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The Boiling Liquid Expanding Vapour Explosion (BLEVE): A bibliometric review and futur trends

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ABSTRACT

The phenomenon "Boiling Liquid Expanding Vapor Explosion" (BLEVE) is one of the most common accidental events in the chemical industry and in the transport of dangerous goods. A bibliographic search in the Web of Science Core Collection reported 375 publications related to BLEVEs from 1979 to the present (August 10, 2022). A bibliometric analysis was conducted using the VOSviewer tool to allow a better understanding of the scientific knowledge on this phenomenon. A comprehensive overview of BLEVE research is presented in terms of annual publication, top journals, countries/regions with the highest productivity, authors and their cooperation networks, key terms, and co-citation analysis. The 375 publications cover 691 authors, 83 journals, 44 countries or territories and 290 institutions. The key publication (highest number of citations and co-citations) for understanding the BLEVE phenomenon is. The results obtained constitute a snapshot of the current state of the art on BLEVEs and can be applied to improve the understanding of research on this topic and establish new trends of research.

1. Introduction

Abbasi and Abbasi (2007a)The term BLEVE is the acronym for "Boiling Liquid Expanding Vapor Explosion" and is associated with one of the worst accidents that can occur in the chemical industry or in the transport of dangerous goods (Casal et al., 2001). This is the case of the San Juan de Ixhuatepec accident -San Juanico- (Mexico DF) in 1984 in which a succession of BLEVEs occurred in the company Petróleos Mexicanos (PEMEX) (Arturson, 1987; Pietersen, 1988), resulting in 503 deaths, 926 serious injuries (353 people with first degree burns, 425 with second degree burns and 138 with third degree burns) and more than 60,000 people evacuated (Barrera, 2017). The term BLEVE was first used by Smith, Marsh, and Walls of Factory Mutual Research Corp. (USA) in 1957 when analyzing the rupture of a vessel containing a superheated mixture of formalin and phenol. They suggested that the vessel underwent a "boiling liquid expanding vapor explosion" (Abbasi and Abbasi, 2008). Subsequently, Walls defined BLEVE as "the rupture of a main liquid-filled vessel into two or more pieces at a time when the temperature of the contained liquid is well above its boiling point at atmospheric pressure" (Walls, 1978). Several authors have subsequently defined the term BLEVE (Birk and Cunningham, 1994; Van den Berg et al., 2006); the definition proposed by the Center for Chemical Process Safety (1999), "BLEVE is a sudden release of a large mass of pressurized superheated liquid to atmosphere", is widely accepted in the scientific community, although some authors qualify some aspects of this definition (Hemmatian et al., 2016, 2019).

From a rigorous point of view, these explosions do not always present thermal effects; BLEVEs may involve water (Hemmatian et al., 2019; Heymes et al., 2020) or a toxic substance such as chlorine with the corresponding toxic dispersion (Abassi and Abassi, 2007a). However, in a significant number of cases, BLEVE is associated with combustible substances (e.g., liquefied petroleum gases - LPG), which, when exploding, generate a fireball. Thermal and mechanical effects occur simultaneously (Abbasi and Abbasi, 2007a; Török et al., 2011; Planas et al., 2015) along with the projection of fragments (Djelosevic and Tepic, 2019; Vaidogas, 2021). A related aspect of BLEVEs is the domino effect they can cause, which has been studied by several authors (Kumar, 2014; Spoelstra et al., 2015).

The *Failure and Accidents Technical Information System* (FACTS) database (TNO, 2021) containing information on 26,509 accidents occurring up to December 2020, showed a total of 297 accidents in which the accidental phenomenon is associated with BLEVE. Of these, 219 accidents (73.73%) were BLEVE accidents, and 78 accidents (26.27%) were BLEVEs together with fireballs. A significant number of BLEVE-type accidents have been reported in the last 100 years (Prugh, 1991a; Abassi and Abassi, 2007a; Abdolhamidzadeh et al., 2011). The

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first reported accident occurred in 1926 in St. Auban (France), associated with a BLEVE of 25 tons of chlorine resulting in 19 deaths (Abassi and Abassi, 2007a). In terms of severity, some of the largest accidents (next to San Juanico, 1984; as mentioned above) were those of Zamestí (Romania, 1939, 10 tons of chlorine, 60 dead) (Abassi and Abassi, 2007a), Ludwigshafem (Germany, 1948, 33 tons of diethyl ether, 209 dead) (Davenport, 1988), Feyzin (France, 1966, 1000 tons of propane, 18 dead and 89 injured) (Török et al., 2011; Bunn, 2016), Rio de Janeiro (Brazil, 1972, 1000 tons of propane, 37 dead) (Abassi and Abassi, 2007a), Els Alf acs (Spain, 1978, 23.6 tons of propylene, 216 dead) (Blomberg et al., 1985; Mans, 1985), Boral (Australia, 1990, 240 tons of LPG, 35,000 affected) (Eckhoff, 2014), La Eunice (USA, 2000; LPG, 2000evacuees) (Bajwa and Easton, 2009), Cairo (Egypt, 2002; butane, 373 dead and 7500 injured) (Tauseef et al., 2017), Tivissa (Spain, 2002, 48 m^3 of LNG, 1 dead and 2 injured) (Planas et al., 2004a), and Kannur (India, 2012, 18 tons of LPG, 20 dead, 7 seriously injured and 17 people with burns) (Kumar, 2013; Bariha et al., 2016), among others.

Quite a number of studies on the BLEVE (or BLEVE plus fireball) phenomenon have been conducted since it was first mentioned in 1957 (Abassi and Abassi, 2007a). A significant part of these studies were devoted to describing the phenomenon (Birk and Cunningham, 1994; Casal et al., 2001; Abassi and Abassi, 2007a; Baker et al., 2011; Hemmatian et al., 2016) and some established mathematical models to estimate its effects (Gong et al., 2004; Planas et al., 2004b; Kamaei et al., 2016; Hemmatian et al., 2017). Other studies focus on the establishment of prevention, control, and mitigation measures to cope with this accidental scenario (Davenport, 1988; Tauseef et al., 2017). Finally, there are some publications that apply case studies to analyse past accidents and extract lessons learned (Planas et al., 2004a, 2015; Park et al., 2006; Bariha et al., 2016; Zhang et al., 2016). Given the importance and considerable quantity of BLEVE research, it is essential to examine its characteristics and the intellectual framework on which it is based.

An increasingly popular option for these studies is bibliometrics. This technique makes it possible to evaluate and predict the evolution of knowledge on a subject using mathematical, statistical and other alternative methods of measurement (Xu et al., 2018). Bibliometric studies have become widespread in many fields since 2006: in medicine, bibliometrics has made it possible to analyse emerging trends, and in the field of economics and finance it can detect useful information that had not been visible with other bibliographic approaches (Díez-Herrero and Garrote, 2020). Furthermore, this methodology has recently been used in the field of chemical safety in studies on pool fire (Liu et al., 2012), the domino effect (Li et al., 2017), risk analysis techniques in process safety (Amin et al., 2019), more regionally the state of process safety in China (Yang et al., 2020), and even for safety aspects linked to a specific chemical such as hydrogen (Wei et al., 2022). The present study aims to conduct a bibliometric analysis to analyse the current state of the literature concerning the BLEVE phenomenon.

2. Methodology

The present research has been developed under the concept of science mapping, which uses bibliometric methods to examine how publications from different disciplines, fields, specializations, or authors relate to each other (Zupic and Čater, 2015).

2.1. Data collection

The references used in this bibliometric analysis were compiled from the Web of Science Core Collection (WoSCC) (www.webofscience.com). This is a web space that provides access to six major interconnected bibliographic databases (Science Citation Index Expanded, Social Sciences Citation Index, Arts and Humanities Citation Index, Emerging Sources Citation Index, Book Citation Index and Conference Proceedings Citation Index). It is complemented by other regional databases (China, Russia, Korea and Latin America) and two chemical databases (Index Chemicus and Current Chemical Reactions). These databases index the content of almost 10,000 journals in science, technology, social sciences, arts and humanities, and more than 100,000 conference and congress proceedings. The site, which is updated weekly, was selected over other alternatives (Scopus or Google Scholar) because it contains the largest number of references. In addition, WoSCC is considered to be a selective database and its analyses are regarded as highly accurate and reliable for the evaluation of research (Díez-Herrero and Garrote, 2020). Each document collected in WoSCC includes information on the journal or source, year of publication, title, abstract, keywords, authors and their affiliations and countries, subject categories and references, stored as plain text to facilitate bibliometric analysis. Publications have been selected by searching for "BLEVE" OR "BLEVES" OR "Boiling Liquid Expanding Vapor Explosion" in the fields Title, Abstract and Keywords. WoSCC provides a unique citation counting function that allows quantifying the relative importance of publications by using an objective measure of influence (Dzikowski, 2018).

