Bibliometric Analysis of Research Trends and Hot Spots of Leakage and Diffusion of Hazardous Gases

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Abstract Dangerous gases widely exist in modern production and people's daily life. Once they are used or maintained improperly, they are very easy to leak, leading to major accidents seriously endangering people's health and asset safety, such as fire, explosion, burns, poisoning, asphyxia, *etc.* In this paper, the data collected from CNKI was taken as the research object, and the relevant research in the field of leakage and diffusion of hazardous gases was analyzed through visual analysis by using the VOSviewer software, so as to provide reference for subsequent scholars.

Key words Dangerous gas; Leakage and diffusion; Bibliometrics

DOI 10.19547/j.issn2152-3940.2022.06.011

Dangerous gas leakage accidents emerge in an endless stream at home and abroad every year, causing poisoning of surrounding residents and a large number of casualties. Dangerous gases widely exist in people's daily life and in the production of oil, natural gas and other industries, are inflammable and explosive, and have strong corrosion and high toxicity. In the process of production, storage and transportation, dangerous gas leakage may result in fire, explosion, poisoning and other safety accidents. As the causes of an leakage accident are complex and diverse, and the accident brings great risks and high control difficulty, once it happens, the consequences are inestimable and the loss is serious[1]. For example, on June 27, 2022, toxic chlorine gas leaked in Aqaba, a port city of southern Jordan. A transport belt carrying containers broke, so that the containers fell onto a cargo ship in the port of Aqaba. As a result, the gas storage tank containing 25 tons of chlorine exploded, and a large amount of yellow gas rose from the ground quickly, resulting in 14 deaths and 251 injuries.

With frequent occurrence of events, it is of great significance to conduct pre-event prevention and post-event risk early warning to greatly reduce economic losses and provide basis for safety assessment and emergency rescue. In this paper, the current research results of the leakage and diffusion of dangerous gases were summarized, and the current research methods, applicable objects, development characteristics and internal connections were analyzed to provide reference for domestic scientific research in future.

1 Main research methods

In the middle of last century, with the frequent occurrence of dangerous gas leakage and explosion accidents, European and American research institutions conducted a series of large-scale field tests and theoretical studies on leakage and diffusion, and proposed a variety of leakage and diffusion models on the basis of leakage and diffusion test data, such as Sutton model, BM model and box model, *etc*[2]. In the late 1980s, many numerical simulation software came out and was widely used. At present, a knowledge system of leakage and diffusion based on theoretical framework, experimental simulation and numerical simulation assisted verification has been basically formed abroad.

In the 1980s, China began to study the leakage and diffusion of dangerous gases, and some research institutes began to carry out a series of wind tunnel tests and flume simulation tests, China's research started relatively late and did not carry out any large field leakage tests. Due to insufficient experimental research and weak theoretical model research foundation, a complete theoretical framework and knowledge system of leakage and diffusion has not been formed. Compared with foreign countries, China's research on the numerical simulation of leakage and diffusion was carried out late due to the development of computer field. Presently, research methods of dangerous gas leakage and diffusion mainly include field test, experimental simulation and numerical simulation.

1.1 Field test Field test research was carried out in foreign countries around the 1970s and 1980s. Generally, the general law model of gas diffusion was obtained through full-size field tests for gases with stability, such as liquefied natural gas, liquefied petroleum gas and other heavy gases and mixed gases. The leakage and diffusion studies were carried out on relatively open sea surface, lake surface and ground, and terrain conditions such as ground roughness and slope, meteorological conditions such as temperature and humidity, as well as the influence of leakage sources should be considered. The initial diffusion conditions of gas are given for free diffusion. The data obtained according to the real scenario simulation has certain universality and applicability, and can not only be used to verify the accuracy of numerical diffusion,

Received: October 13, 2022 Accepted: December 3, 2022

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but also provide valuable data support for the establishment of numerical models. However, it needs a lot of funds to support, and the data repetition availability is poor; there is a great risk, so it is not the optimal method to study gas leakage and diffusion. China's research started late, and domestic early large-scale experimental research is basically blank.

