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RESEARCH ARTICLE

Global development and trend of wind tunnel research from 1991 to 2014: a bibliometric analysis

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Abstract

Development and trend of global wind tunnel research from 1991 to 2014 were evaluated by bibliometric analysis. Based on the statistical data from Science Citation Index Expanded from Web of Science, publication performance of wind tunnel research was analyzed from various aspects, including publication output, category distributions, journals, countries, institutions, leading articles, and words analysis. The results show that scientific articles associated with wind tunnel increased dramatically, with *Journal of Wind Engineering and Industrial Aerodynamics* as the most productive journal. The USA has been leading in publication output since 1991, while China has become a new-rising force of wind tunnel research. NASA was the dominant institution in wind tunnel field which published most single institution articles and nationally and internationally collaborative articles. The citation lifecycles of the leading articles exhibited different patterns of their trends, but all reached a plateau in certain years. Based on synthesized analysis of title words, abstract words, author keywords, and *KeyWords Plus*, computational fluid dynamic (CFD) was found to be a hot issue, which needs experimental validation by wind tunnels. Wind loads and wind turbine also caused increasing attentions while lepidoptera and sex pheromone were less studied. In the wind tunnel articles, numerical simulation of CFD was increasingly mentioned while field measurement showed minor change, suggesting the rapid developments of CFD.

Keywords Wind tunnel · Keyword · Research trend · SCI-EXPANDED · Scientometrics

Introduction

Wind tunnel experiments are widely employed in mechanical engineering (Sakamoto and Haniu 1990), civil engineering (Meroney et al. 1996), and environmental studies (Jenkins et al. 1996). Wind flows around the aircrafts, buildings, and cars were frequently investigated in the engineering applications (Baals and Corliss 1981; Amitay et al. 2001; Surry 1991; Suzuki et al. 2003). In addition, numerous studies on air pollution and meteorology applications were conducted in wind tunnels (Baker and Hargreaves 2001).

A bulk of publications on wind tunnel research have been published in the last century as wind tunnel offers a laboratory-scale platform for various research fields. The earliest publication recorded in Web of Science was "The modification of wind-tunnel results by the wind-tunnel dimensions" published in 1923 (Munk 1923). This work improved the results by managing different wind tunnel dimensions, and provided solid foundations for the later studies. With expanding scientific activities, publications have been increasing and review articles have summarized the progress of wind tunnel studies (Ahmad et al. 2015; Ross and Altman 2011; Stathopoulos 1984). However, few attempts have been made to examine the global performance and trend of wind tunnel research by adopting the bibliometric analysis. Bibliometrics is a useful tool to map the literature around a research field (Vergidis et al. 2005; Falagas et al. 2006). The publication performance of many research topics has been evaluated by analyzing the publication output, distribution pattern of subjects, journals, countries, institutions, citations, for example, drinking water (Fu et al. 2013), aerosol (Xie et al.

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2008), water resource (Wang et al. 2011), and estuary pollution (Sun et al. 2012). However, traditional bibliometric analysis in scientific research fields has many deficiencies: their original data are usually insufficient. Many studies only select several journals or categories to represent global research trends related to a topic (Mela and Cimmino 1998; Klein and Hage 2006). The change in the citations or publication counts of countries and organizations cannot completely indicate the development trend or future orientation of the research field (Chiu and Ho 2007). More information, closer to the research itself, including source title, author keyword, *KeyWords Plus*, and abstracts (Xie et al. 2008; Li et al. 2009) should be introduced in study of the research trend. To depict a comprehensive wind tunnel research image in the whole scientific world, multi-evaluations of publications performance are required, looking at a wide range of journals, countries, institutions and making in-depth analysis of detail information such as title words, abstract, author keywords, and *KeyWords Plus*.

As an extended study of our previous study (Mo et al. 2018), this work made a bibliometric evaluation of wind tunnel research trend within a period of 1991 to 2014. Publication performance was quantitatively determined in terms of various parameters, including not only annual outputs, journals, Web of Science categories, leading countries, and institutions, but also the impact analysis using total citations and citations. Research tendency and hotspot were identified by synthetic analysis of title words, abstract words, author keywords, and *KeyWords Plus*. The bibliometric characteristic of publications in wind tunnel research can help better understand the global research situation, research trend, and hotspot.

Data collection and methodology

All statistical data were collected from the online version of Science Citation Index Expanded (SCI-EXPANDED) databases of the Thomson Reuters' Web of Science Core Collection. A total of 8618 journals were indexed in the Journal Citation Reports (JCR) of 2014. The schematic for searching process of wind tunnel publications is shown in Fig. 1. Because abstract information has been included in SCI-EXPANDED database since 1991, the investigated period was limited to 1991–2014. "Wind tunnel," "wind tunnels," "wind tunnelling," and "wind-tunneling" were searched in the topic field in terms of title, abstract, author keywords, and *KeyWords Plus*, limiting to the document type of article in the period of 1991 to 2014. From the 10,965 articles which met the above selection criteria, those articles that are only searched out by *KeyWords Plus* were excluded by using another filter, the "front page" proposed by Fu et al. (2012). Only the articles with the searching keywords in their "front page" including article title, abstract, and author keywords were selected for analysis. A total of 10,241 articles were retrieved from the SCI-EXPANDED database and regarded as the wind tunnel publications. The information of author names, affiliation, article title, year of publication, Web of Science categories, and citations in each year for each article were recorded into the Spreadsheet software Microsoft Excel 2010. Then, the number of authors, country of origin of the collaborators, and impact factors (JCR 2014) of the publishing journals were retrieved from the original statistical data (Li and Ho 2008). It should be noted that "corresponding author" was used instead of "reprint author" that was designated in the SCI-EXPANDED database, and the single author (single institution) was both first author (first author's institution) and corresponding author (corresponding author's institution) when authorship was not specified in the single author article (Ho 2012, 2013). Articles from England, Scotland, Northern Ireland, and Wales were rearranged into UK, Hong Kong into China, USSR and Russia into Russia, and Acad Sci USSR into Russian Academy of Sciences, and Yugoslavia and Serbia into Serbia (Chuang and Ho 2014; Li et al. 2014). Articles with addresses within the same country were categorized into "single country article" and articles with addresses from multiple countries were classified into "internationally collaborative article" (Li and Ho 2008). Similar classification method was applied to the "single institution article" and "inter-institutionally collaborative article."

Results and discussion

Language of publication

English was the dominated language of the publications, with 99% of 10.241 articles. It was followed by French (48 articles), German (37), Chinese (16), Japanese (12), Russian (5), Croatian (4), Portuguese (4), Spanish (4), Turkish (3), and one for each of Hungarian and Rumanian. Such high percentage (99%) of English articles was also reported in wetland research (Zhang et al. 2010). Of the 135 non-English articles,

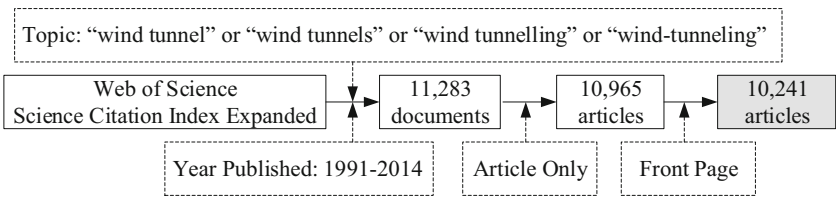

Fig. 1 Schematic for searching the articles of wind tunnel research

43% had no citations ($TC_{2014} = 0$), 22% had only one citation ($TC_{2014} = 1$), and 10% had two citations ($TC_{2014} = 2$). In contrast, 20, 12, and 8.5% of 10,106 English articles had $TC_{2014} = 0$, $TC_{2014} = 1$, and $TC_{2014} = 2$, respectively. The most frequently cited non-English article entitled "Experimental characterization of airflow pattern in a cheese-ripening room and consequences on the exchanges between air and products" (Mirade et al. 2004) was published in French with TC_{2014} of 17.