In order to collect all relevant documents, the time period is set as "all years" in the retrieval process, i.e., from 1900 to the date of the search (August 10, 2022). The first publication in WoSCC dates back to 1979. The result is a total of 458 publications related to the term BLEVE (WoSCC is updated weekly, which can lead to minor changes if the query is performed on a different date). Of the total number of publications, a total of 83 references were manually eliminated as they did not correspond to the object of study, which means that the final study was carried out on a total of 375 publications.

2.2. Bibliometric analysis

Five bibliometric methods (Zupic and Čater, 2015) were used to perform an analysis of scientific performance and mapping. The first presents the publication history, categorized by country, journal and author. The second shows the most reiterated words present in the keywords of all the documents. The third shows the network of co-citations and collaborations. The fourth shows the network of co-authorships, i.e., collaboration between authors. The fifth connects the documents based on shared references, making it possible to identify emerging fields, in this case prospects for future studies. In this paper, these five methods have been combined to facilitate the understanding and monitoring of the results associated with the BLEVE phenomenon.

The visual presentation of key information in this study was performed using VOSviewer. VOSviewer is a scientometric and knowledge graph analysis tool developed by Van Eck and Waltman (Van Eck and Waltman, 2007, 2010). It embeds core normalization, layout, clustering, and density map visualization methods for standardizing and visualizing the resulting matrix of knowledge units. The theoretical basis of VOSviewer is detailed in Wei et al. (2022). In addition, MS Excel has been used for some calculations and representations of the work and Word Cloud Generator has been used to represent the keyword map.

3. Results and discussion

3.1. Temporal distribution

Fig. 1 shows the annual and cumulative distribution of publications over the study period, a total of 375 publications. The cumulative trend of publications over time can be used as an indicator of the importance of the phenomenon of BLEVE explosions in the chemical industry and in the transport of dangerous goods, especially by road and rail.

The first publication in WoSCC is from 1979: "Possible mechanism for pressurized liquid tank explosions or BLEVEs" by Robert C. Reid in the journal Science (Reid, 1979). The term BLEVE dates to 1957 and is discussed in at least one earlier reference from 1978, "What is a BLEVE?" (Walls, 1978), not reported in WoSCC.

In the first period, up to 1990, the number of annual publications is very small, which leads us to believe that the phenomenon was still not

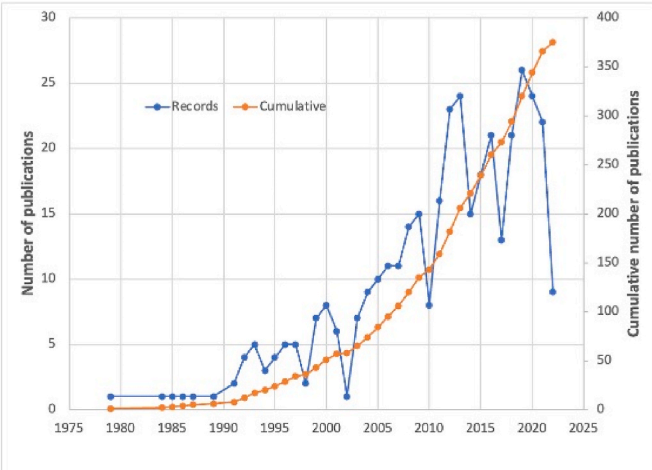

Fig. 1. Temporal distribution of BLEVE publications from 1979 to 2022.

very well known or studied. Nevertheless, some of these publications can be considered relevant in that they form the basis of the literature on BLEVE explosions. Along with the article by Robert C. Reid (1979), a notable article is "BLEVEs: their causes, effects and prevention" (Martinsen et al., 1986), which analyses the BLEVE phenomenon in terms of its causes and possible consequences and establishes a first set of prevention measures with the aim of avoiding this type of accidental event. Two articles in WoSCC relevant to the object of study refer to the detailed analysis of the San Juan de Ixhuatepec accident in 1984 (Arturson, 1987; Pietersen, 1988), considered the most representative in the study of BLEVEs. In general, in this first period, the study of BLEVEs was associated with flammable substances, mainly LPG, which is why the article by Theodore C. Lemoff "BLEVEs in the BLEVEs study" is noteworthy, while Lemoff's paper "BLEVEs without ignition" (Lemoff, 1989) analyses the BLEVE phenomenon without a subsequent ignition.

It is observed that the scientific output for this phenomenon is in line with Price's Law, as cited in Dabi et al. (2016). Price's Law states that the number of publications is the most used indicator to analyse the scientific productivity of a particular discipline. The foundations of the scientific study of BLEVEs can be considered to have been laid up to around 1990. This is the period of the pioneering authors of this object of study.

Although there are some publications prior to 1990 as indicated above, it is in this decade when the need to study the BLEVE phenomenon arose. Several accidents with catastrophic consequences in the 1970s and 1980s made BLEVE one of the most serious accidental events. Londiche and Guillemet (1991) attribute 900 deaths and more than 9000 injuries to 77 BLEVE accidents between 1941 and 1990, such as the Els Alfacs (Spain) accident in 1978 (Blomberg et al., 1985; Mans, 1985) or the San Juan de Ixhuatepec (Mexico) accident in 1984 (Arturson, 1987; Pietersen, 1988; Barrera, 2017). One of the most remarkable aspects is the lack of knowledge of the firefighters in dealing with this type of event; they approached the burning containers with water hoses, and when the explosion occurred, they died. For example, in the Feyzin accident (France) in 1966, 12 of the 18 people who died were firefighters (Bunn, 2016).

From 1990 onwards, there was a period of exponential growth associated with the expansion of the field of research. The subject attracted a growing number of researchers and the aspects to be explored expanded. This second phase in the study of BLEVEs would be between 1990 and 2012, with oscillations in some years, such as 2001, when there was only one publication on this phenomenon (Pierorazio and Birk, 2002). The third phase (2012–2022) shows a consolidation of knowledge. The growth of scientific production changes from a linear model to a curve shape that moves from an exponential to a logistic model. During this period, publications on BLEVEs have remained practically constant at around 20 publications per year. Numerous topics are now being studied, such as the mechanics of pressure vessel failure in the event of BLEVE (Jankuj et al., 2022) or the formation of shock waves near the vessel due to BLEVE (Wang et al., 2022), among others.

In summary, publications over the years have included theories on the concept and mechanism of BLEVEs, simple risk models and consequence calculations, reviews of existing work, analyses of BLEVE accidents, work involving new BLEVE models and methods, and studies involving computational fluid dynamics (CFD) to study the mechanics and consequences of BLEVEs.

By Price's law, the fourth phase involves a period in which publications progressively decrease. In view of the results presented (see Fig. 1), we cannot consider the study of BLEVEs to have reached this moment of maturity, which means that these studies will continue in the coming years. There are still many issues to be studied associated with the BLEVE phenomenon, as shown by the high number of contributions to conferences in recent years, often published in scientific journals afterwards.

3.2. Source analysis

Of the 375 publications on the BLEVE phenomenon collected in WosCC, 263 (70.13%) are research articles published in academic journals (of these 11 are reviews), and the rest are distributed between contributions to conference proceedings and book chapters. Academic journals are important information carriers for the dissemination, communication, and inheritance of scientific achievements (Van Nunen et al., 2018; Zou et al., 2018). Therefore, the analysis presented in this section focuses exclusively on publications in academic journals.

The analysis of academic journals allows us to identify the distribution of the main journals in which the BLEVE phenomenon is addressed. The results show that 263 articles have been published in 83 journals in the fields of engineering, environmental sciences ecology, thermodynamics, material science, public environmental occupational health, energy fuels, mechanics, chemistry, and others. The field of research engineering stands out, with 215 publications (with the caveat that the same academic journal may be classified under different research areas). The journals with the highest scientific production in reference to BLEVEs are listed in Table 1. Publications with at least 3 publications in WoSCC in the period under study have been considered. Information is provided on the Science Citation Index 2021(SCI, 2021) which indicates the scientific influence of the average article in a journal, as well as the quartile which measures the importance of the journal in its field of research.

Journal of Loss Prevention in the Process Industries (JLPPI) is the most prolific journal with 66 articles (26.30% of the total number of articles collected in WoSCC). The focus of the journal is on loss prevention as practiced in the process industries with an emphasis on chemical and process plant safety. It is published in the UK and occupies a 2nd-quartile position in the Chemical Engineering area (SCI 3.916). In 2021 its relative position was 62/142.

The following two journals have SCIs that place them in the first quartile of different disciplines, which shows the relevance and interest of the BLEVE phenomenon as a research element. *Process Safety and Environmental Protection* (PSEP), with 33 articles (13.15%), is published in the UK. It is an international journal that publishes high quality articles in the fields of engineering related to industrial process safety and environmental protection in the subject areas Chemical Engineering and Environmental Sciences. The *Journal of Hazardous Materials* (JHM), with 25 articles (9.96%), has the best SCI of the journals dealing with BLEVE (14.224) and ranks 9th out of 279 academic journals in the field of Environmental Sciences. It is published in the Netherlands and focuses on the understanding of the hazards and risks posed by certain materials to public health and the environment. The article with the highest number of citations on BLEVE, "The boiling liquid expanding vapor

Table 1
Top source journals ranked by the quantity of publications, 1979–2022.

