25
6	PRAD	7	4.32%	56	4.05%	8.00
7	NAOV	6	3.70%	58	4.20%	9.67
8	Subsea IP Holdings	6	3.70%	136	9.84%	22.67
9	CALI	5	3.09%	86	6.22%	17.20
10	SHEL	4	2.47%	11	0.80%	2.75

Note: HYDL stands for Hydril Co.; VETC stands for Vetco Gray Inc.; COOI stands for Cooper Technologies Co.; BRPE stands for BP Chem Co. Ltd.; SLMB stands for Schlumberger Technology Corp.; PRAD stands for Prad Res&Dev Corp.; NAOV stands for Nat Oilwell Varco LP; CALI stands for Chevron Usa Inc.; SHEL stands for Shell Oil Co.

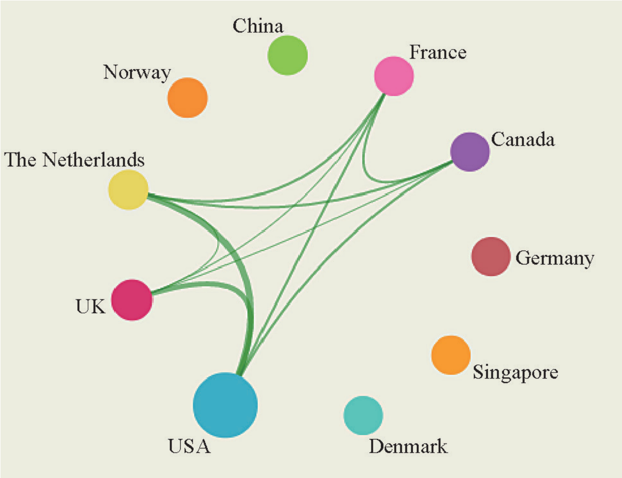

Figure 2.2.3 Collaboration network of the major producing countries or regions of core patents on the engineering development focus “Equipment and technology for deepwater oil and gas development”

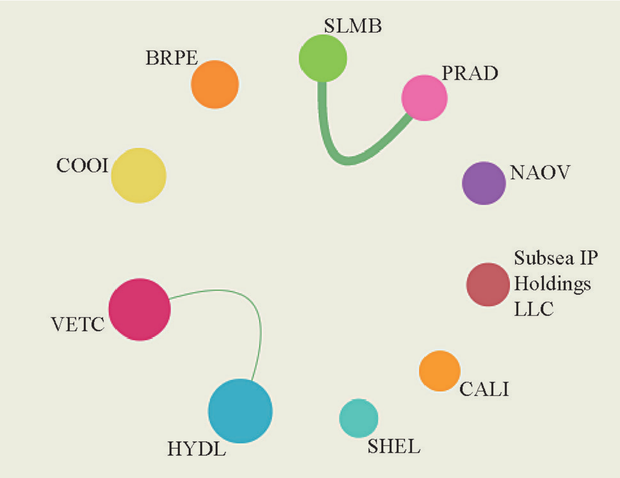

Figure 2.2.4 Collaboration network of the major producing institutions of core patents on the engineering development focus “Equipment and technology for deepwater oil and gas development”

trend in these field points is toward four directions: drilling apparatus and ancillary facilities with high degree of automation, underwater operation and facilities, multifunctionality of deepwater technologies and equipment, and innovations in deepwater high-techs. Technological innovations and breakthroughs will gradually subvert traditional exploration and exploitation methods, thereby considerably reducing the costs and risks involved and stimulating the development of onshore oil and gas operations. The share of deepwater production in global offshore oil and gas operations is expected to bypass 30%, thereby making it a strategic energy source of increasing significance.

Recently, China’s investment in marine oil and gas exploration and development has increased year by year. More and more research institutions, including China University of Petroleum (Beijing), China University of Petroleum (East China), Ocean University of China, Shanghai Jiao Tong University, Southwest Petroleum University, Dalian University of Technology, Institute of Oceanology under Chinese Academy of Sciences, Guangzhou Ocean Geological Survey, CNOOC Research Institute, and China Petroleum Drilling Institute, are involved. Currently, a number of major research projects on deepwater oil and gas development have received supports from units such as the Ministry of Science and Technology and the Natural Science Foundation, including the “973” project—“Fundamental Research on Safe and Efficient Well Drilling of Deep-water Oil and Gas Applications,” undertaken by China University of Petroleum (East China), along with China National Petroleum Corporation, China National Petroleum Research Institute, China National Offshore Oil Research Institute, China National Petroleum Research Institute, Chinese Academy of Sciences, China University of Petroleum (Beijing), Shanghai Jiao Tong University, China Shipping Oilfield Services Co., Ltd., and China National Petroleum Corporation Marine Engineering Co., Ltd. The project adopts the industry-university-research (IUR) joint model to form a theoretical foundation tailored for safe and efficient deepwater operations in the South China Sea, with a view to provide the theoretical support for a leapfrog development in China’s deepwater oil and gas technologies.

China has constructed various types of equipment for utilizing offshore oil and gas, including HYSY981, the sixth generation of deep-water drilling platform, and HYSY201, an S-shaped lifting pipe, that are able to operate at a maximum depth of 3000 m below the sea. However, the proportion of homemade ancillary devices remains limited. For underwater production systems and technologies related to deep-sea installation, repair, and personnel rescue, we still need to rely on foreign countries.

Based on the current development of China’s deepwater oil and gas equipment and related technologies, we propose the following suggestions. First, allocation of scientific and technological resources can be further optimized by establishing a special fund for “Deep-sea Oil and Gas Drilling,” with an emphasis on supporting elementary scientific research and achieving technological breakthroughs. Second, more efforts should be devoted to the development of engineering technologies and devices for deep-sea oil and gas applications, so as to enhance the proportion of key components produced at home, develop sufficient capacity for systematic deep-sea operations, and catch up with foreign counterparts. Third, steady progress should be actively made in offshore oil and gas operations in the Polar Regions to enhance China's leadership in the field of polar oil and gas drilling. Fourth, swifter action is to be observed in the implementation of human resource development strategy to strengthen innovation capacity and establish a strong talent pool of international standard in the field of deep-sea oil and gas development. Finally, collaboration with international community is to be fortified by active participation in key international research programs on deep-sea oil and gas development, and self-reflection upon what to be learned and enhanced from such experiences.