1.2 Experimental simulation A laboratory simulation test is easy to control the change of test conditions, and it is a simulation experiment carried out in the laboratory after simplifying a field test, including wind tunnel experiment and flume simulation experiment. It saves certain funds compared with the field test, and has better reproducibility and intuitiveness. For some special gases with active chemical properties, such as hydrogen fluoride, liquid ammonia, *etc.*, their diffusion is easy to be affected by atmospheric environment, and they have corrosive and toxic properties. The advantages of laboratory simulation are much greater than field tests, and the uncontrollability of results can be avoided to a certain extent. However, outdoor conditions are complex and changeable, and the laboratory simulation test has simplified the external conditions to a certain extent, so it cannot accurately obtain the real situation of leakage and diffusion, and there is a certain deviation.

1.3 Numerical simulation With the development of computer and the rapid improvement of the level of numerical calculation, the development of computional fluid dynamics (CFD) has been promoted, and a number of fluid leakage and diffusion simulation software have been put online in the development of computer technology, mainly conducting real simulation research on practical problems. The process is usually divided into several steps, such as constructing mathematical models reflecting practical problems, solving numerical algorithm, and visualization of results. Based on the principle of fluid mechanics, with the support of computer hardware, simulation calculation is conducted according to different actual conditions, and simulation results are displayed. Because numerical simulation is not affected by the actual conditions, different simulation results can be obtained under different setting conditions. For example, Fluent software developed by American ANSYS company and CFX, Phoenics, Star-CD, *etc.*, have a good development prospect in the simulation of gas leakage and diffusion. The advantage is that the required boundary conditions can be changed at will, and the model has lower requirements and simple setting. Compared with other methods, it has less manpower, material and financial costs.

1.4 Interconnections between research methods There is a mutual verification relationship between the research methods of hazardous gas leakage and diffusion, which provides evidence for research results. Many mathematical models suitable for the study of gas diffusion have been obtained through relevant field tests, while new gas diffusion phenomena may appear in continuous tests, so new mathematical models will be derived, or existing mathematical models will be modified to enrich the leakage diffusion theory. Experimental simulation is a small experiment, and the similarity theory can be used to study a larger reality model. It has strong controllability, and provides important information support for the test of data simulation results. Numerical simulation relies on the computer to conduct iterative operation, reduces the deviation and distortion caused by manual operation, makes the physical model construction and boundary condition design of leakage more realistic and refined, and is closer to the actual field. At present, the more suitable method is to carry out experimental research and computer numerical simulation at the same time to ensure the accuracy of research.

2 Bibliometric analysis of numerical simulation of gas leakage and diffusion

2.1 Research and analysis methods In this paper, an open-ended search on the database of China National Knowledge Infrastructure (CNKI) was conducted with the subject SU = ("gas " and " leakage and diffusion"), and a total of 656 journal articles were retrieved. By using bibliometric tool VOSviewer and CNKI literature search reports, the bibliometric method was used to analyze the overall number of published articles in this field in the past 30 years, as well as the total citation status of published journals to analyze their influence, and searches high citation literature to analyze research hotspots and trends. In addition, VOSviewer and Origin software were used for mapping, visual retrieval of information, and co-word network was mainly used to analyze the research status of gas leakage and diffusion.

2.2 Analysis of annual number of published articles As shown in Fig. 1, an article related to gas leakage and diffusion was published for the first time in 1994. In the past 30 years, the number of published articles gradually increased. By September 1, 2022, a total of 656 journal articles have been published, with a total citation frequency of 8 108 and an average citation frequency of 12.36 per article.

On the whole, the number of published articles was on the rise in the past 30 years. According to the passage of time line, it can be seen that the research on gas leakage and diffusion started relatively late in China. From 1994 to 2005, it was in the initial stage, and showed a small cliff-like growth in 2006, with a steady rise on the whole. By 2021, the total number of published articles reached 60, and it is expected to continue to grow in 2022. As mentioned above, with the rapid development of computers in the 21st century, the diversification of research methods also has a certain impact on the number of published articles on gas leakage and diffusion, and computer numerical simulation has become a research trend.

A total of 296 articles were published in core journals, and the number of articles published in *China Safety Science Journal* was the largest, up to 29, with a total citation frequency of 924 and an average citation frequency of 31.86 per article. Its impact factor is 1.294 . The journal was founded in 1991, and can timely reflect the development trend and level of safety science in China. Other journals included *CIESC Journal*, *Natural Gas Industry*,

Journal of China University of Petroleum (Edition of Natural Science), *Chemical Industry and Engineering Progress*, *etc.* The top 5 journals in the field of gas leakage and diffusion in the past 30 years are shown in Table 1.