Rank	Source Journal	WoS CC	% of total	SCI 2021	Quartile 2021
1	Journal of Loss Prevention in the Process Industries	66	26.30	3916	Q2 Engineering, Chemical
2	Process Safety and Environmental Protection	33	13.15	7926	Q1 Engineering, Chemical Q1 Engineering, Environmental
3	Journal of Hazardous Materials	25	9.96	14,224	Q1 Engineering, Environmental Q1 Environmental Science
4	Process Safety Progress	13	5.18	1294	Q4 Engineering, Chemical
5	Fire Safety Journal	5	1.99	3780	Q2 Engineering, Civil Q3 Material Science, Multidisciplinary
6	Journal of Pressure Vessel Technology	5	1.99	1046	Q4 Engineering, Mechanical
7	Engineering Failure Analysis	4	1.59	3634	Q2 Engineering, Mechanical Q2 Material Science, Characterization and testing
8	Experimental Thermal and Fluid Science	4	1.59	3370	Q2 Engineering, Mechanical Q2 Physics, Fluids and plasma Q2 Thermodynamics
9	International Journal of Heat and Mass Transfer	4	1.59	5431	Q1 Engineering, Mechanical Q1 Mechanics Q1 Thermodynamics
10	Journal of Failure and Prevention	4	1.59	NA	NA
11	Industrial Engineering Chemistry research	3	1.20	4326	Q2 Engineering, Chemical
12	Reliability Engineering System Safety	3	1.20	7247	Q1 Engineering, Industrial Q1 Operations research and management science
13	Safety Science	3	1.20	6392	Q1 Engineering, Industrial Q1 Operations research and management science

Note: WoS CC = Number of publications in Web of Science Core Collections; SCI 2021 = Science Citation Index (year 2021); Quartile = Position of the journal in the research areas.

explosion (BLEVE): Mechanism, consequence assessment, management" (Abassi and Abassi, 2007a), is published in the JHM.

In fourth position with 13 publications (5.18%) is the journal *Process Safety Progress* (PSP) with an SCI of 1.294 (Q4, Chemical Engineering). It is published in the United States and focuses on chemical process safety, with the peculiarity that it publishes interesting case studies on accidents that have occurred. In 5th and 6th place with 5 articles published each (1.99% of the total) in the period of time analysed are the journals *Fire Safety Journal* (FSJ), published in Switzerland and focusing on research on fire safety science and engineering (SCI 3.780; Q2/Q3), and *Journal of Pressure Vessel Technology Transactions* (JPVT), published by the American Society of Mechanical Engineers (ASME) in the United States (SCI 1.046; Q4), which researches the design and analysis of materials, manufacturing processes, operation and inspection of pressure vessels for the prevention of failures and accidents. The five articles published in JPVT are by the researcher Albrecht M. Birk, among which "On the transition from non-BLEVE to BLEVE failure for a 1.8 m^3 propane tank" (Birk and Van der Steen, 2006) is notable for its citations (27 in WoSCC).

Of the other academic journals listed in Table 1, *International Journal of Heat and Mass Transfer* (IJHMT; SCI 5431), *Reliability Engineering System Safety* (RESS; 7247) and *Safety Science* (SS; 6392) stand out for their importance and impact.

3.3. Analysis of productive countries

According to the results analysed, the total number of publications associated with the BLEVE concept come from 44 countries or territories around the world. Of these 44 countries, 19 are in Europe, 14 in Asia, 4 in North America, 3 in Latin America, 3 in Africa and 1 in Oceania. The total number of publications is 428, higher than the 375 retrieved from WoSCC. An article can be written by authors from different countries or regions, leading to duplication in the count (Liu et al., 2012). Table 2 lists the countries or regions with 10 or more publications. In addition, 18 more countries (40.90%) contributed at least 5 papers.

The leading country in terms of publications on the BLEVE phenomenon is China with 83 entries in WoSCC (22.13% of the total number of entries), which are concentrated from 2015 onwards. This situation means that China can be considered one of the main emerging scientific forces (Zou et al., 2018); the same situation occurs in different areas of research such as biotechnology (Ampese et al., 2022), marketing (Kar and Harichandan, 2022), and Big Data (Xu and Yu, 2019), among others. The second position is occupied by Canada with a total of 43 references (11.47%); Canada stands out for the contribution of Albrecht M. Birk, one of the reference researchers, with 35 publications. All countries with at least 15 publications account for 80% of the total number of publications. Together with China and Canada, USA (33 publications; 8.80%), Italy (32; 8.53%), India (30; 8.00%), France (29; 7.73%), Spain (18; 4.80%); the Netherlands (18; 4.80%), and the UK (15; 4.00%) complete the list (in order of number of publications).

Fig. 2 shows via VOSviewer the map of collaborations between different countries and regions with at least 3 publications on the BLEVE concept. In the network, a node is assigned to each co-author of the publication, and the size and colour of a node denote the number of publications and the cluster to which each node belongs (Li et al., 2017). The thickness of the links denotes the intensity of the collaboration. A total of five clusters have been detected, of which three are considered relevant to the purpose of this study.

Zheng et al. (2016) indicate that collaborating countries tend to be geographically correlated, clustering around the most productive countries or territories in terms of number of publications. Fig. 2 shows an accumulation around China (green cluster). As an Asian country, China's most important relations are with India (Asia) and Russia, which is a European country but with most of its territory in Asia; however, it also collaborates with countries and regions further afield, especially the UK and Germany. A second cluster is centred around France and Canada (blue cluster), countries linked by tradition and language, with a

Table 2
Top countries ranked by the quantity of publications, 1979–2022.

Rank	Country/Region	WoS CC	% of total	Citation	Avg. Citation
1	China	83	22.13	505	6.08
2	Canada	43	11.47	683	15.88
3	USA	33	8.80	394	11.94
4	Italy	32	8.53	450	14.06
5	India	30	8.00	754	25.13
6	France	29	7.73	223	7.69
7	Netherlands	18	4.80	287	15.94
8	Spain	18	4.80	339	18.83
9	UK	15	4.00	158	10.53
10	Norway	13	3.47	155	11.92
11	Australia	11	2.93	47	4.27

Note: WoS CC = Number of publications in Web of Science Core Collections; Citation: number of citations; Avg. Citation = Average of citations for document.

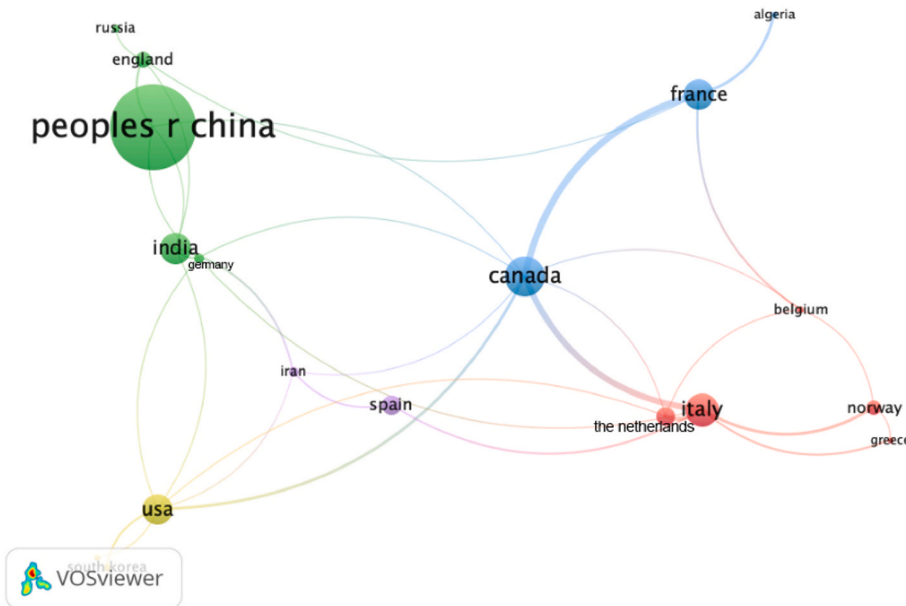

Fig. 2. Countries or territories collaboration network of BLEVE research.

significant number of publications (see Table 2). This second cluster is notable for the intensity of the linkage, which denotes a strong collaboration between the two countries. It also includes Algeria, although with a much lower specific weight. The third cluster (red) centres on Italy and is made up of European countries, most notably the Netherlands. These two countries (Italy and the Netherlands) are home to Europe's leading centres of research on safety and industrial chemical accidents, hence their strong association and high numbers of publications. Norway, Belgium, and Greece complete this red cluster, with a smaller contribution. The two remaining clusters (yellow and violet clusters) represent more dispersed locations: the yellow cluster consists of the USA and South Korea, and the violet cluster is formed by Spain and Iran; in this case the relationship is due to the contributions of the Iranian researcher Behrouz Hemmatian, whose doctoral thesis was supervised by Professor Casal, who continues to collaborate with him on publications. Although five clusters have been defined, the map in Fig. 3 shows other relationships between countries in different clusters, indicative of occasional collaborations that have not been maintained over time.