2.2.3 New fracturing methods, fluids, proppants, and additives

(1) Concept elaboration

With worldwide rapid socioeconomic development, the consumption of oil and gas resources is continuously increasing, and the conventional oil and gas resources can hardly satisfy the growing demand. Simultaneously, the mining technologies in the oil and gas industry are developing at such a rate that unconventional sources of oil and gas can be utilized economically. The past decade, in particular, viewed the increase of vigorous development in extracting unconventional oil and gas resources (such as tight oil/gas, shale gas, and coalbed gas), which has become a novel growth point of future oil and gas production. However, unconventional oil and gas reservoir generally have complex formation structure, thereby increasing the difficulty and cost of production. Therefore, in the effort to extract unconventional oil and gas resources, the problem now at hand is to determine the methods of extraction that are more reasonable, efficient, and cost-effective, among which fracturing is the most basic approach that can increase production. At present, one typical fracturing method is water-based fracturing, which, however, is plagued by issues such as excessive consumption of water, environmental and reservoir pollution, and difficult recovery. Under this background, novel fracturing methods and technologies, such as hybrid fracturing, multistage unlimited fracturing, fiber fracturing, HiWAY channel fracturing, waterless fracturing, and LPG fracturing, have embraced swift development, thereby defining the worldwide major research hotspots in the recent years. The novel techniques solve in varying degrees some existing problems of conventional fracturing, by considerably increasing the output and rate of recovery from unconventional oil and gas resources. The research and application of these technologies will play an important role in the development of unconventional oil and gas business in areas such as the lack of water resources, serious environmental pollution and difficult transportation of equipment.

(2) Concept elaboration, key technologies to be resolved, and future trends for the concerned engineering branches, and an overview of the development priorities in different countries.

Research on novel fracturing methods, fluids, proppants, and additives has achieved rapid development. Currently, researchers are focusing on the following areas:

- Multistage unlimited fracturing

Extracting unconventional oil and gas, particularly shale gas, requires long horizontal well with multistage fracturing technology. The total length of the horizontal section is 1000–3000 m, or longer, which indicates that the formation should be fractured 20–60 times, provided a spacing of 50 m between the two stages. Restricted by the width of oil tubes, conventional ball-drop fracturing can initiate 15-stage fracturing at maximum during one trip. In order to reduce the working hours and cost of fracturing, research is directed toward multistage unlimited fracturing. Coiled tubing infinite grade sliding sleeve segmented fracturing is a recent multistage fracturing technique that is capable of achieving 97 stages of fracturing in one trip, with its record being 104 stages in a single well. The maximum vertical length of the well fractured using this method is 4681 m, and the maximum depth is 6256 m. The technique uses a novel stepless casing sliding sleeves, which are included in the casing going down the well for well cementation. After fixing the casing in place, the sliding sleeves are opened one after another for staged fracturing at one shot. At present, bridge plug method and ball sliding sleeve technique are the two types of multistage fracturing technologies, which are more commonly used in the field. Different from ordinary multistage fracturing methods, key technologies that multistage unlimited fracturing aims to achieve are how to be free from the limitation imposed by the number of fracturing stages, where is the accurate location to fracture, and how to make the fracturing fluids travel directly to the target layer and achieve real-time monitoring of fracturing pressure simultaneously. Multistage unlimited fracturing is a novel type of fracturing processes that serve as a key tool for production boost and reservoir stimulation of unconventional oil and gas resources, including oil and gas reservoirs of low permeability, thin oil layers, shale gas and coalbed gas, boasting considerable advantages in increasing the production output and efficiency for oil fields. The current trend is to increase the number of fracturing stages in a single trip, as well as in a single well, and to move toward deeper wells.

The technique was developed by Canadian energy company NCS. Following a series of record-breaking feats in 2014 on the number of stages achieved in a single well, it won the 2014 SPE Technology Award for the Canadian region and the 2014 World Oil Best Completion Technology Award. At present, NCS is the holder of this technique, whose applications in other countries are entirely relied on the technical services of the company.

- FracInsight precise fracturing

In order to solve the problem that the perforation section of many horizontal wells does not yield oil or gas during the reservoir development, Halliburton has developed a novel "fracturing positioning" module—FracInsight. The module selects accurately perforation and fracturing stage locations from formation evaluation data along the horizontal section of a well. FracInsight is a repeatable interpretation workflow, the essence of which is to create a more consistent fracturing operation by eliminating redundant perforation clusters and fracturing stage locations, and therefore reduce inconsistent breakdown and treatment pressures, and maximize the output. The key part to be tackled in this technology is to combine the production index and the fracture index to optimize stage and cluster placement for an accurate prediction of the fracture. The novel technology has been introduced into applications in North America, including countries such as Canada and Mexico. However, only several dozens of analysts have a desirable proficiency in this technology. Future development of the technology points toward a full integration of the production index and the fracture index to create fracturing with enhanced accuracy, and the cultivation of more analysts to help advance the technology in a better direction.

Building on the CYPHER2.0 Seismic-to-Stimulation Service, the technology is a brand new "fracturing positioning" module developed by Halliburton. The technology has been introduced into applications in North America, including countries such as Canada and Mexico.

