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RESEARCH ARTICLE

Highly cited articles in wind tunnel-related research: a bibliometric analysis

Ziwei Mo[1] · Hui-Zhen Fu[2] · Yuh-Shan Ho[3]

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Abstract
Wind tunnels have been widely employed in aerodynamic research. To characterize the high impact research, a bibliometric analysis was conducted on highly cited articles related to wind tunnel based on the Science Citation Index Expanded (SCI-EXPANDED) database from 1900 to 2014. Articles with at least 100 citations from the Web of Science Core Collection were selected and analyzed in terms of publication years, authors, institutions, countries/territories, journals, Web of Science categories, and citation life cycles. The results show that a total of 77 highly cited articles in 37 journals were published between 1959 and 2008. *Journal of Fluid Mechanics* published the most of highly cited articles. The USA was the most productive country and most frequent partner of internationally collaboration. The prolific institutions were mainly located in the USA and UK. The authors who were both first author and corresponding author published 88% of the articles. The *Y* index was also deployed to evaluate the publication characteristics of authors. Moreover, the articles with high citations in both history and the latest year with their citation life cycles were examined to provide insights for high impact research. The highly cited articles were almost earliest wind tunnel experimental data and reports on their own research specialty, and thus attracted high citations. It was revealed that classic works of wind tunnel research was frequently occurred in 1990s but much less in 2000s, probably due to the development of numerical models of computational fluid dynamic (CFD) in recent decades.

Keywords Article life · Scientometrics · Wind tunnel · *Y* index · Web of Science Core Collection

Introduction

Wind tunnel is a tool commonly used in aerodynamic research (Stathopoulos 1984). In wind tunnel experiments, effects of air flow were investigated on solid object, such as planes (Amitay et al. 2001), building (Surry 1991), cars (Suzuki et al. 2003), and birds (Kvist et al. 2001). They can simulate turbulent characteristics, wind conditions, and pollutant dispersion at a scale-down condition (Cook 1978). Compared with other research methods of field measurement and numerical modeling, wind tunnel experiments in the laboratory have large advantages. By employing the wind tunnel, scaling down the size of an actual condition is more affordable and time-efficient to evaluate the effects of individual factor in the controllable conditions (Ahmad et al. 2005). Moreover, the experimental results from wind tunnel could provide data for the validation of numerical models (Oberkampf and Trucano 2002).

As wind tunnel technique were deployed in a wide range of scientific fields, including mechanics (Shen and Warhaft 2000; Metzger and Klewicki 2001), civil engineering (Meroney et al. 1996; Cermak 2003), mechanical engineering (Sakamoto and Haniu 1990; Mann 1998), environmental science (Pavageau and Schatzmann 1999; Jenkins et al. 1996), and meteorology and atmospheric sciences (Pruppach and Beard 1970; Raupach et al. 1996), massive articles related to wind tunnel research were published over the last century. In recent decades, the advances in computational fluid dynamics (CFD) modeling on high-speed digital computers have reduced the demand for wind tunnel testing (Fujii 2005). However, CFD results with too simplifying assumptions are

Responsible editor: Philippe Garrigues

✉ Yuh-Shan Ho
ysho@asia.edu.tw

[1] College of Environmental Sciences and Engineering, Peking University, Beijing 100871, People's Republic of China

[2] Department of Information Resources Management, School of Public Affairs, Zhejiang University, No. 866 Yuhangtang Road, Hangzhou 310058, People's Republic of China

[3] Trend Research Centre, Asia University, Taichung 41354, Taiwan

still not completely reliable, which need verification from wind tunnel experiments (Oberkampf and Trucano 2002).

With expanding efforts contributing to wind tunnel field, the development and characteristics of the high impact research were still not clear and have not been evaluated. Bibliomentric analysis is one of the common ways to measure the publication performance, hotspots, and research trend (Fu et al. 2013; Li et al. 2014). Numerous studies have examined the bibliometric characteristics of different research fields in terms of annual productions, journals and subject categories, countries, institutions, and authors (Ho 2012, 2013; Ma and Ho 2016). Citation analysis was also conducted to characterize scholarly contribution by authors and publications (Lefaivre et al. 2011). 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; Patterson and Harris 2009). In the recent years, the highly cited articles were assessed in several research specialty, such as wetlands (Ma et al. 2013), adsorption (Fu and Ho 2014), and medicine (Baltussen and Kindler 2004). In addition to the analysis of output, countries, institutions, authors, and subject categories, citation life cycles of most frequently articles were used to depict the historic citations and their projections (Cano and Lind 1991; Bouabid 2011).