Publication outputs

The annual productions of publication were analyzed for different research fields such as aerosol (Xie et al. 2008), water resource (Wang et al. 2011), and drinking water (Fu et al. 2013), giving an overview of the research development. This study illustrated the annuals number of articles associated with wind tunnel and citations per article during period of 1991 to 2014, as shown in Fig. 2. The publication outputs increased steadily from 261 in 1991 to 470 in 2009 with a slight fluctuation. Then, the number of articles showed a sharp increase in the following 3 years, reaching 747 in 2012 and maintaining over 700 afterwards. This indicated that wind tunnels research received much attention in recent years, especially from 2009. People expected that development of numerical method (Fujii 2005) which was emerging technology at that time might slow down the study of wind tunnel experiment. Actually, some of the wind tunnel experiments in the design process of industrial products such as aircraft and automobiles were replaced by numerical simulations. It is worth mentioning that number of articles with wind tunnels increased even with such changes probably because the wind tunnel experiment is a popular laboratory-scale method in various studies such as aerodynamics, civil engineering, and meteorology. The development of the measurement techniques such as particle image velocimetry (PIV) and pressure sensitive paints (PSP) also contribute to the remarkable increase of wind tunnel publication. The improvement of camera resolutions, laser systems and reduction of their cost would further facilitate the rapid progress of wind tunnel research (Adrian 2005; Mclachlan and Bell 1995). In addition, its complementary research method-computational fluid dynamics modeling developed rapidly in recent years, which needed validations by wind tunnel measurements (Oberkampf and Trucano 2002).

As for the citations per publication (*CPP*), the mean number fluctuated between 12 and 17 from 1991 to 2006, with a peak in 1996 and 2000. After that, the average citations of an article decreased from 1.0 in 2007 to 0.28 in 2014 because the citations need time to accumulate (Picknett and Davis 1999). As shown in Fig. 2, it took *CPP*s about a decade to reach a plateau. This phenomenon was also found for articles in wetland research (Ma et al. 2013), highly cited publications ($TC_{year} \geq 100$) in materials science field (Ho 2014), and classic articles ($TC_{year} \geq 1000$) in Science Citation Index Expanded (Ho 2013).

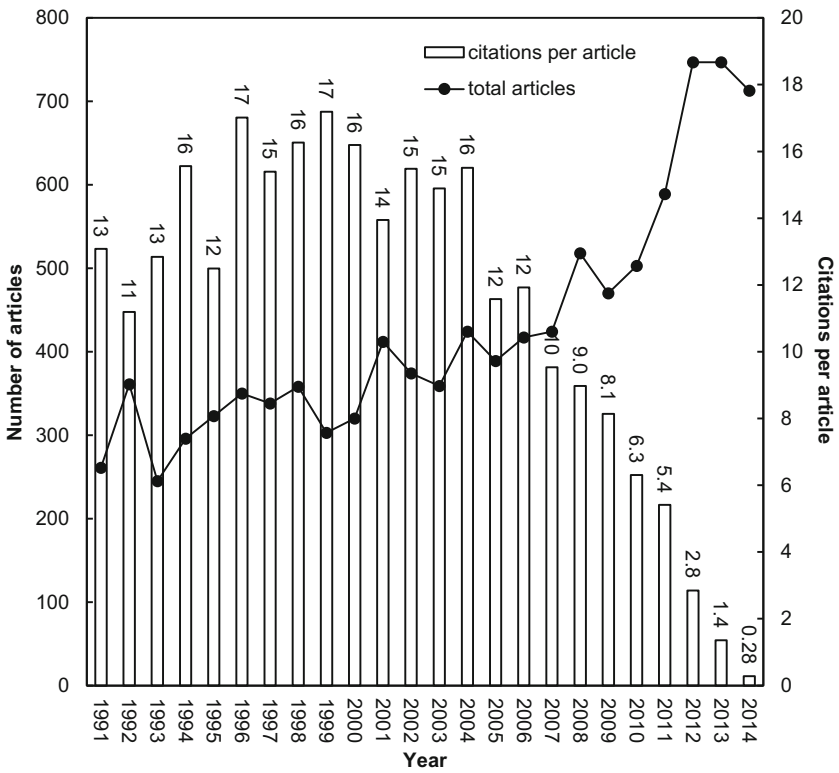

Fig. 2 Annual number of articles and citations per publication by year

Web of Science categories and journals

Articles of wind tunnel research were distributed across 134 categories out of the total 176 Web of Science subject categories in 2014. Mechanics contributed the most (2608 articles), representing 25% of the total 10,236 articles. It was followed by 1992 (19%) articles from aerospace engineering, 1859 articles (18%) from civil engineering, and 1686 articles (16%) from mechanical engineering. These four most prolific categories had been taking the lead in recent decade. Particularly for the mechanics, the number of publications sharply increased from 2009, and was expected to enlarge the gap between mechanics and other categories the future (Fig. 3). According to the category description in the Web of Science (http://admin-apps.webofknowledge.com/JCR/static_html/scope_notes/SCIENCE/2011/SCOPE_SCI.htm), Mechanics included fluid mechanics, gas mechanics, and mathematical modeling, which frequently performed wind tunnel experiments to study the action of forces, particularly the wind force. Thus, wind tunnel articles were mostly published in this Web of Science category.

In total, 10,241 articles were published in a wide range of 1165 journals. Among these journals, 1075 (92% of 1165 journals) journals contained less than 20 articles in the study period and 518 (44%) journals published only one article. As shown in Table 1, top 15 journals (> 100 articles) totally contributed 4016 articles (40% of 10,241 articles). *Journal of Wind Engineering and Industrial Aerodynamics* was the most productive journal, with 1121 articles (11% of 10,241 articles), followed by *Journal of Aircraft* (610; 6%), *AIAA Journal* (388; 3.8%), *Journal of Spacecraft and Rockets* (224; 2.2%), *Atmospheric Environment* (208; 2%), and *Experiments in Fluids* (205; 2.0%). Compared with other research topics, the percentage of the preponderant journal was high (11%), which suggested that wind tunnel research was centralized in specific study areas, such as mechanics, civil engineering, and aerospace engineering. This phenomenon showed some difference from other research fields, which gained broad interests from multidisciplinary angle. For example, the top productive journal *British Medical Journal* contributed only 4.3% of total number of articles on homeopathy research (Chiu and Ho 2005), *Human and Ecological Risk Assessment* (3.0%) on risk assessment (Mao et al. 2010), and *Water Research* (4.2%) on drinking water (Fu et al. 2013). In addition, the journals with the highest IF_{2014} was *Nature* with six articles (IF_{2014} = 41.456), followed by *Science* with two articles (IF_{2014} = 33.611), *Bulletin of the American Meteorological Society* with two articles (IF_{2014} = 11.808), *Advanced Functional Materials* with one article (IF_{2014} = 11.805), and *Nature Communications* with two articles (IF_{2014} = 11.470).