- StimMORE fracture diversion technology

The technology is a novel technology developed by Schlumberger. In the process of fracturing fluid diversion, both gels and foams are commonly used diverting agents. Their residuals may have an adverse effect on long-term production of the reservoir. StimMORE technology uses a low-cost fiber-laden diversion fluid, which generates an effective blockage, and is completely degradable, thus leaving no residual formation damage. It adds fiber to the mortar and creates bridge plugs by proppants and fibers over the fractures. The low density of fibers prevents them from precipitating and in turn allows them to be carried to target locations. The shape of the fibers is such that they are able to lie across the interconnected channels and cracks, with a considerably lower solid content than that of simple particles. This temporary obstruction during the pumping increases the pressure at the end of the wellbore, thereby making it sufficient to induce the creation of additional fractures in the rest of the formation. Fibers will be degraded and dissolved a few days later, leaving no damage on the formation. The key part of this technology to be solved are how to monitor the diverting effect of the diversion fluids in real time, and how to further enhance the performance of the fiber-laden fluid so that it can be used in more adverse formation conditions such as ultra-high temperature and/or ultra-high pressure. Future development of this technology is to device more accurate monitoring apparatus and better fiber-laden diversion fluid, so that it can be applied in more complex formations with higher accuracy.

StimMORE fracture diversion technology is developed by Schlumberger. It is used in combination with StimMAP live micro-seismic monitoring technology, and it can monitor the development of cracks in real time and adjust promptly the pumping schemes, resulting in lower well completion costs and maximum reservoir contact.

Schlumberger provides guidelines on the application of the technology in all regions.

- Hybrid fracturing technology

Although water fracturing provides easy drainage and less damage to fluid conductivity of the fractures, it suffers poor sand-carrying capacity and difficulties in maintaining the crack width, rendering areas in the vicinity of the wellbore prone to sand blocks.

If proppants in the form of small particles were used for reducing their terminal speeds, fractures would be susceptible to re-closure under high formation pressures, thereby imposing a considerable impact on the stimulation effects of water fracturing. The emergence of hybrid fracturing has significantly enhanced such defects of water fracturing as high fluid loss, low viscosity, and poor sand-carrying capacity. This method allows proppants of larger particle size to be pumped in, expands the fracture width, and reduces the reservoir damage.

In hybrid fracturing, slickwater is first pumped into the wellbore to make full use of water's strong ability to generate fractures, thereby promoting the formation of long cracks. Cross-linked fluids containing gels and proppants of certain grain size are then pumped into the well, producing viscous fingering in the long fractures, which lowers the terminal velocity of the proppants and helps to sustain fracture conductivity. After a comprehensive evaluation and comparison of conventional hydraulic fracturing and the novel hybrid fracturing, the half-length of the effective fractures generated by the hybrid fracturing are longer, which allows significant elongation of the cracks and expanded scope of crack-affected zone, enhanced sand-transport capacity, and fewer fluid loss and water consumption.

One of the key issues to be solved for hybrid fracturing is how to generate longer effective fractures to achieve better sand-carrying capacity and lower fluid loss. Another central issue is how to reduce reservoir damage, as the degree of damage to the reservoir caused by hybrid fluids is significantly lower when compared with cross-linked fluids.

The technology is now heading toward longer half-length of factures and less pollution to the formations. Controlled by the two American companies, Anadako Oil and Baker Hughes, it has achieved remarkable results after its field applications in multiple shale plays in the USA.

- Fiber fracturing technology

In general, the water fracturing technology can neither make the proppants fill the hydraulic cracks properly, nor can it effectively improve issues like the permeability. The use of new fiber-based fracturing fluids (FiberFRACs) as fracturing agents can effectively ameliorate problems such as unsatisfactory crack width by hydraulic fracturing , insufficient sand-carrying capacity of the fracturing fluid, rapid sedimentation of proppants at the bottom of the fractures around the wellbore, etc.

The principle of the fiber fracturing technology relies on adding the fiber materials to the fracturing fluid to improve its apparent viscosity, so that the proppants can remain suspended during the fracturing process. Some fibrous structures can be dissolved automatically after fracturing, to further improve the conductivity of the modified fractures. This new technology has improved sand suspension and fracture conductivity without the use of large equipment, reducing the engineering costs.

Degradable fiber fracturing technology has significant benefits in suitable reservoirs, such as brittle and shallow shale reservoirs, and works better with slickwater fluids and light proppants.

Future development trends of this technology are aimed at further improving the performance of the fracturing fluid and choosing more suitable proppants with better compatibility, to expand its range of applications.

This technology has been developed and put into use by a few companies like Schlumberger. Further, the technology has performed well in tight gas reservoirs in North America. It is also accessible to Petroleos Mexicanos, which has achieved good results when exploiting a tight sandstone gas in the Burgos Basin.

- Waterless hydraulic fracturing technology

Waterless hydraulic fracturing technology mainly comprises: nitrogen fracturing, CO_2 fracturing, LPG fracturing, and other technologies.

Nitrogen fracturing uses nitrogen as a fracturing matrix, to generate fractures and enhance reservoir permeability, with the goal of increasing productivity This fracturing process is free from water and solid particles, which not only eliminates water sensitivity and water lock damage caused by the water content of conventional fracturing fluids, but also eliminates the blockage of perforations and fractures by solid particles. However, the low density of the nitrogen results in poor proppant-transport properties. The lack of proppants in the fracturing process leads to gradual closure of newly opened fractures after a certain period of time, adversely affecting the end effects of fracturing and the economic benefits of this technology.

Recently, the liquid nitrogen fracturing technology has garnered a lot of research interest. This technique uses of liquid nitrogen (–195.8 °C) as a fracturing fluid to perform reservoir stimulation. The mechanism of its auxiliary functions in crack initiation is divided into two components: the thermal shock caused by the contact of extremely low temperature liquid nitrogen with the rock, and the thermal stresses acting on the fracture surface during the abovementioned process, which shatters the rock surface when it exceeds the tensile strength of the rock.