3.3.1. Institutions

A total of 290 institutions have been involved in the 375 publications collected that address the BLEVE phenomenon (an author may be affiliated with more than one organisation, or a publication may be authored by authors from different institutions). Of the 375 documents, 136 do not present information regarding the institutions of their

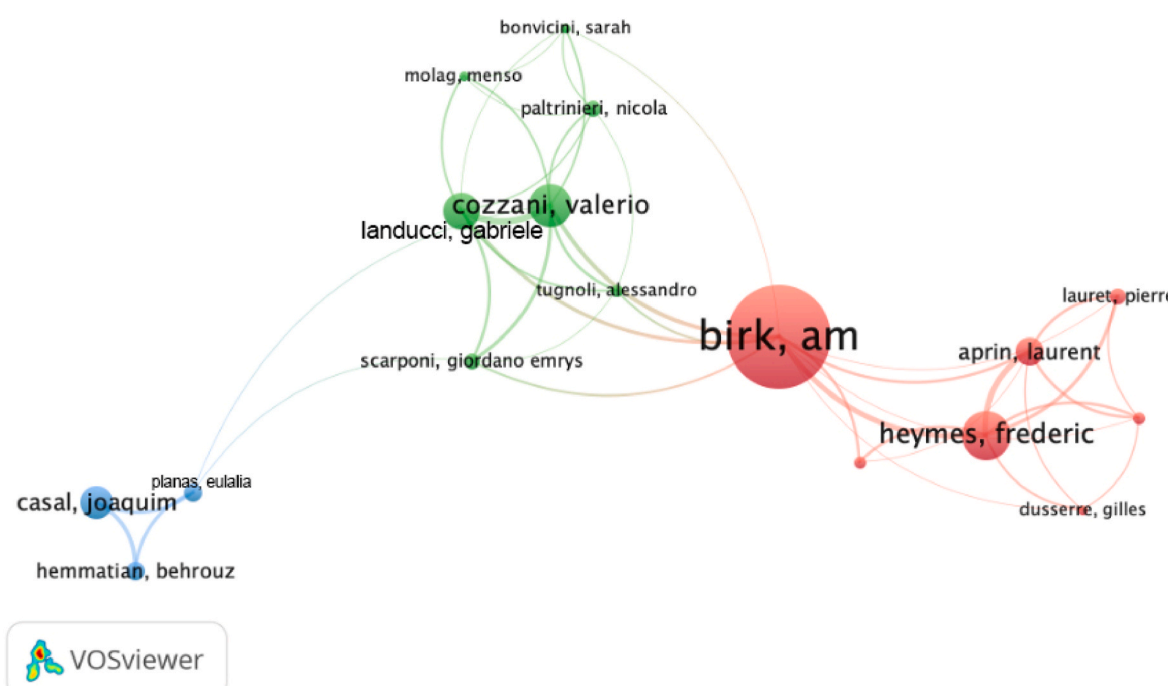

Fig. 3. Authors collaboration network of BLEVE research.

authors. Table 3 shows the 10 most productive institutions publishing on BLEVEs, which are all universities, most notably Queens University in Canada (29 publications; 7.73%), home to the leading researcher in the study of this phenomenon, Albrecht M. Birk. Pondicherry University in India is in second position (16; 4.27%), with a remarkable number of citations associated with its publications and linked to articles of reference by the researchers Shalid A. Abbasi and Tasneem Abassi. This is followed by a group of European universities (two Italian and one Spanish), followed by a group of universities in China. The study of the BLEVE phenomenon is strongly diversified in terms of the countries of the different institutions with the highest number of publications.

3.4. Prolific authors and their cooperation network

The BLEVE phenomenon is a growing area of research (see Fig. 1) that is attracting the attention of researchers. The total of 375 papers collected in WosCC involve 691 different authors. Most authors (516; 74.67%) accredit a single publication on BLEVEs, 16.41% (97 authors) accredit at least 3 publications, and only 11 authors (1.59%) have published nine or more papers. This result is consistent with those of other bibliometric studies where only a small group of authors concentrate a significant share of publications on a specific topic (Liu et al., 2012; Van Nunen et al., 2018; Sharifi et al., 2021; Luo et al., 2022).

Table 4 shows the 11 most productive authors publishing on the BLEVE phenomenon (minimum of 9 publications). The ranking is based on the author's total number of publications and not on the order of authorship (Van Nunen et al., 2018). To better contextualize the contribution of each of these authors, they have been ranked according to the total number of published papers and information has been provided regarding the number and average number of citations per paper. These two parameters are considered critical in the analysis of the impact of the most prolific authors (Dzikowski, 2018). The most cited paper of each author is indicated.

In terms of total publications, Albrecht M. Birk is the most productive author with 35 publications on the BLEVE phenomenon. The Canadian Professor Birk focuses his research on the effects of fire on pressure vessels and thus on the BLEVE phenomenon. Birk can be considered the pioneer in systematic publications on the BLEVE phenomenon with several landmark publications around 1995 (Birk and Cunningham, 1994, 1996; Birk, 1995, 1996) and some more recent ones (Birk et al., 2019, 2020), which shows that he has not left the subject of study since his first articles. In terms of total number of publications, Birk is far ahead of a second group that includes Shalid A. Abbasi with 17 publications and Joaquim Casal, Valerio Cozzani and Frederic Heymes with 16 publications.

When considering contributions in terms of the average number of citations per publication, a wide range is observed, between 4.44 and 37.23. At the top of the ranking are professors from Pondicherry University in India, Shalid A. Abbasi (33.18) and Tasneem Abbasi (37.23), who collaborate with each other. They specialize in process safety and industrial accident prevention, with several publications concerning the field of explosions in the chemical sector (Abbasi and Abbasi, 2007b; Abbasi et al., 2010; Tauseef et al., 2011; Tauseef et al., 2017) along with those more specific to the BLEVE phenomenon (Abbasi and Abbasi, 2007a, 2008). The third position in this ranking (also in terms of number of publications) is occupied by Professor Joaquim Casal of the Universitat Politècnica de Catalunya (Spain) with an average of 20.56. Casal is a Spanish reference in the study of industrial safety in chemical facilities from the perspective of the analysis and modelling of accidental phenomena such as pool fires (Chatris et al., 2001; Muñoz et al., 2004, 2007) or jet fires (Gomez-Mares et al., 2008; Palacios et al., 2009; Casal et al., 2012). He has 16 publications on the BLEVE phenomenon, some with a significant number of citations (Planas et al., 2004a; Planas et al., 2004b; Casal and Salla, 2006) and others more recent, which indicates that BLEVEs continue to be a subject of study for Casal (Hemmatian et al., 2019, 2020). Nine of these 16 publications were co-authored 9 with Professor Eulalia Planas (see Table 4), also from the Universitat Politècnica de Catalunya. Meanwhile, the authors with the lowest average number of citations per publication belong to China, a country that joined the study of BLEVEs later with later publications which do not form part of the initial conceptual framework of this field of research.

The average number of authors per publication is 3.52. Of the total number of papers collected in WosCC, 17.87% (67 publications) were by one author, 20.8% (78 publications) had two authors, 22.93% (86 publications) had three authors and 38.40% (144 publications) had four or more authors, up to a maximum of 12 authors. It can be concluded that there is a great deal of collaborative research on BLEVEs, as multi-authored publications represent more than 80% of the total number of publications. A high number of co-authored publications indicates a closer relationship between authors within the same domain and a greater opportunity for future collaborations (Wang et al., 2014).

Fig. 3 shows the co-authorship network of different contributors, where only authors with at least 3 papers are shown. Each circle represents one author, and the size of the circle corresponds to the number of publications. The connections represent co-authorships, and the thickness of the lines corresponds to the number of co-authorships. Authors with a higher number of publications play an important role in the co-authorship network, and in several cases significant relationships between them can be observed.

Around the figure of Professor Birk there is an accumulation of authors (red cluster), most notably a collaboration with Heymes which has led to recent publications (Birk et al., 2019; Birk et al., 2020; Eyssette et al., 2021). Part of this first network of collaborators is Professor Aprin, from the same university as Heymes, together with other French authors. A second influential group (green cluster) is led by Professors Cozzani and Landucci, and includes mainly Italian authors. Cozzani is a professor at the Università di Bologna, an expert in chemical process safety, and noteworthy for his publications on the study of the domino effect of chemical accidents (Cozzani et al., 2009; Necci et al., 2015; Li et al., 2017). Regarding publications concerning the BLEVE phenomenon, most of his publications are co-authored with Professor Landucci from the Università di Pisa (Paltrinieri et al., 2009; Iannaccone et al., 2021). The lead authors of this cluster (green), Cozzani and Landucci,

Table 3
Top institutions ranked by the quantity of publications, 1979–2022.