To examine the high impact publication in the research field, wind tunnel-related articles with at least 100 total citations were selected for bibliometric analysis in the Science Citation Index Expanded (SCI-EXPANDED) from 1900 to 2014. Quantitative characteristics and performance of the highly articles were determined by the publication years, journals, Web of Science categories, countries, institutions, authors, and citation life cycles. Moreover, *Y* index was employed to assess the characteristics and contributions of individual authors with highly cited articles. This work can provide insights into the high impact research in wind tunnel field.

Methodology

The analysis provided in this study is based on the SCI-EXPANDED database of the Web of Science Core Collection from Thomson Reuters (updated on July 27, 2015). According to Journal Citation Reports (JCR) from 2014, it indexes 8618 journals with citation references across 176 Web of Science subject categories in the science edition. The keywords "wind tunnel," "wind tunnels," "wind tunnelling," and "wind-tunneling" were searched in the topic field, including title, abstract, author keywords, and *KeyWords Plus*, in the Web of Science Core Collection within the publication year limitation from 1900 to 2014 and the document type limitation to article only. KeyWords Plus supplies additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI (now Thomson Reuters, New York) database, and substantially augments title-word and author-keyword indexing (Garfield 1990). In total, 11,970 articles were found. Two additional filters, namely TC_{year} (Ho 2012) and the "front page" (Fu et al. 2012), were used to retrieve highly cited articles. The total number of times an article was cited from its publication until the end of last year was recorded as TC_{year}. This indicator is an invariant parameter, which can ensure repeatability, in comparison with the index of citation from Web of Science Core Collection which has been updated from time to time (Fu et al. 2012). Thus, the total number of times an article was cited from its publication until the end of 2014 was designated as TC_{2014} (Ho 2012). This study selected the articles with $TC_{2014} \geq 100$ as highly cited articles. The other filter, the front page (Fu et al. 2012), was used to identify articles with the indicated keywords on their front page, including the article title, abstract, and keyword section. Articles that could be found only through KeyWords Plus were excluded. Finally, 77 articles (0.64% of the 11,970 total articles) were found to be highly cited articles in wind tunnel-related research. These records were downloaded into spreadsheet software, and additional coding was manually performed using Microsoft Excel 2010 for calculation (Li and Ho 2008).

Results and discussion

A total of 77 highly cited wind tunnel-related articles ($TC_{2014} \geq 100$) were published in SCI-EXPANDED between 1959 and 2008. English was the only one language used. The maximal value of TC_{2014} was 442, and the average value was 153.

Effect of time on citation analysis

The relationship between the number of highly cited articles and their citations per publication ($CPP = TC_{2014}$/years) by decade was analyzed (Ho 2012), which could help identify the important period of conducting the research. Figure 1 illustrates the distribution of these 77 highly cited articles over decades, and their citations per publication ($CPP = TC_{2014}$/year). Most of the highly cited articles were published in 1990s, with 43 articles (56% of total 77 articles), followed by 2000s with 20 articles (26%). Only a few articles were published from 1950s to 1980s, ranging from one to six articles, while no highly cited article was recorded before 1950s. There were also no highly cited articles in the recent 5 years (2009–2014), probably because citations need time to accumulate. This indicated that highly cited articles were not necessarily associated with time but always occurred in the past one or two decades, which were also found in biomass research (Chen and Ho 2015). The 1990s' articles had highest *CPP* (163), followed by *CPP* of 157 in 1980s, 155 in 1970s,