Country/territory and institution

Six indicators proposed by Ho and co-workers including total publications (*TP*), independent publications (*IP*), collaborative publications (*CP*), first authored publications (*FP*),

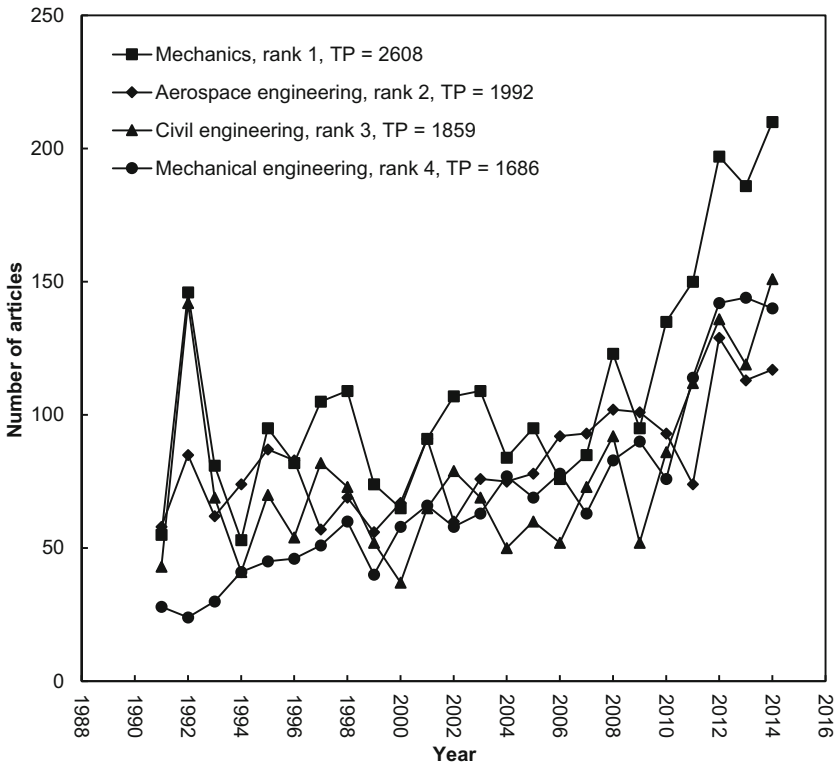

Fig. 3 Comparison the growth trends of subject categories containing 1000 above trend of wind related articles

Table 1 The 15 most productive journals with the number of articles, impact factor, and Web of Science category. ($TP > 100$)

Journal	*TP* (%)	IF_{2014}	Web of Science category
Journal of Wind Engineering and Industrial Aerodynamics	1121 (11)	1.414	Civil engineering Mechanics
Journal of Aircraft	610 (6.0)	0.556	Aerospace engineering
AIAA Journal	388 (3.8)	1.207	Aerospace engineering
Journal of Spacecraft and Rockets	224 (2.2)	0.533	Aerospace engineering
Atmospheric Environment	208 (2.0)	3.281	Environmental sciences Meteorology and atmospheric sciences
Experiments In Fluids	205 (2.0)	1.670	Mechanical engineering Mechanics
Wind and Structures	194 (1.9)	0.584	Construction and building technology Civil engineering Mechanics
Boundary-Layer Meteorology	191 (1.9)	2.470	Meteorology and atmospheric sciences
Journal of Chemical Ecology	148 (1.4)	2.747	Biochemistry and molecular biology Ecology
Journal of Fluids and Structures	140 (1.4)	2.021	Mechanical engineering Mechanics
Journal of Fluid Mechanics	140 (1.4)	2.383	Mechanics Fluids and plasmas physics
Aeronautical Journal	120 (1.2)	0.405	Aerospace engineering
Journal of Turbomachinery-Transactions of the ASME	110 (1.1)	0.930	Mechanical engineering
Journal of the American Helicopter Society	109 (1.1)	0.796	Aerospace engineering
Aerospace Science and Technology	108 (1.1)	0.940	Aerospace engineering

TP total articles, IF_{2014} impact factor in Journal Citation Reports 2014 published by Thomson Reuters

corresponding authored publications (*RP*), and single authored publications (*SP*) were used to compare publications of countries and institutions, respectively (Chiu and Ho 2005; Ho and Kahn 2014). It was generally accepted that the first author was the person who contributed most to the work and writing of the article (Riesenberg and Lundberg 1990). The corresponding author responsibilities include supervision of the planning and execution of the study, along with writing the paper (Burman 1982). At the institutional level, the determined institution of the corresponding author might be a home base of the study or origin of the paper (Ho 2012). There were 105 articles without affiliations in Web of Science.

A total of 10,136 articles with author affiliations were distributed in 89 countries, as shown in the Fig. 4. Specifically, 41 countries (46%) published 1 to 10 articles, 41 countries (46%) published 11 to 500 articles, 6 countries (7%) published 501 to 1500 articles, and 1 country (the USA) published more than 3000 articles. There were 8211 (81%) single country articles from 64 countries and 1925 (19%) internationally collaborative articles from 86 countries. The ratios between single country and internationally collaborative articles was approximately 8:2, which was similar to many other topics such as drinking water (Fu et al. 2013), estuary pollution (Sun et al. 2012), and climate change (Li et al. 2011). This suggested that most of the articles were finished within one individual country while internationally collaborative articles still much less in most of research fields.

The top 21 countries or territory published more than 100 articles are listed in Table 2 with six indicators including total publications (*TP*), independent publications (*IP*), collaborative publications (*CP*), first authored publications (*FP*), corresponding authored publications (*RP*), and single authored publications (*SP*) were used to compare publications of countries and institutions respectively (Chiu and Ho 2005; Ho and Kahn 2014). There were 11 European countries, 6 Asian countries, 2 American countries, 2 Oceania countries, and no African countries on the list of the top 21 countries. The most productive African country was Egypt, ranked 30th. Apart from China, seven major industrial countries (G7: USA, UK, Japan, Germany, Canada, France, and Italy) ranked top eight in the number of total publications. A total of 7133 articles (70%) were from G7 countries while 1046 articles (10%) were produced from China.