Liquid CO_2 fracturing technology uses liquid CO_2 as a fracturing medium, which is injected into the reservoir for fracture generation, sand transport, and displacement. Simultaneously, the liquid CO_2 is rapidly gasified under the temperature of formation, mixing with the crude oil and greatly reducing the viscosity of the oil, while increasing its fluidity. CO_2 can react with the water in the reservoir to generate carbonic acid, mitigating the swelling of clay minerals, removing crack congestion, increasing gas solubility of the reservoir, and eventually, achieving the goal of increased productivity.

In recent years, some scholars have proposed the use of supercritical CO_2 fracturing, where CO_2 is in a supercritical state, as the temperature and pressure exceeds the critical values of 31.1 °C and 7.38 MPa, respectively. A supercritical fluid is neither a gas nor a liquid, with different basic properties. With its density close to that of a liquid, its viscosity is closer to a gas (about 5% that of water). It has very low surface tension, but a diffusion coefficient higher than a liquid, giving it a strong permeability.

It is easy to reach the supercritical state under the stimulation conditions in wells, as both the critical pressure and temperature of CO_2 are fairly low. Supercritical CO_2, one of the most widely used supercritical fluid for the time being, supercritical CO_2, when used as fracturing fluid for stimulation, has demonstrated its own advantages over slickwater-fracturing and foam-fracturing: (1) CO_2, cheap and easy to obtain, is neither flammable, explosive, nor corrosive in the supercritical state. (2) The viscosity of supercritical CO_2 is low, similar to a gas, with low (near zero) surface tension, high fluidity, and low friction coefficients. (3) No clay swelling is observed in the reservoir with supercritical CO_2, eliminating the water lock effect, rock wettability alteration and other hazards from the root, effectively protecting the reservoir from damage. (4) Being a cleaning fluid that generates little damage, the use of supercritical CO_2 for fracturing promises rapid and thorough flow back, which shortens the production cycle. (5) Compared with conventional fracturing fluids, supercritical CO_2 has strong diffusivity and permeability, allowing it to readily penetrate into the pores and micro fractures in the reservoir, which is conducive to creating a large number of micro fracture networks.

The main aspect of the technology to be addressed is the solid particulate transport ability of supercritical CO_2, and further modification of fracturing equipment. Currently, many countries have shown interest in CO_2 fracturing. In-depth research has been conducted on CO_2 fracturing by the USA and China, among other countries.

- The application of novel nanomaterials in fracturing

Traditional cross-linked guar-gum fracturing fluids cause a great deal of damage to the geological formation. In order to reduce the amount of polymers remaining in the cracks, a wide range of oxidants, enzymes, and other gel breakers have been researched, but their effects on oil and gas production are unsatisfactory. Therefore, the use of water as a fracturing fluid has resumed in some areas. On one hand, this method has low cost and good performance in the field, but on the other hand, it has high fluid loss. Therefore, methods of increasing viscosity and reducing filtration loss based on less formation damage have become a new research topic. Conventional elastic surfactant fracturing fluids have been used for gravel packing and hydraulic fracturing for over twenty years. In this method, the surfactant can be naturally arranged in the brine to form threadlike micelles (TLMs). TLMs, similar to polymers, are thickened by overlapping and entangling micelles. Generally, the TLM system can be rapidly filtered in porous media, resulting in a low efficiency of crack creation, which limits its application in this field.

To mitigate this problem, some researchers abroad added nano-particles to the surfactants to create associations between the surfactant micelles in the fracture fluids, forming a three-dimensional network of surfactant micelles. In this way, wall stimulation, lower fluid loss and higher liquid efficiency are achieved. The micelles contain gel breakers, and are able to reach any place within the system, ensuring a thorough breakdown of the gels. Fracturing fluids with nanoparticle-enhanced surfactants can be applied in several types of reservoirs. Compared with conventional guar gum, its yield is higher and more sustainable. It is especially suitable for wells sensitive to damage due to fluid conductivity. In addition, additives such as gel breakers have also been developed for this system.

Further, nanomaterials, such as controllable electrolytic metals (CEMs), also find applications in downhole equipment, because CEMs have the unique properties of high strength, low weight, and controllable dissolution rate. CEMs are ideal materials for downhole tools used in repair-free well operations. They facilitate fluid control and can be dissolved in the liquid within the wellbore, ensuring unimpeded flow of the fluids after each stage of fracturing, thereby enhancing production capacity.

Nanomaterials have been gradually put into use in modern fracturing technology, and are playing an increasingly important role in it. Nanomaterials will gradually become low cost, and be used in customized applications (catered to different formation conditions) in the future.

- New types of proppants

Proppants are injected into the ground along with the fracturing fluids. They help keep the fracture open to facilitate gas extraction. With the emergence of sand transport with higher viscosity, proppants have gradually evolved into many types, including sand, resin-coated sand, ceramic particulate, glass microsphere, walnut shell, steel ball to polymer microspheres, etc. The proppant should be able to sustain the closure pressures, which range from 35–70 MPa for typical formations. Its type, shape, strength, hardness, wear resistance, acid and alkali resistance, corrosion resistance, toughness, grain size, filling density, distribution state, and flow conductivity will have a direct impact on its fracturing effects.

During transport, proppants are susceptible to accumulation inside cracks, creating "islands", and causing other phenomena such as backflows, diagenesis, compaction, burial, and dissolution. They are prone to forming plugs or contributing to crack closure, reducing the production of oil or gas. Therefore, new proppants with ultra-high strength, ultra-low density, self-suspension, new rod-shape and functional orientation have recently received widespread attention. Ideal proppants should have the following features: high strength, smooth surface, chemically inertness, low cost, low density, convenient and practical, resistant to backflows, and not easily buried.

However, at present, even the best proppant is not able to satisfy all these conditions. It is hoped that, in the future, technology can create a proppant that is not only easily transported to the target location, but also has excellent fracturing effects and good stability, so that lasting benefits are possible in every single operation.