Rank	Organizations	Country	WoS CC	% of total	Citation	Avg. Citation
1	Queens University	Canada	29	7.73	350	12.07
2	Pondicherry University	India	16	4.27	1148	71.75
3	Università di Bologna	Italy	15	4.00	295	19.67
4	Universitat Politècnica de Catalunya	Spain	15	4.00	231	15.40
5	Università di Pisa	Italy	13	3.47	246	18.92
6	Beijing Institute of Technology	China	12	3.20	52	4.33
7	University of Science and Technology of China	China	10	2.67	152	15.20
8	Texas A&M University	USA	8	2.13	139	17.38
9	École nationale supérieure des mines d'Alès	France	8	2.13	81	10.13
10	Vilnius Gediminas Technical University	Lithuania	8	2.13	24	3.00

Note: WoS CC = Number of publications in Web of Science Core Collections, Citation: number of citations, Avg. Citation = Average of citations for document.

Table 4
Top authors ranked by the quantity of publications, 1979–2022.

Rank	Authors	Institution	Country	WoS CC	% of total	Citations	Avg. Citation	Most cited document
1	Birk, Albrecht M.	Queens University	Canada	35	9.33	620	17.71	Birk and Cunningham (1994)
2	Abbasi, Shalid A.	Pondicherry University	India	17	4.53	564	33.18	Abbasi and Abbasi (2007c)
3	Casal, Joaquim	Universitat Politècnica de Catalunya	Spain	16	4.27	329	20.56	Planas et al. (2004b)
4	Cozzani, Valerio	Università di Bologna	Italy	16	4.27	287	17.94	Paltrinieri et al. (2009)
5	Heymes, Frederic	École Nationale Supérieure des Mines d'Alès	France	16	4.27	150	9.38	Laboureur et al. (2015)
6	Landucci, Gabriele	Università di Pisa	Italy	14	3.73	247	17.64	Paltrinieri et al. (2009)
7	Abbasi, Tasneem	Pondicherry University	India	13	3.47	484	37.23	Abbasi and Abbasi (2007c)
8	Planas, Eulalia	Universitat Politècnica de Catalunya	Spain	9	2.40	117	13.00	Planas et al. (2004b)
9	Aprin, Laurent	École Nationale Supérieure des Mines d'Alès	France	9	2.40	101	11.22	Laboureur et al. (2015)
10	Chen, Sining	China University of Mining & Technology	China	9	2.40	40	4.44	Chen et al. (2008)
11	Liu, Zhenyi	Beijing Institute of Technology	China	9	2.40	42	4.67	Li et al. (2018)

Note: WoS CC = Number of publications in Web of Science Core Collections, Citation: number of citations, Avg. Citation = Average of citations for document.

have also published jointly with Professor Birk (Scarponi et al., 2017, 2018, 2019). A third accumulation (blue cluster) of lesser relevance is around Professor Casal (Universitat Politècnica de Catalunya) and his co-authors from the same university (see the case of researcher Behrouz Hemmatian discussed above) and with recent publications on BLEVEs (Hemmatian et al., 2017, 2019, 2020).

3.5. References co-citation analysis

In bibliometrics, quality is understood as the impact of a publication in relation to the number of citations it receives (Van Leeuwen et al., 2003; Smith, 2007). This index has been used for decades in the formal evaluation of scientific publications (Liu et al., 2012). However, some authors consider it a measure of visibility rather than quality (Walter et al., 2003). The number of citations per publication considered in this study is provided by WoSCC although other sources could be considered, for example Google Scholar or Scopus. The 375 publications have received a total of 4082 citations (2536 unique citations). The average number of citations per publication was 10.97. Of the 375 publications, 97 (25.87%) have not received any citations at the time of data extraction (August 10, 2022). 3.20% (12 publications) have been cited at least 50 times, and only 1 publication (0.27%) has more than 100 citations in WosCC, namely 193 citations (Abbasi and Abbasi, 2007a). Table 5 presents the articles with at least 50 citations in WosSCC. Citation frequency reflects the number of times publications on BLEVE have been cited by other publications listed in WoSCC.

Generally, the number of citations increases over time and, therefore, older publications tend to have a higher citation frequency (Qui and Chen, 2009). All the publications listed in Table 5 were published more than 15 years ago. This result is in line with other research fields and is considered reliable as publications require a significant amount of time to be widely accepted. Ten years is considered sufficient to accumulate a significant number of citations (Pilkington and Meredith, 2009). It is noteworthy that most of the publications with a high number of citations are basically concentrated in two journals, *Journal of Loss Prevention in the Process Industries (*7 of the 12 publications) and *Journal of Hazardous Materials* (4 publications), which is indicative of their specialization in this field of research.

The article with the highest number of citations, "The Boiling Liquid Expanding Vapor Explosion (BLEVE): Mechanism, consequence assessment, management" (Abbasi and Abbasi, 2007a) is a compilation article that defines the BLEVE phenomenon and details the thermodynamic basis and accident modelling, according to various models, of the extent of thermal, pressure wave and fragment projection consequences. It also presents case studies of BLEVE-type accidents through history and establishes a set of prevention, control and mitigation measures for this accidental event. It is a fundamental article for the knowledge and study of BLEVEs. The article with the second highest number of citations, "The Boiling Liquid Expanding Vapor Explosion" (Birk and Cunningham, 1994) is one of the first articles of reference in the study of BLEVEs by

Table 5
Top publications ranked by the quantity of citations, 1979–2022.

Rank	Title	Author(s)	Journal name	Year	Citations	Citations/ year
1	The boiling liquid expanding vapor explosion (BLEVE): Mechanism, consequence, assessment, management	Abbasi, T.; Abbasi, S.A.	Journal of Hazardous Materials	2007	193	12.06
2	The boiling liquid expanding vapor explosion	Birk, A.M.; Cunningham, M.H.	Journal of Loss Prevention in the Process Industries	1994	69	2.38
3	Blast overpressures from medium scale BLEVE tests	Birk, A.M.; Davinson, C.; Cunningham, M.H.	Journal of Loss Prevention in the Process Industries	2007	68	4.25
4	Liquid temperature stratification and its effects on BLEVEs and their hazards	Birk, A.M.; Cunningham, M.H.	Journal of Hazardous Materials	1996	68	2.52
5	Experimental evaluation of LPG tank explosion hazards	Stawcyk, J.	Journal of Hazardous Materials	2003	65	3.25
6	Risk reduction in road and rail LPG transportation by passive fire protection	Paltrinieri, N.; Landucci, G.; Molag, M.; Bonvicini, S. et al.	Journal of Hazardous Materials	2006	59	4.21
7	Calculating overpressure from BLEVE explosions	Planas, E.; Salla, J.M.; Casal, J.	Journal of Loss Prevention in the Process Industries	2004	59	3.11
8	Explosion of a road tanker containing liquefied natural gas	Planas, E.; Gasulla, N.; Ventosa, A.; Casal, J.	Journal of Loss Prevention in the Process Industries	2004	58	3.05
9	A procedure for analyzing the flight of missiles from explosions of cylindrical vessels	Hauptmanns, U.	Journal of Loss Prevention in the Process Industries	2001	58	2.64
10	Possible mechanism for pressurized-liquid tank explosions or BLEVEs	Reid, R.C.	Science	1979	58	1.32
11	Accidental risk of superheated liquids and a framework for predicting the superheat limit	Abbasi, T.; Abbasi, S.A.	Journal of Loss Prevention in the Process Industries	2007	57	3.56
11	Scale effects with fire exposure of pressure-liquefied gas tanks	Birk, A.M.	Journal of Loss Prevention in the Process Industries	1995	53	1.89

Professor Albrecht M. Birk, author of 4 of the 12 articles with the highest number of citations.

The citation count of a publication does not take into consideration the relationship between the cited references and needs to be complemented by co-citation analysis (Li and Hale, 2015). Co-citation analysis is based on the premise that between two or more documents that are co-cited (cited together) in a third and subsequent work, there is, at least from the citing author's perspective, a thematic similarity; and that the greater the frequency of co-citation, the greater the affinity between them. In this way, the analysis of co-citations of articles is considered a way to contribute to the study of the thematic organisation of the literature of scientific disciplines and specialities (Li and Hale, 2015).

Fig. 4 shows the co-citation analysis obtained using the VOSviewer application. The co-citation map includes publications that have been cited at least 20 times in the 375 publications on the BLEVE phenomenon in WoSCC. Of the 2536 unique citations, 35 have met this condition. The size of the circle represents the number of citations received by the documents and the thickness of the lines denotes the number of times two documents have been co-cited in other publications.

Circles of the same colour represent the same cluster with a similar theme among the publications. The joint citation map presents how the references of the publications on the BLEVE phenomenon are grouped and shows four distinct clusters (three of highest importance).

The two most important groups are the green cluster (left) and the red cluster (right). At the top, there is a third cluster (blue) with fewer connections. Finally, at the bottom, there is a small cluster (yellow) of very little significance compared to the previous ones. In general, it can be observed that the different clusters are extensively intertwined with each other. This makes it difficult to define sub-areas of research.