The USA ranked top of all six indicators, demonstrating its leading position in wind tunnel research. This was because the USA has the most technologically advanced, efficient, and affordable wind tunnels for civilian and military test, such as the National Full-Scale Aerodynamics Complex (NFAC), The

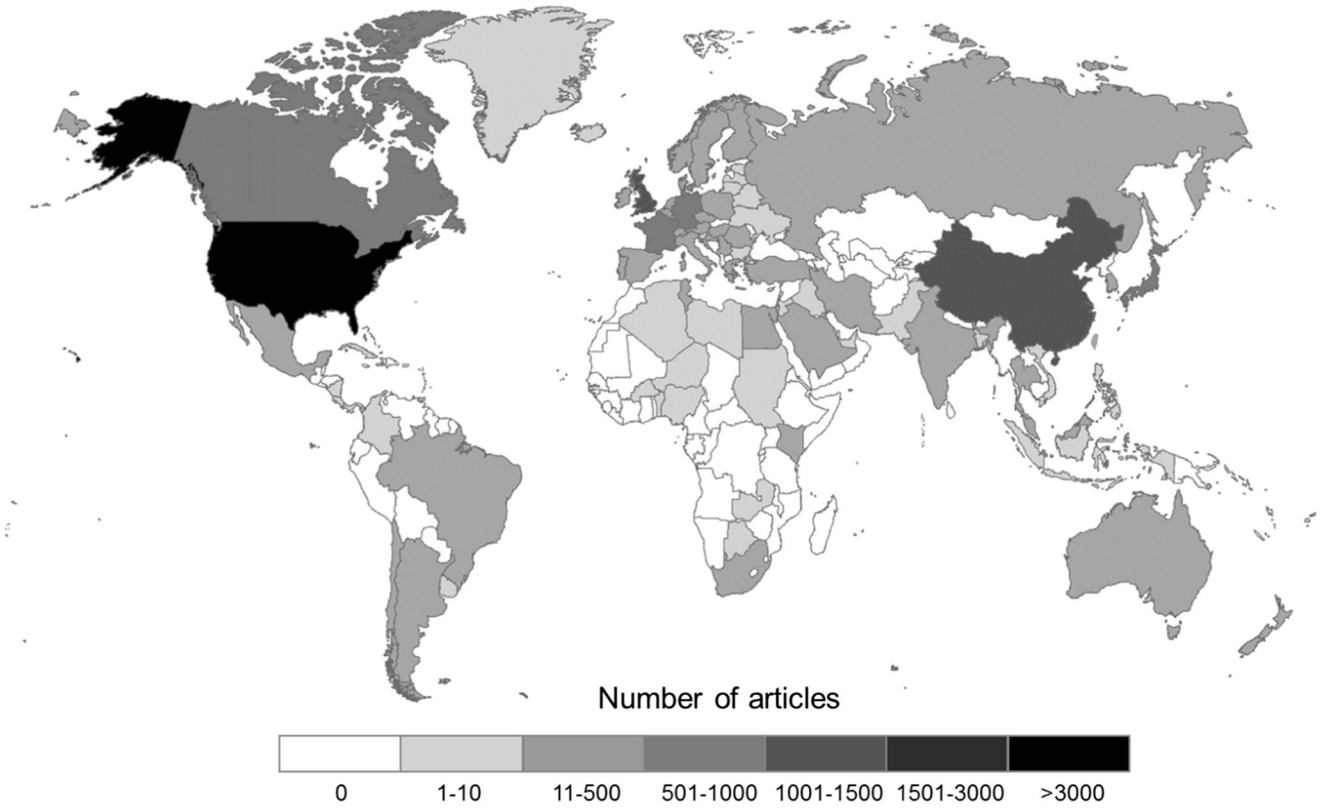

Fig. 4 Global geographical distribution of wind tunnel research outputs

Unitary Plan Wind Tunnel, and The 12-Foot Pressure Wind Tunnel in Ames Research Center of NASA (Baals and Corliss 1981). The infrastructure provided substantial supports for the increasing demand of wind tunnel research. The percentages of total *IP* and *CP* of the USA were 30 and 38%, much more than those from the 2nd and 3rd ranking countries of China and the UK, respectively. While ranking 2nd in publications, China ranked 6th and 12th in the percentages of *CP* and *SP*. This indicated that China still had less collaborative work and less work from single person in spite of enormous amounts of total publication output.

Figure 5 shows the top five countries which had published more than 800 articles. As the super country of wind tunnel research, the USA had been leading in publications from 1991 to 2014. Especially from 2009, the number of publications from the USA increased dramatically, reaching over 200 in 2012. This could be explained by the national investments of large-scale projects such as Aeronautics Test Program (ATP) to perform and participate in the research (Marshall 2010). Without any articles published in 1991, China had contributed increasing number of publication during the last 20 years. The article amount grew fast from 8 in 2000 to 126 in 2012, and reached around 160 articles in 2013 and 2014. This rapid increase was probably attributed to the large-scale initiatives on basic research in China, such as the "211 Project," "973 Plan," and "985 Project" (Chen 2011). This phenomenon was also found in various research fields (Fu et al. 2013; Li et al. 2014). The number of articles from the UK, Japan, and Germany were similar during the 24-year period, growing steadily from about 25 in 1991 to about 50 in 2014 in spite of some fluctuations. China surpassed UK, Japan, and Germany in publication outputs in 2004, and was narrowing the gap from the USA, suggesting the new-rising force of wind tunnel research from China.

The top 10 institutions were ranked by the number of articles (Table 3). Besides the six indicators mentioned above, the publication pattern including the number and percentage of single institution articles (*IP*), internationally collaborative articles (*ICP*), and nationally collaborative articles (*NCP*) of each institution were also listed in Table 3. Among the top 10 institutions, two were in China, two in the USA, two in Japan, and one in each of the Canada, France, Italy, and the UK, respectively. NASA with 424 articles including 213 (50% of 424 articles) single institution articles, 38 (9.0%) internationally collaborative articles, and 173 (41%) national collaborative articles, ranked top on five indicators except *ICPR* in Table 2. The Chinese Academy of Sciences (CAS), with 2nd most articles of 172, has no single author publication and ranked 27th in *ICP* while the other four indicator all ranked 2nd, implying CAS still lack of international cooperation. On the other hand, the University of Western Ontario has most internationally collaborative articles while much less nationally collaborative articles (ranking 77th). The ratio of *ICP* and *NCP* from the University of Western Ontario was approximately

Table 2 The top 21 most productive countries (*TP* > 100)

Country/ territory	TP	*TP R* (%)	*IP R* (%)	*CP R* (%)	*FP R* (%)	*RP R* (%)	*SP R* (%)
USA	3197	1 (31)	1 (30)	1 (38)	1 (28)	1 (28)	1 (32)
China	1046	2 (10)	2 (10)	6 (12)	2 (9.4)	2 (10)	12 (1.9)
UK	1032	3 (10)	4 (7.9)	2 (20)	3 (8.3)	3 (8.1)	2 (11)
Japan	901	4 (8.9)	3 (8.1)	7 (12)	4 (7.5)	4 (7.5)	4 (6.2)
Germany	839	5 (8.2)	5 (6.3)	3 (16)	5 (6.5)	5 (6.3)	3 (8.8)
Canada	716	6 (7.0)	6 (5.8)	5 (12)	6 (5.7)	6 (5.8)	5 (5.6)
France	639	7 (6.3)	7 (4.5)	4 (14)	7 (4.7)	7 (4.6)	6 (4.5)
Italy	443	8 (4.4)	8 (3.1)	8 (10)	8 (3.4)	8 (3.4)	11 (2.2)
Australia	365	9 (3.6)	10 (2.4)	10 (8.5)	10 (2.5)	10 (2.5)	7 (3.8)
South Korea	296	10 (2.9)	9 (2.5)	14 (4.7)	9 (2.6)	9 (2.6)	15 (1.2)
Netherlands	285	11 (2.8)	13 (1.5)	9 (8.6)	11 (1.8)	11 (1.8)	8 (3.3)
Sweden	217	12 (2.1)	16 (1.1)	11 (6.8)	12 (1.5)	13 (1.4)	9 (2.8)
Belgium	172	13 (1.7)	17 (0.95)	13 (4.9)	17 (1.2)	17 (1.2)	13 (1.8)
Russia	164	14 (1.6)	14 (1.4)	20 (2.4)	15 (1.3)	14 (1.3)	10 (2.7)
Switzerland	164	14 (1.6)	20 (0.7)	12 (5.5)	18 (1.1)	18 (1.0)	24 (0.71)
Taiwan	163	16 (1.6)	11 (1.7)	27 (1.4)	13 (1.4)	12 (1.5)	18 (1.0)
India	154	17 (1.5)	12 (1.5)	26 (1.5)	14 (1.3)	15 (1.3)	14 (1.3)
Spain	150	18 (1.5)	15 (1.1)	16 (2.9)	16 (1.2)	16 (1.3)	28 (0.51)
Denmark	147	19 (1.4)	17 (0.95)	15 (3.6)	19 (1.0)	19 (1.0)	16 (1.1)
New Zealand	110	20 (1.1)	21 (0.67)	17 (2.9)	20 (0.80)	20 (0.82)	18 (1.0)
Israel	104	21 (1.0)	21 (0.67)	18 (2.5)	22 (0.75)	22 (0.74)	21 (0.81)