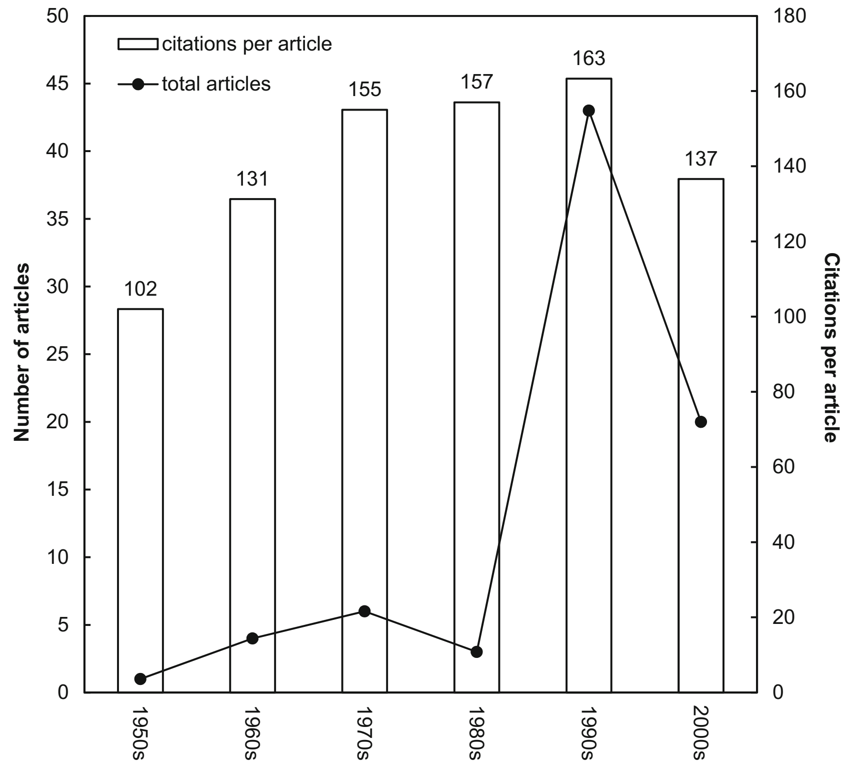

Fig. 1 Number of articles and citations per article by decade

137 in 2000s, and 131 in 1960s. The most cited article entitled "Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy" by Raupach et al. (1996) and the second most cited article "Local isotropy in turbulent boundary layers at high Reynolds number" by Saddoughi and Veeravalli (1994) were published in 1990s, with TC_{2014} of 442 and 402, respectively. Additionally, most of the top 10 TC_{2014} articles (7 of 10 articles) were published in 1990s. These most frequently cited articles led to the high *CPP* in the decades of 1990s. As most highly articles and highest *CPP* appeared in 1990s, it was suggested that wind tunnel research rapidly developed and obtained great achievements during this decade. This phenomenon can likely to explain that with several decade developments, wind tunnel research has become advanced enough to produce classical works in 1990s (Fujii 2005). The earliest highly cited articles entitled "Atomic recombination in a hypersonic wind-tunnel nozzle" by Bray (1959) has TC_{2014} of 102, while the most recent articles entitled "AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings" by Tominaga et al. (2008) has TC_{2014} of 172.

Journal and Web of Science subject category

Journals and subject category are basic units in bibliometric analysis (Chiu and Ho 2007; Leydesdorff and Rafols 2009), which can explain the distributions of the research scope in a certain topic. The highly cited wind tunnel-related articles were published in 37 journals in 28 Web of Science categories in the science edition. Of the 37 journals, 22 journals (59% of 37 journals) contained only one highly cited article, 6 (16%) journals contained two articles, 4 (11%) journals contained three articles, 1 (2.7%) journal contained four articles, 3 (8.1%) journals contained six, and 1 (2.7%) journal contained nine articles. Table 1 lists the top 15 journals with more than two highly cited articles. *Journal of Fluid Mechanics* published the most of highly cited articles (9; 12% of 77 highly cited articles). It was followed by *Journal of Experimental Biology*, *Atmospheric Environment*, and *Boundary-Layer Meteorology*, which all published six articles. *Nature* with the highest IF_{2014} (41.456) published three highly cited articles. However, highly cited articles were also published in some journals with low impact factors, for example, *Journal of Enhanced Heat Transfer* ($IF_{2014} = 0.244$), *Journal of Agricultural Science* ($IF_{2014} = 0.653$), and *Journal of Fluids Engineering-Transactions of the ASME* ($IF_{2014} = 0.932$). It implies that the highly cited articles were published not only in high impact factors as expected but also in low impact factors (Ho 2013).

The distribution of the Web of Science subject categories for research topics has been studied (Chiu and Ho 2007). As for the wind tunnel research, Web of Science category of meteorology and atmospheric sciences with 77 journals published the most highly cited articles (22 articles; 29% of 77 articles), followed by mechanics with 137 journals (17; 22%), fluid and plasma physics with 31 journals (12; 16%),

Table 1 Top 15 journals with more than two highly cited articles

Journals	TP (%)	IF_{2014}	Web of Science category
Journal of Fluid Mechanics	9 (12)	2.383	Mechanics
			Fluids and plasmas physics
Journal of Experimental Biology	6 (7.8)	2.897	Biology
Atmospheric Environment	6 (7.8)	3.281	Environmental sciences
			Meteorology and atmospheric sciences
Boundary-Layer Meteorology	6 (7.8)	2.470	Meteorology and atmospheric sciences
AIAA Journal	4 (5.2)	1.207	Aerospace engineering
Quarterly Journal of the Royal Meteorological Society	3 (3.9)	3.252	Meteorology and atmospheric sciences
Journal of the Atmospheric Sciences	3 (3.9)	3.143	Meteorology and atmospheric sciences
Nature	3 (3.9)	41.456	Multidisciplinary sciences
Physics of Fluids	3 (3.9)	2.031	Mechanics
			Fluids and plasmas physics
Proceedings of the National Academy of Sciences of the United States of America	2 (2.6)	9.674	Multidisciplinary sciences
Journal of Wind Engineering and Industrial Aerodynamics	2 (2.6)	1.414	Civil engineering
			Mechanics
Environmental Science & Technology	2 (2.6)	5.330	Environmental engineering
			Environmental sciences
Journal of Chemical Ecology	2 (2.6)	2.747	Biochemistry and molecular biology
			Ecology
Geomorphology	2 (2.6)	2.785	Physical geography
			Multidisciplinary geosciences
Measurement Science & Technology	2 (2.6)	1.433	Multidisciplinary engineering
			Instruments and instrumentation