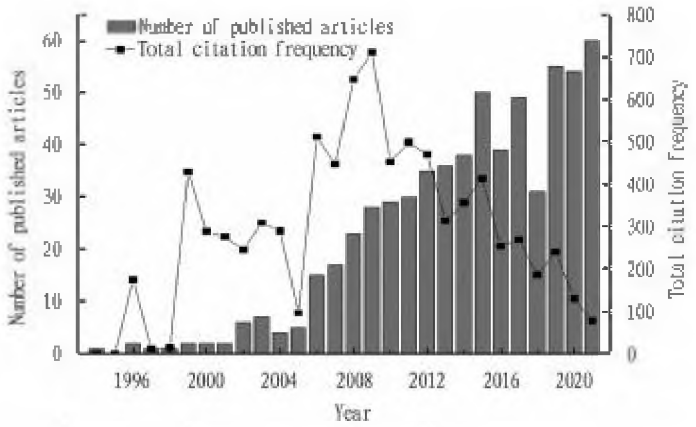

Fig. 1 Changing trend of published articles on gas leakage and diffusion from 1994 to 2021

2.3 Analysis of the main research force Fig. 2 shows the top 6 research institutions in terms of the number of published papers on gas leakage and diffusion in recent 30 years. The figure shows the total and annual number of published papers by each institution from 2006 to 2021. It can be seen that the number of articles published by China University of Petroleum (East China) was the largest, with its first article published in 2008 and remarkable achievements in a short period of time. In 2019, the number of published articles peaked, up to 7. By 2021, a total of 38 papers have been published, focusing on the study of leakage and diffusion of underwater, submarine, buried and other gas pipelines. Southwest Petroleum University published articles earliest, and the first paper was published in 2006. A total of 28 papers have been published by 2021, and remarkable research achievements have been made in recent years, mainly focusing on the analysis of dynamic flow fields such as diffusion law and mechanism of hydrogen-doped and sulfur-containing natural gas.

Table 1 Top 5 journals in the field of gas leakage and diffusion from 1994 to 2021

Journal	Number of published articles	Citation frequency	Average citation frequency per article	Impact factor
China Safety Science Journal	29	924	31.86	1.294
CIESC Journal	10	107	10.70	1.010
Natural Gas Industry	9	488	54.22	2.353
Journal of China University of Petroleum (Edition of Natural Science)	6	177	29.50	1.198
Chemical Industry and Engineering Progress	5	48	9.60	0.877

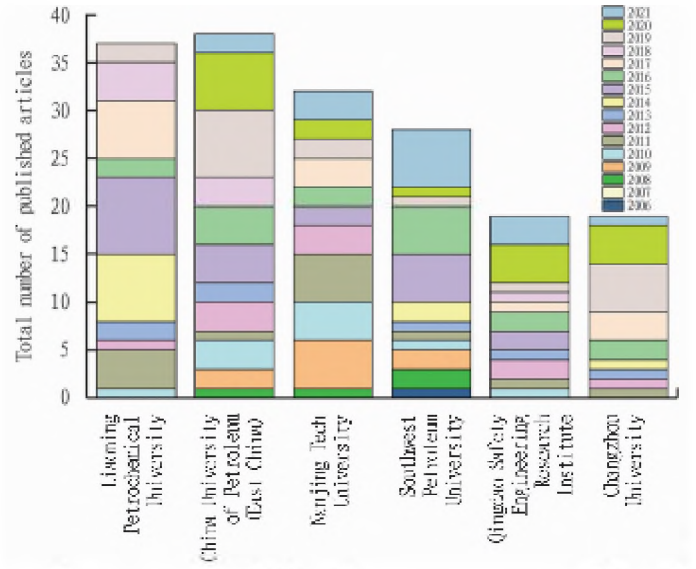

Fig. 2 Research institutions with a large number of published articles on gas leakage and diffusion in recent 30 years

The co-occurrence visual knowledge chart of authors studying gas leakage and diffusion in recent years is shown in Fig. 3. As can be seen from Fig. 3, author cooperation was mainly centered on Chen Guoming from Shanghai Minimally Invasive Xintong Medical Technology Co., Ltd., and there was a large network of author cooperation, with a total number of 18 articles published. There was close cooperation within the team. Another large network of author cooperation was centered on Jiang Juncheng from Changzhou University, and there was close cooperation inside and outside the team, with a total number of 13 articles published. In general, it can be seen that the cooperation relationship between authors publishing more articles was linear, and there was unidirectional cooperation between different institutions. It was connected by one author or more authors, and the cooperation network is relatively simple.