TP total number of articles, *TP R (%)* rank and the percentage of total articles, *IP R (%)* rank and the percentage of single country articles, *CP R (%)* rank and the percentage of internationally collaborative articles, *FP R (%)* rank and the percentage of first authored articles, *RP R (%)* rank and the percentage of the corresponding authored articles, *SP R* rank and the percentage of the single authored articles

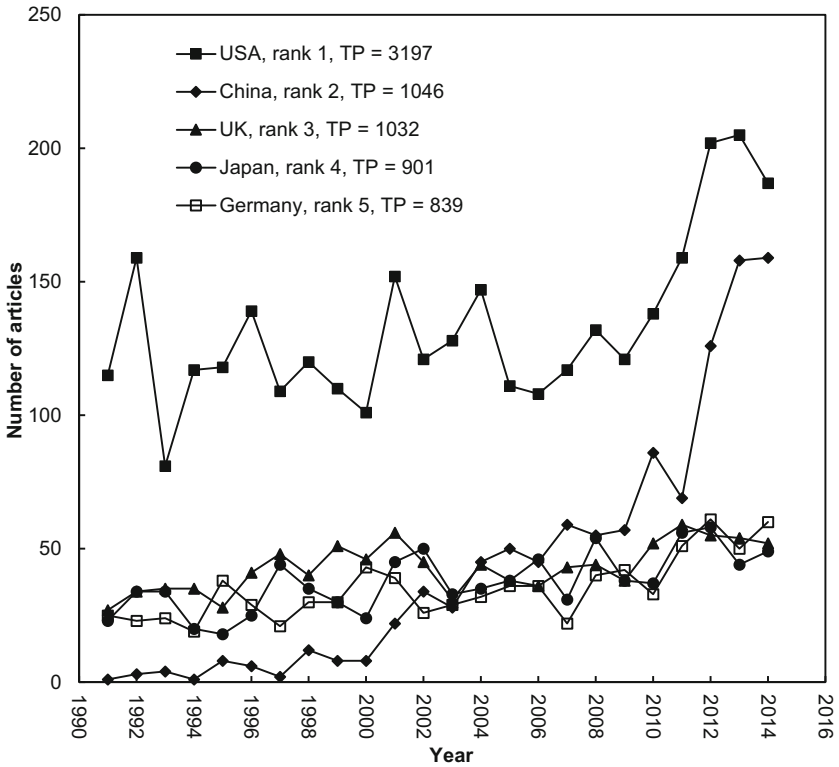

Fig. 5 Publications of the five most productive countries during 1991–2014

4.8, which was much larger than those from most of the institutions with a ratio of less than 1.0. This suggested University of Western Ontario was more likely to cooperate with foreign institutions compared with domestic ones, which was also found for ONERA in France (*ICP*/*NCP* = 31:22), Politecn Milan in Italy (*ICP*/*NCP* = 29:7), and University of Southampton in the UK (*ICP*/*NCP* = 25:20). From Table 3, we also noticed that NASA (213 articles, 50%), ONERA (64 articles, 55%), and Politecn Milan (47 articles, 57%) published more than 50% of articles as single institution publications, while two university in Japan (namely University of Tokyo and Tohoku University) produced much less proportions of single institution articles, accounting for 24 and 27%, respectively. These indicators revealed that NASA, ONERA, and Politecn Milan had strong capabilities of independently carrying out the research projects.

Leading articles in 2014

Highly cited articles are particularly important because a high citation count is an indication of high impact or visibility in the research community (Wohlin 2005). Highly cited articles also provide a useful insight into which authors and topics are influencing a research discipline over time (Smith 2008). However, the citations of an article have been changing over time (Ho 2012). It was found that articles gained more citations in the following years since the time of publications, but received less attentions thereafter, for example in thermodynamic research (Fu and Ho 2015) and articles in materials science field (Ho 2014). The articles with high of citations in last year (C_{year}) of an article could be considered as the top articles (Ho 2012). The top articles with citations in last year (C_{2014}) could be a good indicator to help researchers to better identify the high impact work in recent research field.

The 12 articles ($C_{2014} \geq 20$) with high impact in last year are shown in Table 4. Among the 12 articles, 3 were published in *Boundary-Layer Meteorology* ($IF_{2014} = 2.47$), 2 in the *Journal of Wind Engineering and Industrial Aerodynamics* (impact factor $IF_{2014} = 1.414$), 2 in *Journal of Fluid Mechanics* ($IF_{2014} = 2.383$), and 1 each in the *International Journal of Heat and Mass Transfer* ($IF_{2014} = 2.383$), *Applied Surface Science* ($IF_{2014} = 2.711$), *Probabilistic Engineering Mechanics* ($IF_{2014} = 1.855$), *Experiments in Fluids* ($IF_{2014} = 1.67$), and *Journal of Geophysical Research-Atmospheres* ($IF_{2014} = 3.44$). Generally, papers published in journals with a high *IF* would probably have high citations.

Eleven authors published the 12 highly cited articles as first authors. D.W Bechert published two articles in 1997 with affiliation of Technical University of Berlin and in 2000 with affiliation of German Aerospace Center, while other first authors published only one article. Nine author published highly cited articles as corresponding authors, with F. Porté-Agel published three high impact articles (Chamorro and Porté-Agel 2009; Porté-Agel et al. 2011; Wu and Porte-Agel 2011) and D.W Bechert publishing two (Bechert et al. 1997, 2000). F. Porté-Agel dealt with the characteristics of wind-turbine wake in atmospheric boundary layer by deploying complementary research methods of computational mathematical models (Porté-Agel et al. 2011; Wu and Porte-Agel 2011) and wind tunnels experiments (Chamorro and Porté-Agel 2009). His work developed and validated a large-eddy simulation (LES) framework for wind energy applications. Bechert's articles deployed oil