- Surface-modification agent (SMA) coating technology

In SMA coating technology, a thin layer of polymer coating is deposited onto the proppants to create an adhesive surface, and thereby increase surface friction. This technology promises rapid coating, stable molecules, strong acid and alkali resistance, and good compatibility with fracturing fluids. It also prevents backflows by improving the viscosity of the fracturing fluids, reducing both sedimentation ratio and deposition rate, and enhancing liquidity. In addition, the coatings are versatile and can be applied to the surfaces of sand and ceramic particles alike. However, it is yet to be determined whether this method can maintain its good performance in different pressure ranges. Moreover, SMA coatings are difficult to dissolve, making equipment cleaning difficult. To tackle this problem, Halliburton developed a water-soluble surface modifier ASMA, which is environmental friendly and has good compatibility with fracturing fluids.

Future development of the surface modifiers should be aimed at consistent performance at different pressure ranges, while simultaneously enhancing the performance of the fracturing fluids.

(3) Current situation and future trends

The rapid development of new fracturing technologies and related materials can be credited to the large-scale development of unconventional oil and gas resource extraction that employs these methods. The development of fracturing technologies for unconventional oil and gas resources is a gradual process. From the gel and N_2 fracturing used in the beginning, to the extensive application of water fracturing and research conducted on new fracturing methods, every innovation brings a revolutionary breakthrough.

At present, in order to meet the needs of the large-scale commercial development of unconventional oil and gas resources, such as shale gas and coalbed methane, fracturing technologies have accomplished multi-stage unlimited fracturing, with control of crack propagation to a certain extent. Fracturing diversion technology has been applied on a large scale, and hybrid fracturing is in the stage of field application. Fiber fracturing and channel fracturing have seen successful on-site trials. Waterless fracturing technologies using LPG, N_2, and CO_2 are still under research and local testing. Research breakthroughs occur every now and then in the USA, Canada, and China, especially in CO_2 (or supercritical CO_2) fracturing. China is now a world leader in this research. Rapid progress has been made in research on fracturing fluids, proppants, additives, small molecules, and guar gum of small molecules with little harm. In addition, new nanomaterials have been widely used in fracturing, such as in nanomaterial-induced association of surfactants and nano-scale downhole equipment. It was found that for proppants, the range of usable densities increases with tensile strength.

In the future, to satisfy the requirements of developing unconventional oil and gas resources that are more economically effective, both conventional water-based fracturing technologies and waterless fracturing technologies will gradually become more efficient and environment-friendly methods with low costs.

(4) Comparisons of major research countries or regions and institutions and their collaborations

From Table 2.2.5, it can be seen that the top 3 countries in terms of the number of core patents on engineering development focus “New fracturing methods, fluids, proppants, and additives” are the USA, China, and Canada. The USA accounts for 78.59% of the world’s total patent output, while China accounts for only 11.43%. The data indicate that the USA is a world leader in deepwater oil and gas development, while China is still at the preliminary stage of research.

From Table 2.2.6, it can be seen that seven of the top 10 institutions that produce these patents are from the USA, with the remaining three institutions from China and Russia. The proportion of China’s institutions is small, which further shows that core technologies in the new fracturing methods are all controlled by American institutions, giving the USA an absolute advantage. Among the American institutions, three oil giants—Halliburton, Schlumberger, and Bakerhughes—control the core technologies. It can be concluded that China is still lacking in this field.

Collaboration networks of major countries or regions and institutions that produce most core patents in the engineering development of new fracturing methods, fluids, proppants, and additives is shown in Figure 2.2.5 and 2.2.6.

From Figure 2.2.5, it can be seen that the USA, the country with highest number of patents, has Canada, UK, France, and China as its top 4 collaboration partners. The top 5 countries with the most fracturing-related inventions, namely, the USA, China, Canada, Holland, and France, are also the largest collaboration partners to each other. Countries or regions like British Virgin Islands and Russia follow the above-mentioned inventor countries, with fairly considerable research on fracturing. The collaboration between these countries has jointly determined which technologies to further develop for new types of fracturing, fluids, proppants, and additives，which are the representatives of new technologies.

It can be seen from Figure 2.2.6, that the number of patents obtained by SLMB and PRAD account for the majority of the patents obtained by all enterprises. collaboration

Table 2.2.5 Major producing countries or regions of core patents on the engineering development focus “New fracturing methods, fluids, proppants, and additives”

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	USA	378	78.59%	3686	84.77%	9.75
2	China	55	11.43%	390	8.97%	7.09
3	Canada	47	9.77%	220	5.06%	4.68
4	The Netherlands	35	7.28%	152	3.50%	4.34
5	France	34	7.07%	135	3.10%	3.97
6	UK	29	6.03%	107	2.46%	3.69
7	Virgin Islands	23	4.78%	93	2.14%	4.04
8	Russia	18	3.74%	40	0.92%	2.22
9	Germany	6	1.25%	32	0.74%	5.33
10	Saudi Arabia	5	1.04%	49	1.13%	9.80

Table 2.2.6 Major producing institutions of core patents on the engineering development focus “New fracturing methods, fluids, proppants, and additives”

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	HALL	200	41.58%	2226	51.20%	11.13
2	SLMB	73	15.18%	554	12.74%	7.59
3	PRAD	51	10.60%	299	6.88%	5.86
4	BAKO	34	7.07%	250	5.75%	7.35
5	CNPC	16	3.33%	121	2.78%	7.56
6	SNPC	9	1.87%	69	1.59%	7.67
7	Trican Well Service Ltd.	6	1.25%	38	0.87%	6.33
8	Carbo Ceramics Inc.	5	1.04%	64	1.47%	12.80
9	Self-Suspending Proppant LLC	5	1.04%	42	0.97%	8.40
10	Tatneft	5	1.04%	2	0.05%	0.40

Note: HALL stands for Halliburton Energy Services Inc.; SLMB stands for Schlumberger Technology Corp.; PRAD stands for Prad Res &Dev Corp.; BAKO stands for Baker Hughes; CNPC stands for China Nat Petroleum Corp.; SNPC stands for Sinopec Corp.