2.4 Analysis of highly cited papers Table 2 shows a list of highly cited articles in the field of gas leakage and diffusion in the past 30 years. Among them, *China Safety Science Journal* published two articles, and each of other journals published one article. A total of three articles involved in the study of gas leakage and diffusion model, which is the hot research content. The most frequently cited article was the review article published by Ding Xinwei in 1999, which has been cited 361 times. This paper reviewed the research status of dangerous gases (including inflammable and toxic gases) at home and abroad, and mainly introduced the numerical models proposed in the research process (including Gaussian smoky-rain model, B. M. Model, FEM3 model, *etc.*) and test conditions (including Burro test, Coyote test and goldfish test, *etc.*)[3]. The two latest published papers with high citation frequency were published in 2008, among which a paper on the leakage of high-sulfur natural gas pipelines published by Yu Hongxi was highly cited. In this paper, the leakage of methane and hydrogen sulfide from

the broken high-sulfur natural gas collecting pipelines was numerically simulated by CFD software FLUENT, and the influence of wind speed, terrain and other factors on gas diffusion was analyzed[4].

Fig. 3 Co-occurrence knowledge chart of authors studying gas leakage and diffusion in recent years

Table 2 Analysis of highly cited papers in the field of gas leakage and diffusion in recent 30 years

Paper	First author	Journal	Publication year	Citation frequency
A review of studies on the discharging dispersion of flammable and toxic gases	Ding Xinwei	*Chemical Industry and Engineering*	1999	361
Study on diffusion model of gas pipeline leaking	Li Youlv	*Natural Gas Industry*	2004	229
Study on the Dispersion of Flammable and Toxic Gases	Ding Xinwei	*Chemical Engineering (China)*	2000	205
Research on discharging dispersion of chemical dangerous gases and its influence factors	Pan Xuhai	*Journal of Nanjing Tech University (Natural Science Edition)*	2001	200
Study on leakage and diffusion model of important toxic substances	–	*Chemical Labor Protection*	1996	161
Analysis on the leaking process of toxic gases from chemical accidents and determination of the risky area	Du Jianke	*China Safety Science Journal*	2002	140
Comparison and analysis of wind tunnel test data and dispersion model prediction for accidental continuous release of dense gases	Jiang Chuansheng	*China Safety Science Journal*	2003	117
Numerical simulation of leakage and dispersion of acid gas in gathering pipeline	Yu Hongxi	*Journal of China University of Petroleum (Edition of Natural Science)*	2008	99
Discussion on Models for gas leakage and diffusion	Peng Shini	*Gas & Heat*	2008	84
Mathematical simulation of heavy gas diffusion for accidental leakage of hazardous materials	Hu Shiming	*Science And Technology of Labour Protection*	2000	83

Note: " – " means the article was published by the Institute of Chemical Labor Protection of the Ministry of Chemical Industry, and has no first author.

2.5 Analysis of keywords Keywords can reflect hot issues in the research field and reflect the core research content of a article. VOSviewer software was used to draw the co-occurrence visual analysis chart of keywords. The occurrence frequency and collinear relationship of keywords is shown in Fig. 4. Seen from Fig. 4, the collinear relationship among keywords was complicated. Various dangerous gases (liquefied petroleum gas, natural gas, liquid ammonia, *etc.*) were combined under different working conditions (pipelines, storage tanks, tunnels, restricted space, *etc.*) and influencing factors (obstacles, wind speed, leakage aperture, leakage rate, *etc.*) to study the gas leakage and diffusion law, concentration field, danger zone, diffusion model, *etc.*, forming a relatively large relationship network, with a wide range of research ideas. Moreover, it can be seen that numerical simulation took a large proportion in the research field of gas leakage and diffusion, which is a hot research trend.