Table 3 The top 10 most productive institutions

Institution	TP	*TPR* (%)	*IPR* (%)	*ICPR* (%)	*NCPR* (%)	*FPR* (%)	*RPR* (%)	*SPR* (%)	*IP* (%)	*ICP* (%)	*NCP* (%)
NASA, USA	424	1 (4.2)	1 (4.0)	2 (2.0)	1 (5.9)	1 (3.0)	1 (3.0)	1 (7.4)	213 (50)	38 (9.0)	173 (41)
Chinese Academy of Sciences, China	172	2 (1.7)	2 (1.4)	27 (1.1)	2 (2.7)	2 (1.3)	2 (1.3)	N/A	73 (42)	21 (12)	78 (45)
University of Western Ontario, Canada	127	3 (1.3)	4 (1.0)	1 (3.2)	77 (0.45)	4 (0.84)	5 (0.81)	5 (1.0)	53 (42)	61 (48)	13 (10)
Tongji University, China	124	4 (1.2)	6 (0.85)	7 (1.6)	5 (1.6)	5 (0.83)	4 (0.83)	59 (0.30)	45 (36)	31 (25)	48 (39)
ONERA, France	117	5 (1.2)	3 (1.2)	7 (1.6)	28 (0.75)	3 (0.87)	3 (0.84)	2 (1.4)	64 (55)	31 (26)	22 (19)
USDA ARS, USA	107	6 (1.1)	8 (0.79)	15 (1.3)	7 (1.4)	6 (0.81)	6 (0.70)	7 (0.81)	42 (39)	25 (23)	40 (37)
University of Tokyo, Japan	101	7 (1.0)	28 (0.45)	23 (1.1)	3 (1.9)	13 (0.51)	12 (0.53)	59 (0.30)	24 (24)	22 (22)	55 (54)
Tohoku University, Japan	86	8 (0.85)	31 (0.43)	23 (1.1)	6 (1.4)	11 (0.53)	11 (0.55)	21 (0.51)	23 (27)	22 (26)	41 (48)
Politecn Milan, Italy	83	9 (0.82)	5 (0.89)	9 (1.5)	157 (0.24)	7 (0.63)	7 (0.63)	N/A	47 (57)	29 (35)	7 (8.4)
University of Southampton, UK	83	9 (0.82)	11 (0.72)	15 (1.3)	35 (0.69)	10 (0.54)	8 (0.58)	35 (0.41)	38 (46)	25 (30)	20 (24)

TP total number of articles, *TPR (%)* rank and the percentage of total articles, *IPR (%)* rank of and the percentage of single institution articles, *CPR (%)* rank and the percentage of articles international collaborative articles, *FPR (%)* rank and the percentage of first author articles, *RPR (%)* rank and the percentage of the corresponding authored articles, *SPR (%)* rank and the percentage of the single authored articles, *IP (%)* the number of single institution articles and the percentage of single institution articles in total articles of each institution, *ICP (%)* the number of internationally collaborative articles and the percentage of internationally collaborative articles in total articles of each institution, *NCP (%)* the number of nationally collaborative articles and the percentage of nationally collaborative articles in total articles of each institution, *NASA* National Aeronautics and Space Administration, *ONERA* Office National d'Etudes et de Recherches Aérospatiales, *USDA ARS* United States Department of Agriculture, Agricultural Research Service

Table 4 Twelve most frequently cited papers in 2014 ($C_{2014} \geq 20$)

Rank (C_{2014})	Rank (C_0)	Rank (TC_{2014})	Rank (*TCPY*)	Title	Reference
1 (47)	77 (3)	3 (302)	2 (23)	Thermophysical properties of high porosity metal foams	Bhattacharya et al. (2002)
2 (39)	401 (1)	135 (73)	5 (18)	Anti-icing performance of superhydrophobic surfaces	Farhadi et al. (2011)
3 (32)	1401 (0)	36 (126)	92 (7.4)	Wind field simulation	Mann (1998)
3 (32)	1401 (0)	1 (442)	2 (23)	Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy	Raupach et al. (1996)
5 (30)	401 (1)	16 (170)	1 (24)	AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings	Tominaga et al. (2008)
6 (29)	160 (2)	2 (406)	4 (19)	Local isotropy in turbulent boundary-layers at high Reynolds-number	Saddoughi and Veeravalli (1994)
6 (29)	10 (6)	225 (58)	6 (15)	Large-Eddy Simulation of Wind-Turbine Wakes: Evaluation of Turbine Parametrisations	Wu and Porte-Agel (2011)
8 (28)	160 (2)	225 (58)	6 (15)	Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms	Porté-Agel et al. (2011)
9 (25)	1401 (0)	17 (168)	45 (9.3)	Experiments on drag-reducing surfaces and their optimization with an adjustable geometry	Bechert et al. (1997)
10 (23)	1401 (0)	194 (62)	29 (10)	A Wind-Tunnel Investigation of Wind-Turbine Wakes: Boundary-Layer Turbulence Effects	Chamorro and Porté-Agel (2009)
11 (21)	1401 (0)	50 (110)	96 (7.3)	Experiments with three-dimensional riblets as an idealized model of shark skin	Bechert et al. (2000)
12 (20)	1401 (0)	5 (240)	20 (11)	Effect of saltation bombardment on the entrainment of dust by wind	Shao and Raupach (1993)

C_{2014} number of citations in 2014, C_0 number of citations in the publication year, TC_{2014} number of citations since its publication to the end of 2014, *TCPY* TC_{2014} per year

channels to demonstrate that surfaces with tiny ribs aligned in the stream wise direction could reduce the turbulent wall-shear stress much more, which were underestimated in previous studies. They both had marked the research milestone by using wind tunnel experiments.

As shown in Table 4, five articles were published in the 1990s, four in the 2000s, and three in the 2010s. The 12 articles showed significant variations in C_{2014}, C_0, TC_{2014}, and *TCPY* values, with no particular pattern. The earliest article entitled "Effect of saltation bombardment on the entrainment of dust by wind" with $C_{2014} \geq 20$ was published in 1993 (Shao and Raupach 1993). Half of the 12 articles have no citation in their publication year ($C_0 = 0$), they, however, became the classic articles in wind tunnel field. In addition, "Thermophysical properties of high porosity metal foams" and "Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy" ranked top three in all of the C_{2014}, TC_{2014}, and *TCPY*.

Figure 6 shows the annual citations of the highly cited articles of wind tunnel research. The article entitled "Thermophysical properties of high porosity metal foams" by Bhattacharya et al. (2002) had the highest C_{2014} while rank 3rd on TC_{2014} and 2nd on *TCPY*. In general, the citations of this article grew fast since its publication. In spite of a sharp decrease in 2013, the citations rose back to the top of all articles in 2014. This work firstly determined thermophysical properties of high porosity fibrous metal foams, while previous studies mostly focused on low porosity media. Therefore, this early report attracted high citations since its time of publication. The recently published articles entitled "Anti-icing performance of superhydrophobic surfaces" by Farhadi et al. (2011) and "Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms" by Porté-Agel et al. (2011) kept their annual number of citations rapidly increasing from the time of its publication. The former one has become the second highest citations article in 2014. Overall, it appeared to be going strong and showed no sign of leveling off. The article entitled "Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy" by Raupach et al. (1996) showed a general increasing trend despite of some fluctuations in certain years. This article ranked top in C_{year} in 2008 ($C_{2008} = 42$) and 2013 ($C_{2013} = 41$). With ranking of 3rd in C_{2014}, 1st in TC_{2014}, and 2rd in *TCPY*, this article had been a high impact publication and still attracted attentions in recent years. The high citations were because this work provided explanations of the mixing-layer analogy for many of the observed distinctive features of canopy turbulence, which had been applied to turbulent transport models and predicting behaviors of canopy turbulence. J. Mann from Denmark published an article entitled "Wind field simulation" in 1998 (Mann 1998). This article was not so popular in following 11 years since its publication, with citations of less than 10 per year. However, this work caused more attentions from other research in recent years and C_{2014} reached 32 (ranking 4th). An efficient algorithm was developed to simulate turbulent wind fields. This article could be highly cited