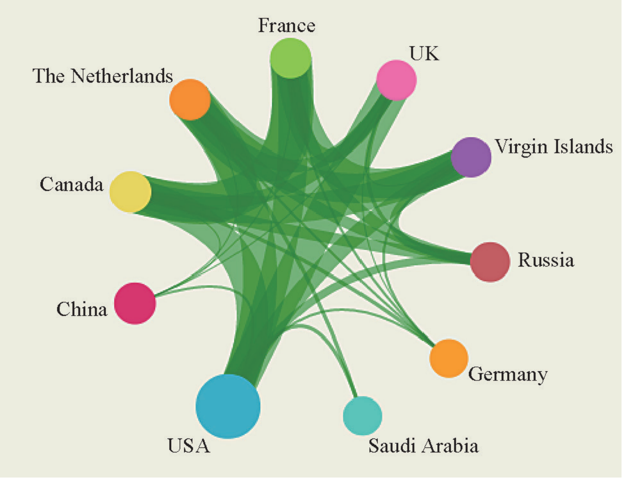

Figure 2.2.5 Collaboration network of the major producing countries or regions of core patents on the engineering development focus “New fracturing methods, fluids, proppants, and additives”

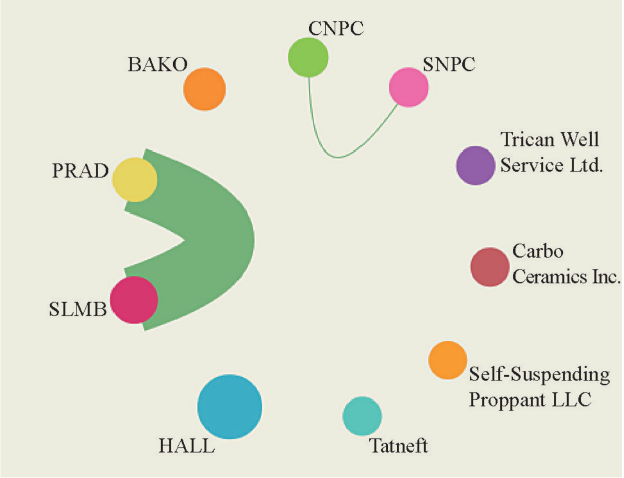

Figure 2.2.6 Collaboration network of the major producing institutions of core patents on the engineering development focus “New fracturing methods, fluids, proppants, and additives”

between the two institutions leads to an absolute advantage over the others. Patents from other institutions take up comparatively small shares in the market. Therefore, the two institutions are at the forefront of innovation and technology in this field, while other research institutions are falling behind at the initial stages of research.

China is now at an early stage in development of new types of fracturing technologies. Quite a large proportion of this development is introduced from abroad. China is still lagging behind in most technologies in this field. Major research and application of new types of fracturing proppants is also undertaken by foreign countries, while domestic researchers are still in the process of catching up. Material performance is the fundamental reason for this slow domestic development.

(5) Current situation and dominant trends in China

Presently, China is still in the preliminary stages of the research on new fracturing technologies, and a large number of technologies draw inspiration from other countries. According to the number of patents that China has disclosed in this regard, China is still catching up to other countries.

As more advanced fracturing methods are being proposed by foreign companies or institutions, China’s research units are following and reproducing their research, such as in the cases of multi-stage unlimited fracturing and fracturing diversion. However, due to problems encountered regarding materials, manufacturing, and further processing, breakthroughs in core technologies have not been possible yet. For example, consider the reusable rubber packer. Imported rubber packers can undergo the process of setting and de-bonding a dozen times, while China’s rubber can only do so two to three times. These performance problems of China’s rubber materials become a hindrance to the overall development of related technologies.

In order to study a development method suitable for extracting unconventional oil and gas resources in China, many organizations in our country have begun researching waterless fracturing. China now has built up considerable advantage. In particular, research on liquid nitrogen and supercritical CO_2 fracturing has entered the stage of field trials, and is expected to see large-scale application within the next five years, while supercritical CO_2 fracturing will be combined with oil and gas displacement, replacement, and burial, to realize green development and utilization of oil and gas.

At present, the main research direction for unconventional oil and gas fracturing in China focuses on large-scale hydraulic jet fracturing, multi-stage unlimited fracturing, channel fracturing, waterless fracturing, new nano-surfactants, new fracturing fluids, super-light and ultra-high strength proppants, etc. In order to speed up the development of new fracturing technologies in China, setting up a special fund for the “new fracturing technology of unconventional oil and gas”, that focuses on the support of basic scientific research to break the bottlenecks existing in the development of unconventional oil and gas, has been proposed. Interdisciplinary IUR teams can be set up by integrating advantages of university and industry research and starting from the basic problems of theoretical design, material processing, etc., to address the key problems in current technological development. Moreover, international collaboration and active participation in major international development programs on unconventional oil and gas will enhance the progress of China’s unconventional oil and gas development.

2.2.4 Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment

Nuclear power equipment technology is the key technology to achieve the thermo-hydraulic function of the reactors, and ensure economical and safe operation of nuclear power plants. It includes design, materials, processing and manufacturing, inspection and testing, safety assessment, acceptance, transportation, decommissioning, and other technologies. Public concerns on the safety of nuclear power keep growing, as do safety requirements of nuclear power equipment, which include higher seismic rating, increased durability, more stable operation, more reliable passive technology, stronger disaster mitigation capacity, etc. At present, only the USA, France, and Russia have developed a complete set of standardized technologies in nuclear power equipment. With an advantageous domestic market for nuclear power equipment, China has been able to fabricate equipment capable of generating a million kilowatts by independent design, manufacturing, and innovation, after cycles of introduction, assimilation, and recreation in recent years.