The main article by the blue cluster set is "The Boiling Liquid Expanding Vapor Explosion (BLEVE): Mechanism, consequence assessment, management" (Abbasi and Abbasi, 2007a) which is mainly complemented by other articles of the same authors (Abbasi and Abbasi, 2007c, 2008). This article (the most cited) has 111 citations and 30 links to other publications in different clusters. The publications in the blue cluster focus on establishing the definition and basis of the BLEVE phenomenon. The red cluster consists of a total of 15 records. The articles "The boiling liquid expanding vapor explosion" (Birk and Cunningham, 1994) with 48 citations and 29 links and "Liquid temperature stratification and its effect on BLEVEs and their hazards" (Birk and Cunningham, 1996) with 46 citations and 30 links are the focus of this cluster. The red cluster addresses the BLEVE phenomenon in an applied way focusing the study on the case of LPG (Droste and Schoen, 1988; Stawczyk, 2003; Planas et al., 2015). The green cluster includes 10 publications focused on modelling the phenomenon and its effects or consequences (thermal radiation, overpressure, and fragment projection). The main article is "Blast overpressures from medium scale BLEVE tests" (Birk et al., 2018) (57 citations and 30 links). The VOSviewer application provides a final (yellow) cluster consisting of only two of the earliest publications on BLEVEs (Reid, 1976, 1979), the first articles to be considered in this bibliometric study.

3.6. Subject terms co-occurrence analysis

The word cloud is a simple and visually appealing visualization method. It is used in various contexts as a means of providing an overview by distilling the most frequently occurring words. This is usually done statically as a summary (Heimerl et al., 2014). Fig. 5 presents the keyword cloud collected from the 375 publications. The term BLEVE (and its derivatives) has been discarded as a keyword because it is the subject of the study and appears in almost all the publications analysed.

The most prominent term is "explosion" together with "overpressure", a logical result as BLEVE is an accidental phenomenon associated with an overpressure situation. Other words such as "model" are also prominent (larger), since a significant number of publications focus on modelling the consequences of a BLEVE. Also relevant is the term "LPG" as a substance that has been reported in most accidents of this type and has been extensively studied. Other terms that stand out are "fireball", an accidental scenario associated with BLEVEs when they involve flammable substances, and "radiation" as the effect associated with fireballs. With less weight are words such as "fragment", "simulation", "tank" (and "vessel"), "risk", etc., terms that will be analysed later in terms of their co-occurrence.

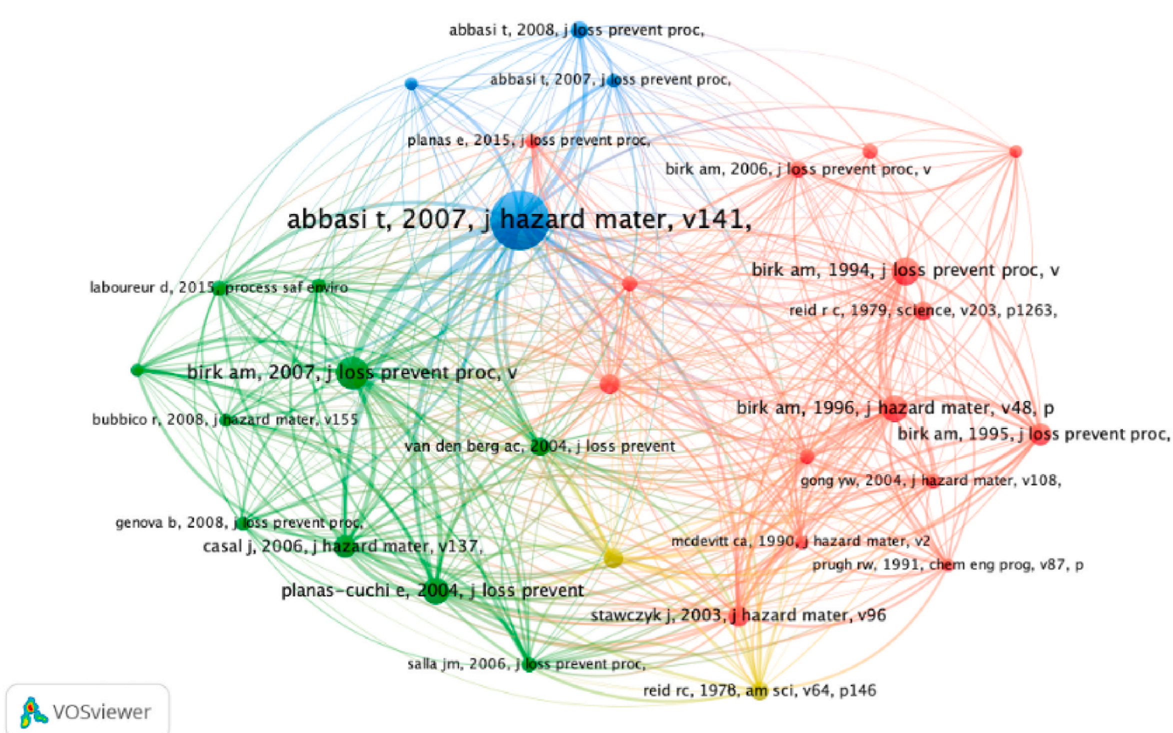

Fig. 4. Co-citations network of BLEVE research.

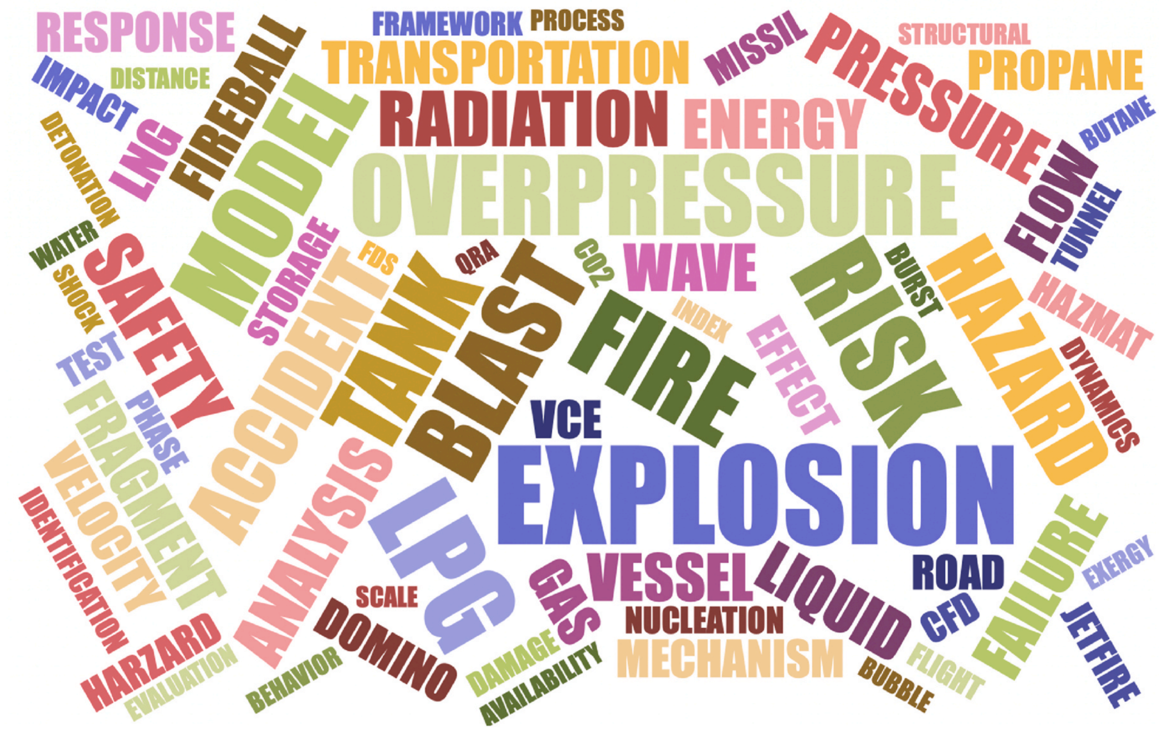

Fig. 5. BLEVE's keyword cloud.