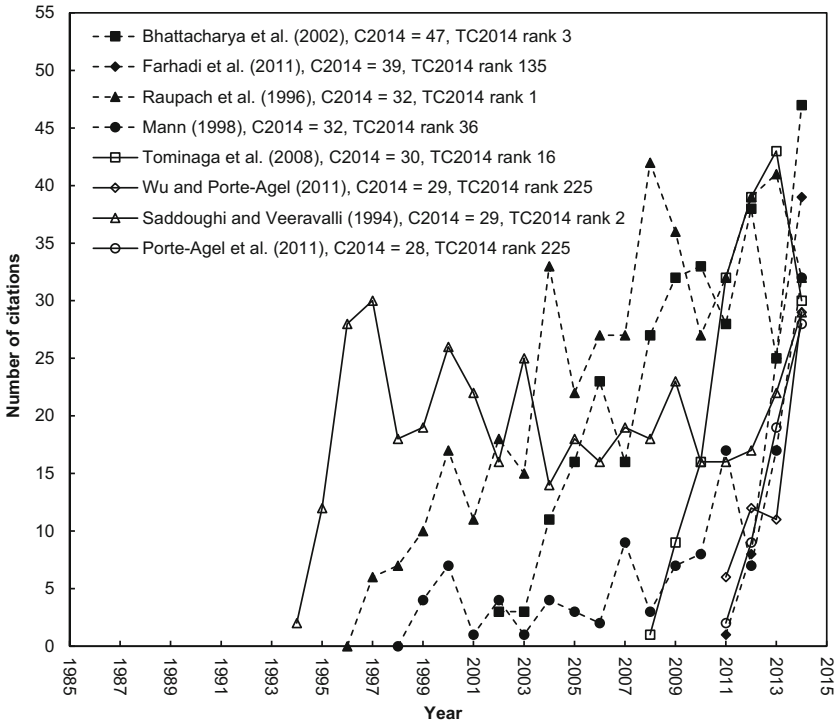

Fig. 6 Article lives of the top eight articles

probably because the method was employed by various researchers such as load calculations on wind turbines and bridges (Cao et al. 2000; Hansen et al. 2006). The citations of article "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings" by Tominaga et al. (2008) increased dramatically to the top with 43 citations in 2013, but decreased to 32 in 2014. The citations of the early published articles "Local isotropy in turbulent boundary-layers at high Reynolds-number" by Saddoughi and Veeravalli (1994) climbed initially to a plateau in 1997 ($C_{1997} = 30$), then maintained steady and even decreased thereafter. In general, the citations of the high impact articles exhibited different patterns of their trends, but would be likely to reach a plateau in certain year.

Research tendency and hotspots

Synthesized analysis of title words, author keywords, abstract, and *KeyWords Plus* has been frequently conducted to screen the research hotspots and tendency in recent decades (Ho et al. 2010; Zhang et al. 2010). This method was proved to be effective in many research topics, such as drinking water (Fu et al. 2013), wetland (Zhang et al. 2010), and material science (Ho 2014). Among 10,241 articles, 10,142 (99%) articles have record information of abstract in Web of Science, 5746 (56%) articles have author keywords, and 6999 (68%) articles have *KeyWord Plus*. The meaning of the single words in titles and abstract sometimes does not make sense, and *KeyWords Plus* have indirect relationship with articles content (Garfield 1990). Therefore, rankings of author keywords words according to their frequency were considered, which can help identify the research hot issues. Table 5 lists the top 20 most frequently used author keywords used during 1991–2014 and four 6-year periods. Other than the search keywords "wind tunnel," the most frequently used author keywords was "aerodynamics," appeared in 200 articles, which was followed by "turbulence" (182 articles), "CFD" (177 articles), and "computational fluid dynamic" (148 articles). As wind tunnel was one of the most important tools in aerodynamics research, the word "aerodynamics" was frequently used across the period of 1991 to 2014. This was similar with the word "turbulence," because turbulence was the research object and key issue of wind tunnel experiments. Moreover, turbulent characteristics were basic descriptions of wind tunnel test conditions. As for the computational fluid dynamic (CFD), it was a numerical model that is complemental method of wind tunnel research. The CFD activities had dramatically increased since the 1990s, and rapidly developed in recent years (Fujii 2005). This could be proved by the increasing ranking of the word "computational fluid dynamic" in Table 5, with a ranking of 332nd (0.21%) in the period of 1991 to 1996 but increased to 5th (3.6%) in 2009 to 2014. The increasing trends were also found for the words of "wind loads," ranking 143rd (0.41%) in 1991 to 1996 period but ranking 8th (2.1%) in 2009 to 2014 period, and "wind turbine," ranking 332nd (0.21%) in 1991 to 1996 period but ranking 11th (1.8%) in 2009 to 2014 period. This indicated that studies about wind loads on building and wind turbine used for transformations of wind power to electric power had caused increasing attentions. On the contrary, the frequency of "lepidoptera" and "sex pheromone" used in

Table 5 Top 20 most frequently used author keywords used during 1991–2014 and four 6-year periods

Author keywords	TP	1991–2014 Rank (%)	1991–1996 Rank (%)	1997–2002 Rank (%)	2003–2008 Rank (%)	2009–2014 Rank (%)
Wind tunnel	885	1 (15)	1 (17)	1 (17)	1 (14)	1 (15)
Wind tunnel test	222	2 (3.9)	143 (0.41)	6 (2.4)	2 (3.8)	2 (5.1)
Aerodynamics	200	3 (3.5)	12 (2.5)	5 (2.7)	3 (3.4)	4 (4.0)
Turbulence	182	4 (3.2)	5 (3.7)	2 (4.3)	4 (3.1)	6 (2.7)
CFD	177	5 (3.1)	N/A	16 (1.3)	5 (2.8)	3 (4.6)
Computational fluid dynamics	148	6 (2.6)	322 (0.21)	10 (1.6)	6 (2.3)	5 (3.6)
Lepidoptera	114	7 (2.0)	2 (8.6)	8 (2.1)	10 (1.8)	35 (0.8)
Wind erosion	103	8 (1.8)	15 (1.9)	14 (1.5)	7 (2.1)	12 (1.7)
Wind tunnel experiment	102	9 (1.8)	33 (1.2)	23 (1.1)	11 (1.8)	7 (2.2)
Numerical simulation	101	10 (1.8)	N/A	9 (2.0)	8 (2.1)	10 (1.8)
Wind loads	100	11 (1.7)	143 (0.41)	15 (1.4)	9 (1.9)	8 (2.1)
Sex pheromone	95	12 (1.7)	4 (4.3)	3 (3.5)	11 (1.8)	117 (0.31)
Wind tunnel tests	93	13 (1.6)	143 (0.41)	19 (1.2)	13 (1.6)	8 (2.1)
Wind tunnel testing	81	14 (1.4)	N/A	16 (1.3)	13 (1.6)	13 (1.6)
Wind	80	15 (1.4)	25 (1.4)	4 (2.8)	22 (1.1)	27 (1.0)
Flight	74	16 (1.3)	6 (3.5)	6 (2.4)	25 (1.0)	62 (0.53)
Boundary layer	72	17 (1.3)	18 (1.6)	10 (1.6)	16 (1.2)	25 (1.0)
Dispersion	71	18 (1.2)	18 (1.6)	10 (1.6)	25 (1.0)	23 (1.1)
Wind tunnels	68	19 (1.2)	51 (0.82)	41 (0.72)	34 (0.91)	14 (1.6)
Wind turbine	65	20 (1.1)	322 (0.21)	328 (0.18)	25 (1.0)	11 (1.8)