Fuel assembly is an important component of the reactor core, and is the only component where chain fission reactions take place, and where fission products are contained. The reactor pumps and valves are important devices for driving the circulation of reactor coolants, and performing the thermo-hydraulic functions of the reactor. Reactor pressure vessels and pipelines are important pressure boundaries in the loops of a reactor system. The integrity of the pressure boundary plays a key role in preventing the leakage of radioactive substances. The reactor containment is the last safety barrier of the reactor. The nuclear power equipment mentioned above is different from ordinary energy equipment. During normal operation, this equipment has to not only withstand high temperature and pressure, but also absorb strong radiation from fission and decay. According to nuclear safety regulations, nuclear power equipment should have a certain degree of safety and structural integrity in case of accidents depicted in the basic reactor design. With the development of the safer 3G and 4G advanced reactor heaps, such as offshore floating nuclear power plants and small modular reactors, more stringent safety requirements have been set for nuclear power equipment.

Fuel assemblies in nuclear reactors are mainly combined rod fuel assemblies, spherical fuel assemblies, liquid molten salt fuel assemblies, etc. Fuel assemblies are used in the strong neutron field inside the reactors for three to five years, and subjected to harsh working conditions, such as high temperature, high pressure, erosion due to rapidly flowing coolants, chemical effects from the fission products, and complexly applied mechanical load. At present, mainstream pressurized water reactors adopt 17×17 rod-like fuel assemblies without any channel boxes, worldwide. Fuel components consist of the fuel rod, draft tube, positioning grid, and the upper and lower headers. The fuel pellets contained in the fuel rods are made from 3% to 5% concentrated uranium. The fuel cladding is the second safety barrier of the reactor, and the positioning grid is an important skeleton that supports the fuel assembly. In order to improve the burnup and increase the economic benefits of nuclear power, countries around the world have actively developed new types of high-performance fuel components with the following characteristics: long cycle time, high burnup, high reliability, operational flexibility, lower storage of spent fuel, longer power plant life, and lower fuel manufacturing costs. Currently, AFA3G is a high-performance fuel component used in commercial operations worldwide.

Nuclear power pumps and valves are divided into two categories, nuclear safety related equipment and non-nuclear safety equipment. Nuclear safety related pumps include reactor coolant pumps, charging pumps, residual heat removal pumps, containment spray pumps, etc; while pressurizer safety relief valves, proportional spray valves, the main steam isolation valves, blasting valves, etc. are some of the nuclear safety related valves valves. The reactor coolant pump (referred to as the nuclear main pump) is an important piece of equipment, used to drive the reactor-loop coolant cycle and discharge the heat inside the core. Reactor coolant pumps are mainly divided into two types—seal and shield. The key technologies of reactor coolant pumps include efficient hydraulic model development, high reliability water lubricated bearings, high stability rotor dynamics, high integrity and moment of inertia flywheels, complex clear flow in the shielded motor main pump, three-stage dynamic and static pressure sealing of the shaft seal core pump, the processing and installation of the stator and rotor of the shield motor main pump, seismic technology, etc. The shaft seal type is adopted in most designs, based on French nuclear power technology, while the shielded motor main pump is based on third generation nuclear power technology developed by the USA firm Westinghouse. The key technologies of nuclear power valves include low flow resistance spool structure design, transient flows at the valve and force distribution on the valve stem, flow vibration and noise control, a large thrust valve-driven mechanism, spool wear and life assessment, and evaluation of valve reliability.

The reactor pressure vessel refers to the pressure vessel of the reactor body, which forms an important part of the reactor coolant pressure boundary. The material it is made of requires a high degree of integrity, high strength and toughness, low radiation sensitivity, ease of manufacture, and low cost. The life of the pressure vessel is directly related to the life of the nuclear power plant. The key technologies of pressure vessels include: manufacturing of large forgings, flange sealing and leakage detection, retention of the molten core in case of accidents, in-service inspection, flange bolt locking mechanisms, irradiation supervision, and underwater maintenance. The reactor pipeline includes a main loop and a secondary loop, where the key technology is pipeline welding and anti-corrosion.

The reactor containment is the outermost structure that constitutes the pressurized water reactor. It is intended for the accommodation and isolation of the reactor pressure vessel, and forms a part of the security system (which includes the main loop and its equipment and shutdown cooling system), serving as a safety barrier. The containment is the last protection against the release of fission products into the surrounding environment. The containment, hemispherical at the top, is usually a pre-stressed concrete cylinder imbedded with steel plates. There are many forms of containment structure with varying structural materials, such as steel, steel-reinforced concrete, pre-stressed concrete, and composites of steel and reinforced concrete or pre-stressed concrete. The third-generation nuclear power containment structure adopts a double-containment design that permits exterior cooling.

Major institutions that produce nuclear power equipment include: Shanghai Electric, Dongfang Electric, Harbin Electric, Westinghouse, Mitsubishi Heavy Industries, Heavy Industries, Busan Heavy Industries, Areva, KSB (Germany), etc.

Through scientific and technological breakthroughs, and infrastructural development for local production of nuclear power equipment, China has become capable of manufacturing and supplying improved second generation nuclear power equipment, with the capacity to generate a million kilowatts. Owing to the introduction, digestion, and absorption of the technologies of the third generation like AP1000, China has successfully manufactured, with independent IP rights, key nuclear power equipment components like the Hualong One and CAP1400, as a part of major national projects on nuclear power development. An industrial system for obtaining nuclear fuels, which includes uranium mining, uranium concentration, fuel component manufacturing and reprocessing of spent fuel, has been developed.