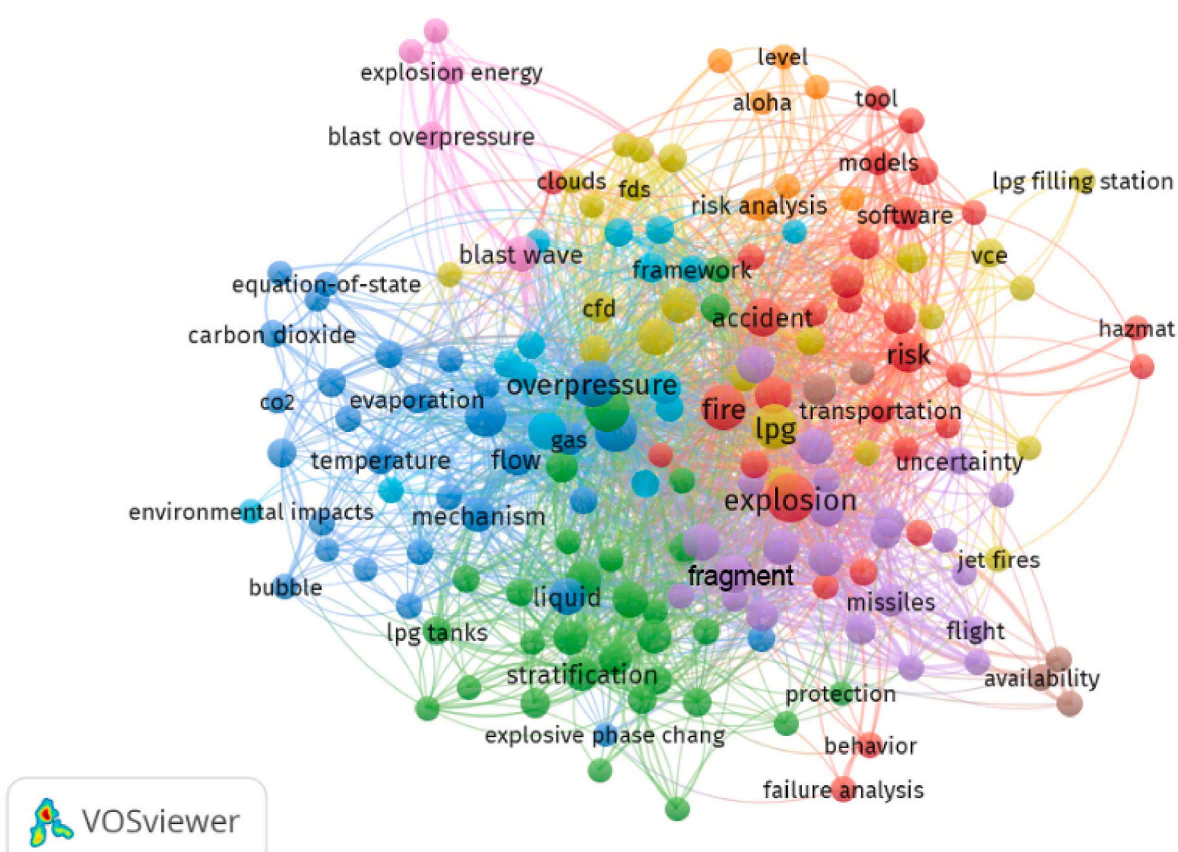

Fig. 6. Co-terms network of BLEVE research.

Term co-occurrence analysis is a technique that examines the actual content of the publication itself. Words in a co-occurrence analysis are derived from "author keywords" and, in their absence, keywords can also be extracted from "article titles", "abstracts" and "full texts" for analysis (Donthu et al., 2021). Equivalent to co-citation analysis, words that frequently appear together are assumed to have a thematic relationship to each other. The analysis of the frequencies of occurrence of words in publications provides information on the main themes and research trends in the object of study (van Nunen et al., 2018). VOSviewer was used for the term co-occurrence analysis. All noun phrases were extracted from the titles and abstracts of the 375 publications on BLEVEs. General terms such as "article" or "conclusion" were discarded and terms with a different spelling such as "explosion" and "explosions" were merged (Liu et al., 2012). Only terms appearing in at least five publications were considered. As a result, a total of 181 terms were identified, of which 153 were finally considered valid. Fig. 6 shows the co-occurrence network in the period 2000–2020. The size of the circles represents the frequency of occurrence of a term; the larger the size, the greater the occurrence of a term in the abstracts, titles, and keywords of publications on BLEVEs. The total distance between terms provides information about their relationship. The shorter the distance between terms, the stronger their relationship. The relatedness of terms is determined by counting the number of times they appear together in titles, abstracts, and keywords (Rodrigues et al., 2014). Colours are used to distinguish the different clusters.

Fig. 6 allows us to establish the thematic terms of the studies on BLEVEs. They are grouped into 9 clusters, the first five of which are particularly relevant due to the number of terms they include. The following analysis focuses on these five most representative clusters. The five groups address various sub-areas of research concerning the BLEVE phenomenon: Cluster 1 (red) "Risk analysis and simulation", Cluster 2 (blue) "Mechanism and thermodynamics"; Cluster 3 (yellow) "Fireball and thermal effects", Cluster 4 (green) "Failures in pressure vessels"; and Cluster 5 (purple) "Fragments and domino effect". Table 6 lists the top twelve terms in each cluster.

The research topics considered in clusters 1 (red) and 2 (blue) are those with the highest frequency of occurrence and focus on the basic aspects of the description and characterization of the BLEVE phenomenon. Cluster 1 focuses on the analysis of the BLEVE risk and modelling of the consequences in case of an accident, while cluster 2 groups together terms associated with the mechanism and thermodynamics of the BLEVE phenomenon. These two clusters constitute the core of the publications on BLEVEs during the study period. The article "The boiling liquid expanding vapor explosion (BLEVE): Mechanism, consequence assessment, management" (Abassi and Abassi, 2007a) is considered very relevant as it establishes a state-of-the-art approach from the perspective of these two clusters.

The importance of cluster 1 ″Risk analysis and consequences" stems from the need to model the consequences of a BLEVE. The two most cited terms in this first cluster are "explosion" and "fire" for two reasons: (i) BLEVE is a mechanical phenomenon, but it is often preceded by exposure to thermal radiation from an external fire (Hemmatian et al., 2015; Shebeko et al., 2000) and, (ii) in the case of BLEVEs of flammable substances, these together with the effects resulting from an explosion give rise to a fireball (Bestratén and Turmo, 1991a; Abbasi and Abbasi, 2007a). The serious consequences of the accidents together with the lack of knowledge of how to deal with this type of phenomenon (Birk, 1996; Heymes et al., 2014) led several researchers to focus on modelling (initially simple) these consequences: explosion overpressure versus distance (Prugh, 1991b; Pettitt et al., 1993), projectile range (Holden and Reeves, 1985; Baum, 1999; Roberts et al., 2000; Hauptmanns, 2001), fireball characteristics (duration and thermal radiation emitted) (Bagster and Pitblado, 1989; Bestratén and Turmo, 1991a; Satyanarayana et al., 1991) or the dispersion of the toxic cloud derived from the explosion (Planas et al., 1998; Khwayyir et al., 2015). This line of research has been maintained and more innovative models have been established for the analysis of the consequences in reference to thermal radiation (Sellami et al., 2018; Wang et al., 2020) or the pressure wave (Planas et al., 2004a; Casal and Salla, 2006; Laboureur et al., 2015; Hemmatian et al., 2017; Birk et al., 2020; Wang et al., 2022). Several correlations have been established that enable estimating overpressure with distance for open field scenarios (Planas et al., 2004b; Casal and Salla, 2006; Sellami et al., 2018) although they may not be appropriate for closed field scenarios, in the vicinity of the tank (Birk et al., 2019). Other models based on numerical simulations use the boiling dynamics of the fluid to determine the overpressure generated by the explosion (van den Berg et al., 2004; Pinhasi et al., 2007; Yakush, 2016). There are studies concerning the effect of the pressure wave on infrastructures (Vaidogas and Kisezauskiene, 2012; Laboureur et al., 2015; Cheng et al., 2022; Li et al., 2022) and analysing the effect of ground loading on the momentum of a BLEVE (Eyssette et al., 2021). Finally, the term "transportation" included in this cluster encompasses several

Table 6
Top-12 subject terms in each cluster of BLEVE publications.

Cluster 1			Cluster 2			Cluster 3			Cluster 4			Cluster 5		
Risk analysis and consequences	Occ.	Links	Mechanism and thermodynamics	Occ.	Links	Fire and thermal effects	Occ.	Links	Failures in pressure vessels	Occ.	Links	Fragments and domino effect	Occ.	Links
explosion	56	99	overpressure	45	92	LPG	38	77	model	35	93	failure	16	56
fire	36	89	hazards	28	67	fireball	20	54	LPG tanks	23	68	safety	16	54
risk	33	93	blast	25	55	thermal radiation	19	60	stratification	20	75	fragment	14	60
accident	26	78	liquid	16	43	vapor cloud explosion	9	35	fire engulfment	20	66	risk assessment	14	38
simulation	17	59	mechanism	12	36	CFD	8	30	tanks	14	35	velocity	13	45
transportation	12	66	superheat limit temperature	10	34	storage	8	26	thermal response	13	41	domino effect	12	44
consequences	12	44	flow	10	33	jet fire	8	19	fire protection	9	33	probability	11	46
software	12	37	gas	9	43	pool fire	7	23	pressure	8	31	missiles	8	29
hazardous materials	10	13	two phase flow	9	23	propane	7	21	tests	7	13	pressure vessel	8	22
modelling	9	28	carbon dioxide	8	19	consequence	7	17	vessels	6	24	impact	7	34
damage	5	19	depressurization	7	34	radiation	6	26	major accident hazard	6	27	uncertainty	5	18
hazard identification	5	17	temperature	7	25	hazards	6	22	road tanker	6	23	flight	5	18

Note: Occ = number of occurrences; Links = number of connexions.

publications that have focused on the analysis of BLEVE accidents over time by modelling the extent of their consequences (Planas et al., 2004a, 2015; Bariha et al., 2016).