TP total number of articles

articles showed a decreasing trend, ranking from 2nd (8.6%) to 35th (0.8%) and from 4th (4.3%) to 117th (0.31%), respectively. Lepidoptera were used as study object in wind tunnels and the dispersion of sex pheromone was intensively studied in the early research of wind tunnel experiment (Picimbon et al. 1997), but received less attention in recent decades. Apart from the top 20 most frequently used author keywords discussed above, the keywords "particle image velocimetry" and "PIV" related to the measurement technique of wind tunnel experiments showed a remarkable increasing trend, ranking from 328 (0.18) and 188 (0.27) in 1997–2002 period to 17 (1.4%) and 21 (1.1%) in 2009–2014 period, respectively. The upgrade of flow visualization technique was an important driving factor to the wind tunnel research. Other potential factors such as the size of wind tunnel, wind speed of measurements, and Reynolds number could also influence the progress of the wind tunnel research though were not reflected from the author keywords analysis.

In addition to the word analysis, word cluster analysis method was adopted to further identify the trends of certain research issues (Mao et al. 2010). This method had been used in many research topics such as drinking water (Fu et al. 2013), wetland (Zhang et al. 2010), and risk assessment (Mao et al. 2010). A detailed description of word cluster analysis method can be found in Mao et al. (2010) and Li et al. (2014). Briefly, article titles, author keywords, *KeyWords Plus*, and abstracts were combined as the word dataset. Then, word clusters, either a serious synonymic single word or congeneric phrases, were identified by specialist judgment. By analyzing the number of publications containing these "word clusters," the overview of the research hotspots could be revealed (Mao et al. 2010). From the word analysis, the numerical method "Computational fluid dynamics" and "CFD" showed an obvious increasing trend of their occurrence frequency in the articles. As such, we made a further explanation of the research trend of numerical simulation in Fig. 7, accompanied with field measurement that was another frequently used method in the wind tunnel research. The supporting words of numerical simulation included numerical modeling, numerical model, numerical simulation(s), CFD, computational fluid dynamics, direct numerical simulation, DNS, large-eddy simulation, LES, Reynolds-averaged-Navier-stokes, and RANS, while those of field measurement comprised of field measurement(s), field experiment(s), field study, field studies, field test(s), field observation(s), and field monitoring. As shown in Fig. 6, in all of the wind tunnel-related articles, the number of articles with numerical simulation increased steadily, with a percentage of from less than 15% in 1990 to around 23% in 2012. This suggested that more wind tunnel articles mentioned numerical simulation in recent years, and this trend might continue growing in the future. As numerical simulation on computers was efficient and cost-

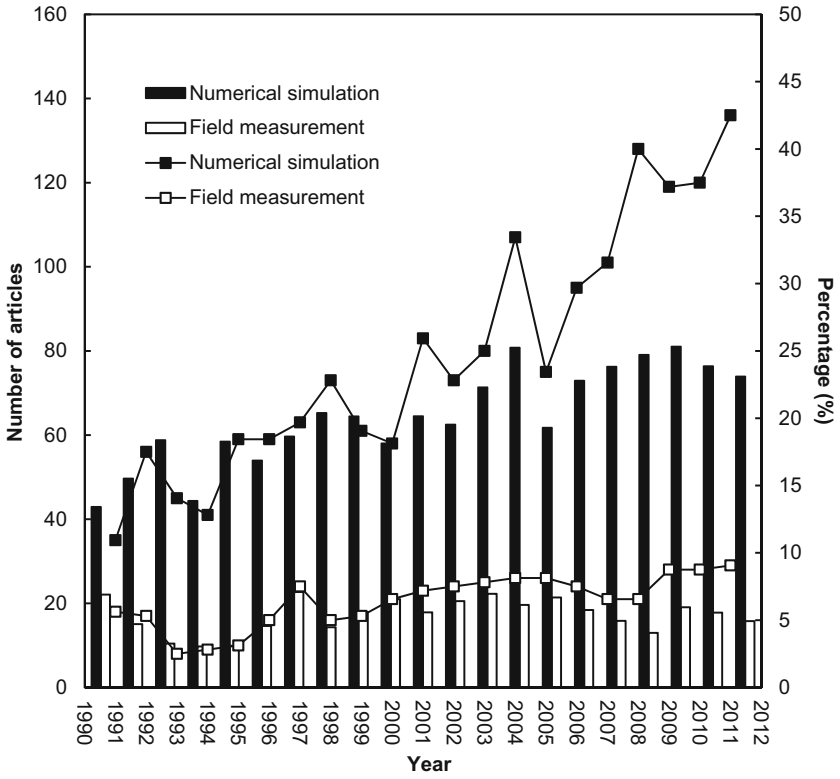

Fig. 7 Comparison of trends of numerical simulation and field measurement

effective, it has been rapidly developed in recent decade. However, the CFD method has not replaced the experimental method. On the contrary, wind tunnel experiments provided support for validation of CFD results (Nielsen 2015). Therefore, the total number of wind tunnel articles was still rising, as shown in Fig. 2, but contained more articles associated with numerical simulation. Meanwhile, the numbers of articles mentioning field measurement did not show an obvious change. The infrastructures of monitoring stations and equipment installation are expensive, and more importantly, a wide range of parameters which might be governing or insignificant are not easy to assess in the complex conditions of real-world (Meroney et al. 1996). Therefore, the studies adopting the field measurements did not show an increasing trend along with the wind tunnel research.

Conclusions

This study evaluated the development and trend of wind tunnel research by adopting bibliometric analysis. Basing on the SCI-EXPANDED database, a total of 10,241 articles were retrieved during a period of 1991 to 2014. English was the dominant language used in these articles. The publication productivity increased sharply suggesting the rapid development of wind tunnel research. *Journal of Wind Engineering and Industrial Aerodynamics* is the most productive. The USA had been leading in publication output since 1991, while China exhibited dramatic growth in recent years and kept narrowing the gap from the USA. NASA showed its dominant position in wind tunnel research, topping in the number of total published articles, single institution articles, internationally collaborative articles, and national collaborative articles. The most frequently cited article in recent year was "Thermophysical properties of high porosity metal foams" by Bhattacharya et al. in 2002. The citation lifecycle analysis shows that the high impact articles exhibited different trends of citations. From synthesized analysis of the distribution and frequency of title words, abstract words, author keywords, and *KeyWords Plus*, we found that CFD was a hotspot, causing increasing concerns in wind tunnel research. Additionally, wind loads on building and wind turbine used for transformations of wind power to electric power also showed a growing trend of being used in the articles. On the contrary, lepidoptera and sex pheromone were less studied in wind tunnel experiments. The comparison of frequency of numerical simulation and field measurement mentioned wind tunnel article further demonstrated that the numerical simulation of CFD developed rapidly while field measurement showed minor change.

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