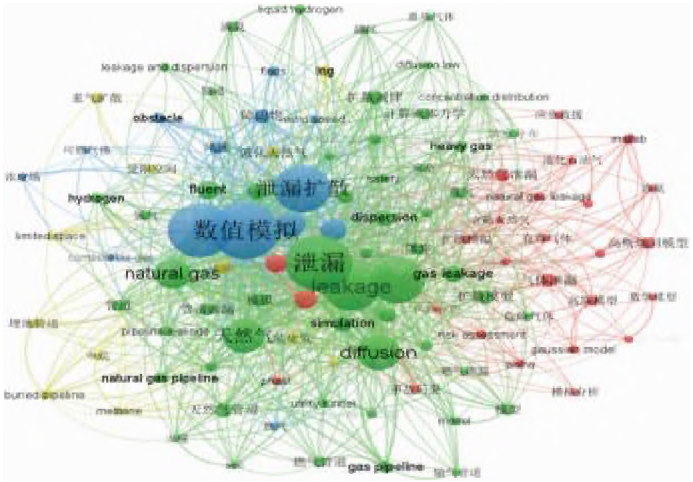

Fig. 4 Co-occurrence chart of keywords in the field of gas leakage and diffusion in the last 30 years

3 Conclusions

Dangerous gas leakage and diffusion is the focus of attention at home and abroad, and has been actively studied. In this paper, the development and change characteristics, trends and research hotspots of published articles on gas leakage and diffusion in the CNKI database were analyzed by using the bibliometric analysis method.

Seen from the number of published articles, although China started late in this field, it had a good development trend. From 1994 to 2003, it was in the initial stage, but since 2004, it showed a steady rising trend. In general, it was related to the rise of computers and the emergence of new research methods at this stage. As can be seen from the proportion of numerical simulation in highly cited papers and the co-occurrence chart of keywords, the keyword nodes of numerical simulation in this field were large, and it is a research hotspot in this field.

With the progress of society, the development of science and technology, and the rise of the petroleum and petrochemical industry, the social unrest brought by dangerous gases still exists widely[5]. In addition, under the influence of external factors, climate conditions are complex and changeable, and have a certain influence on atmospheric motion. Therefore, it is necessary to continue the research on gas leakage and diffusion to enrich the characteristics of gas diffusion under different working conditions and improve emergency response measures to prevent accidents.

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aster investigation and assessment by using satellites, unmanned aerial vehicles and field surveys. According to preliminary investigation and understanding, the heavy rainfall brought losses to 7 818 households, 248 communities, 73 villages and 22 towns in Wuyuan County, Urat Middle Banner, Hangjin Back Banner, Linhe City, Urat Front Banner, and Urat Back Banner.

4 Conclusions

By summarizing the experience and achievements of meteorological forecast service of prefectural meteorological bureaus, it can be seen that advance forecast and early warning and strengthening the linkage of departments are the key for meteorological departments to conduct meteorological service.

Early warning should be advanced to send information to every corner. First of all, it is necessary to raise the political position from the ideological perspective and tighten the responsibility of flood control. Forecasters and early warning personnel should strengthen monitoring and timely release important information such as the start time of the process and the period, falling area and intensity of heavy rainfall to relevant decision-making departments and the masses. Especially at the geological disasters or mountain flood prone spots, everyone should receive timely and accurate forecast and early warning information. Only by perfecting the last mile of information release can the " call and response" service be smoothly carried out, so as to gain precious time for disaster relief and people transfer.

Linkage between departments should be strengthened to minimize disaster risks. It is needed to maintain barrier-free communication with the local major meteorological disaster emergency command offices, gave full play to its command and dispatch role, remind members to pay close attention to weather changes, prepare for and respond to rainfall and secondary and derivative disasters. It is necessary to timely order the meteorological bureau of each banner and county to initiate emergency response to meteorological disasters, initiate regional joint prevention mechanism, learn water situation information from the hydrological department, and report real-time rain and water situation to the downstream banners and counties, so as to provide scientific basis for downstream decision-making and provide reference for the scientific management and flood discharge of the department of water resources. At the same time, it should strengthen the linkage with the departments of fire protection and natural resources and share the resources between departments. All these will help governments at all levels mobilize personnel, organize dike protection and rescue, implement safety measures village, and transfer personnel in time to ensure the safety of people's lives and property.

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