Cluster 2 ″Mechanism and thermodynamics" focuses on keywords concerning the state of matter: "liquid", "gas" and "two-phase flow". The term "temperature" and the critical value at which a BLEVE can occur, "superheat limit temperature", are also highlighted. The first associated publications on the BLEVE phenomenon are associated with Professor Reid. Reid established the superheat limit theory with homogeneous nucleation as the basis for BLEVEs (Reid, 1976; Reid, 1976); a BLEVE was a special type of explosion with homogeneous nucleation. In the 1990s, different hypotheses on the origin of BLEVEs were established questioning Reid's theory (McDevitt et al., 1990; Prugh, 1991a, 1991b; Birk and Cunningham, 1994, 1996), an aspect that has not ceased to be the subject of study (Salla et al., 2006). During this period, some authors even proposed the possible existence of a worse explosion than BLEVE, the Boiling Compressed Bubble Explosion (BLCBE) (Venart, 1993; Venart et al., 1993; Yu and Venart, 1996). It is now considered that BLEVE may or may not include homogeneous nucleation (Li et al., 2018; Heymes et al., 2020), with homogeneous nucleation to be considered in cases of higher power BLEVEs (McDevitt et al., 1990). The most current studies in this area focus on determining the separate and combined contribution of the liquid and vapor phases (Ma et al., 2022). The strength of the BLEVE is now considered to come from the energy of the liquid and vapor of the explosion. The vapor energy is immediately available while the less intense liquid phase energy is released after the phase change (Birk et al., 2019; Heymes et al., 2020).

Pool fire and jet fire (terms included in cluster 3 ″Fire and thermal effects") are the types of fire that usually precede a BLEVE when they involve a pressurized vessel (Landucci et al., 2009b; Hemmatian et al., 2015; Shebeko and Shebeko, 2015; Virdi and Pamnani, 2021). Moreover, when the substance contained in this vessel is flammable, the BLEVE is accompanied by a fireball (Bestratén and Turmo, 1991a; Abbasi and Abbasi, 2007a). This is the basis for the study of cluster 3, which focuses on the analysis of the phenomenon from the perspective of thermal radiation and its consequences and is closely related to the analysis of cluster 1 in terms of the importance of modelling and consequence calculation. The relationship established between the presence of LPG or propane in the studies in which the BLEVE is accompanied by a fireball is important in this cluster, as it allows this combined accident to be established in cases where the substance stored under pressure is flammable. Several studies have been carried out analysing the BLEVE phenomenon with LPG (Gong et al., 2004; Susan et al., 2005; Birk et al., 2013; Spoelstra et al., 2015; Kamaei et al., 2016; Tauseef et al., 2017), highlighting those that analyse events in which this type of accident has taken place (Park et al., 2006; Török et al., 2011; Li et al., 2015; Planas et al., 2015; Bariha et al., 2016) or establish safety measures to prevent, control or mitigate these accidents (Bestratén and Turmo, 1991b; Melhem et al., 1993; Birk, 1996, 2014; Shebeko et al., 1996, 2000; Paltrinieri et al., 2009; Heymes et al., 2014).

The CFD (computational fluid dynamics) concept appears in this cluster 3 ″Fire and thermal effects" and has been used in several publications for the analysis of the mechanics and risks of BLEVEs. There are several applications that CFD can have in the study of BLEVEs; for example, linked to the formation, development and impact (consequences) of fireballs, it allows simulations to be carried out considering various factors such as fuel mass and air flow velocity to determine the evolution of the fireball (e.g., height and diameter) (Sellami et al., 2018; Wang et al., 2020). In the case of pressure waves, CFD analysis (in relation to cluster 4) has also been used to examine different aspects of pressurized liquid storage (degrees of filling, initial pressures, temperatures of tank contents) to understand the extent to which initial conditions influence the blast wave (Li et al., 2022; Ustolin et al., 2022). Studies on BLEVEs based on the application of CFD is one of the main techniques used in the study of BLEVEs and their consequences; thus there are several current studies that analyse the effect of BLEVEs on infrastructure, such as bridges, tunnels, roads or buildings (Cheng et al., 2022; Li et al., 2022).

Clusters 4 ″Failures in pressure vessels" (green) and 5 ″Fragments and domino effect" (purple) are closely related. Therefore, the analysis of either cluster will involve reference to the other. Likewise, the term "CFD" in cluster 3 is also closely related to the aspects covered in clusters 4 and 5.

Several studies have dealt with BLEVE failures of pressure vessels, constituting the central focus of attention of cluster 4 "Failures in pressure vessels". One of the main topics of study over the years has been the discussion about which occurs first, the BLEVE or the rupture of the vessel. In this regard, some authors consider that BLEVE is triggered inside the vessel causing the limit superheat explosion that causes the vessel to rupture; while others believe that it is the rupture of the vessel by some weakening process that leads to BLEVE (Birk et al., 2019). Various causes can lead to this weakening of the vessel walls, such as corrosion, design failure or, in most cases, exposure to an external fire (Landucci et al., 2009a; Hemmatian et al., 2015; Shebeko and Shebeko, 2015; Virdi and Pamnani, 2021). Fire exposure of vessels has led to the study of interior temperature stratification in the situation preceding a BLEVE (Birk and Cunningham, 1996; Shi et al., 2012, 2013). The liquid temperature is considered to be almost uniform when only the wall of the liquid space is heated; however, temperature stratification was evident when the walls of the liquid and vapor space were heated simultaneously (Shi et al., 2012). These aspects give rise to two possible types of BLEVEs: single-phase BLEVEs that require an opening in which the full opening of the vessel occurs very rapidly (Laboureur et al., 2015; Birk et al., 2019), and two-phase BLEVEs in which the opening of the vessel stops at some point and is subsequently restarted. Thus, the distance the shock wave will reach depends on how fast the vessel opens (Birk et al., 2019).

Along with the consequences of overpressure and thermal radiation, BLEVEs are often accompanied by fragment projection. The last cluster considered in this study, cluster 5 "Fragments and domino effect" (purple), focuses on this aspect. Fragment projection has been addressed as a topic of study by several authors (Genova et al., 2008; Sun et al., 2012; Tugnoli et al., 2014; Vaidogas, 2021). Also relevant in this cluster is the term "domino effect" which can be related to fragment projection (Sun et al., 2012, 2016; Lisi et al., 2015) but also to overpressur e and thermal radiation (Kumar, 2014).

4. Conclusions

This study is a bibliometric survey of available publications on the BLEVE phenomenon. The countries, institutions, and authors of publications collected in VoSCC have been analysed. Interest in BLEVE has grown exponentially over time and continues to be an important subject of study in the chemical industry and in the transport of dangerous goods. China is the country with the most publications, but these are recent, with a low average number of citations. Canada comes second, largely thanks to Professor A.M. Birk, one of the leading researchers of the BLEVE phenomenon. At the level of institutions, the first position is held by Queens University (Canada), to which Birk belongs. The second position is held by Pondicherry University in India, with the notable authors S.A. Abbasi and T. Abbasi. The analysis of authors gives rise to three clusters centred on the professors A.M. Birk, V. Cozzani, and J. Casal, who are considered benchmark figures in the study of BLEVEs.

Most of the publications are in peer-reviewed scientific journals. The Journal of Loss Prevention in the Process Industries stands out with 66 publications, being a journal of reference in the study of the chemical industry and the transport of hazardous goods. Most of the publications are included in Chemical Engineering journals (Process Safety and Environmental protection, Journal of Hazardous Materials, etc.). The article with the highest number of citations is "The Boiling Liquid Expanding Vapor Explosion: Mechanism, consequence, assessment, management" (Abbasi and Abbasi, 2007a). It is an article of reference and fundamental for the study of BLEVEs.

The co-terms analysis made it possible to establish five relevant clusters: (Cluster 1) “Risk analysis and simulation”, (2) “Mechanism and thermodynamics”, (3) “Fire and thermal effects”, (4) “Failures in pressure vessels” and (5) “Fragments and domino effect”. The main lines of research on the BLEVE phenomenon from its origins to the present day have been identified. It has been determined that the topics of study in recent years have focused on the study of failures in pressure vessels as a preliminary step to a BLEVE, the separate and combined contribution of the liquid and vapor phases considering the phase change (homogeneous or heterogeneous, boiling waves, …) and the formation of shock waves close to the vessel causing the BLEVE, among others.

Significant research on the phenomenon BLEVE has been carried out, but there are still many issues to be investigated. Without being exhaustive: the effects of vessel failure mechanics on BLEVE strength; the effects of weakened length of vessel, fill level, burst pressure, temperature stratification, pre-nucleation (PRV action) on BLEVE strength; ground loading and impulse from a BLEVE to better understand the impact on infrastructure such as bridges, roads and buildings; and impact of BLEVE near structures and inside structures.

CRediT authorship contribution statement

Xavier Baraza: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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