Shanghai Nuclear Engineering Research and Design Institute, a part of the State Nuclear Power Technology Corporation (SNPTC), established a strategic collaboration initiative with Shanghai Jiao Tong University for the development of nuclear materials, key technologies of nuclear pumps, retention tests on molten cores, and containment water film cooling tests. SNPTC established a research institute with Tsinghua University, as a joint effort to carry out passive safety thermo-hydraulic tests for third generation nuclear power plants. Dalian University of Technology joined hands with Shenyang Blower Works Group Corporation, and set up a research institute to develop reactor cooling pumps and nuclear Class II & III pumps. Although China is still catching up in the design of nuclear power equipment, it is getting close to the world leader in this field, after years of introduction, assimilation, and re-creation. In terms of the manufacturing of nuclear power equipment, governmental support and self-upgrading by enterprises have improved China's competitiveness, making it a world leader in this area.

Table 2.2.7 and Table 2.2.8 show that benefiting from the national strategy of actively and steadily developing nuclear power in China, China has made outstanding achievements in the field of independent research and development of nuclear power technology. The USA remains the leading position in the rapid development of nuclear power technology because of its abundant accumulation of nuclear power technology, original innovation and technology. Although the Japanese Fukushima nuclear accident, but the electric power market demands and the development of nuclear power equipment technology do not stop. Korea independently developed the APR1400 Generation-III nuclear power technology and has achieved good overseas performance, with a certain independent intellectual property rights. Although the French nuclear power accounted for relatively high, in recent years, as it is trapped in Areva's decline in performance, there is no outstanding performance in the field of technological innovation.

As can be seen from Figure 2.2.7, cooperation between the USA and other countries is relatively close, but there is a lack of cooperation between China and other countries.

As can be seen from Figure 2.2.8 is the cooperation between CNNC and CGNPC, and the cooperation between Korea Atomic Energy Agency and Korea Electric Power is more closely.

Table 2.2.7 Major producing countries or regions of core patents on the engineering development focus "Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment"

No.	Country/Region	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	China	97	31.91%	265	33.97%	2.73
2	Japan	79	25.99%	191	24.49%	2.42
3	USA	64	21.05%	211	27.05%	3.30
4	Korea	40	13.16%	92	11.79%	2.30
5	France	8	2.63%	6	0.77%	0.75
6	Russia	7	2.30%	8	1.03%	1.14
7	Canada	5	1.64%	1	0.13%	0.20
8	Sweden	3	0.99%	2	0.26%	0.67
9	Germany	2	0.66%	4	0.51%	2.00
10	UK	2	0.66%	1	0.13%	0.50

Table 2.2.8 Major producing institutions of core patents on the engineering development focus “Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment”

No.	Institution	Published patents	Proportion of published patents	Citation frequency	Proportion of citation frequency	Average citation frequency
1	CNNU	31	10.20%	93	11.92%	3.00
2	GENE	31	10.20%	98	12.56%	3.16
3	TOKE	25	8.22%	48	6.15%	1.92
4	KAER	21	6.91%	32	4.10%	1.52
5	CGNP	17	5.59%	53	6.79%	3.12
6	MITO	14	4.61%	18	2.31%	1.29
7	WESE	13	4.28%	43	5.51%	3.31
8	BABW	11	3.62%	57	7.31%	5.18
9	UYQI	11	3.62%	36	4.62%	3.27
10	KEPC	10	3.29%	17	2.18%	1.70

Note: CNNU stands for China Nuclear & Power Eng Co. Ltd.; GENE stands for General Electric Co.; TOKE stands for Toshiba Co.; KAER stands for Korea Atomic Energy Res; CGNP stands for China Guangdong Nuclear Power Group Co.; MITO stands for Mitsubishi Electric Corp.; WESE stands for Westinghouse Electric Corp.; BABW stands for Babcock & Wilcox Co.; UYQI stands for Tsinghua Univ; KEPC stands for Korea Electric Power Corp.

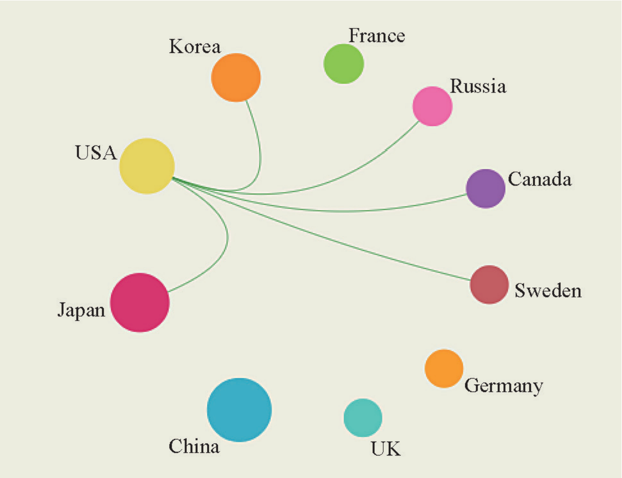

Figure 2.2.7 Collaboration network of the major producing countries or regions of core patents on the engineering development focus “Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment”

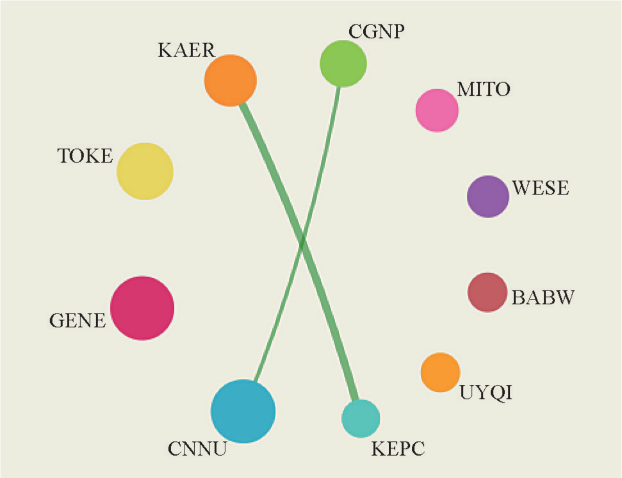

Figure 2.2.8 Collaboration network of the major producing institutions of core patents on the engineering development focus “Nuclear equipment: fuel assembly, pump, valve, vessel, pipe, and containment”

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