TP total number of highly cited articles, TC_{2014} number of citations till 2014, C_{2014} number of citations in 2014

environmental sciences with 221 journals (11; 14%), mechanical engineering with 130 journals (6; 7.8%), biology with 85 journals (6; 7.8%), and multidisciplinary sciences with 56 journals (5; 6.5%). The most frequently cited article in wind tunnel-related research with TC_{2014} was published in the journals in category of meteorology and atmospheric sciences (Raupach et al. 1996). It should also be noted that journals could be classified in two or more categories in Web of Science, for instance, *Journal of Fluid Mechanics* was listed in "mechanics" and "fluid and plasma physics"; thus, the sum of percentages was higher than 100%.

Citation life cycles of highly cited articles

Total citation (TC) is a popular indicator which has been changing over time. To avoid the ambiguity and repeat the scientific number, TC_{year} and C_{year} were proposed by Ho (2012). TC_{2014} means the number of total citations from publication year to the end of 2014, while C_{2014} represents the number of citations in 2014 only. Table 2 lists the 77 highly cited articles with their C_{2014} and TC_{2014}. The most frequently cited article is "Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy," with TC_{2014} of 442. It is followed by "Local isotropy in turbulent boundary layers at high Reynolds number" ($TC_{2014} = 406$), "Thermophysical properties of high porosity metal foams" ($TC_{2014} = 302$), "A wind tunnel investigation of internal circulation and shape of water drops falling at terminal velocity in air" ($TC_{2014} = 288$), and "Identification of semiochemicals released during aphid feeding that attract parasitoid *Aphidius ervi*" ($TC_{2014} = 244$). However, the high TC_{2014} does not necessarily mean high C_{2014}. The article "A wind tunnel investigation of internal circulation and shape of water drops falling at terminal velocity in air" and "Identification of semiochemicals released during aphid feeding that attract parasitoid *Aphidius ervi*" ranked 3rd and 4th in TC_{2014}, but ranked 14th and 18th in C_{2014}, with C_{2014} of 15 and 13, respectively. This was reasonable because the most frequently cited articles might not be influential in recent years (Fu and Ho 2015). In comparison, the article entitled "Wind field simulation" by Mann (1998) ranked 2nd in C_{2014} (32) while ranked 45th in TC_{2014} (126). The phenomenon was not special in wind tunnel reasearch but also found in other research fields, such as biomass burning (Chen and Ho 2015) and materials science (Ho 2014b).

The relationship of citation frequency and literature aging of highly cited articles was found and categorized into five

Table 2 The 77 most frequently cited articles in wind tunnel field

Rank (TC_{2014})	Rank (C_{2014})	Article title	References
1 (442)	2 (32)	Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy	Raupach et al. (1996)
2 (406)	5 (29)	Local isotropy in turbulent boundary layers at high Reynolds number	Saddoughi and Veeravalli (1994)
3 (302)	1 (47)	Thermophysical properties of high porosity metal foams	Bhattacharya et al. (2002)
4 (288)	14 (15)	A wind tunnel investigation of internal circulation and shape of water drops falling at terminal velocity in air	Pruppach and Beard (1970)
5 (244)	18 (13)	Identification of semiochemicals released during aphid feeding that attract parasitoid *Aphidius ervi*	Du et al. (1998)
6 (240)	8 (20)	Effect of saltation bombardment on the entrainment of dust by wind	Shao and Raupach (1993)
7 (228)	51 (6)	A wind tunnel study of turbulent flow close to regularly arrayed rough surfaces	Raupach et al. (1980)
8 (208)	51 (6)	Hydrodynamic aspects of design and attachment of a back-mounted device in penguins	Bannasch et al. (1994)
9 (205)	11 (17)	On the onset of high-Reynolds number grid-generated wind tunnel turbulence	Mydlarski and Warhaft (1996)
9 (205)	36 (8)	Direct simulation of particle dispersion in a decaying isotropic turbulence	Elghobashi and Truesdell (1992)
11 (195)	9 (19)	Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance	Belnap and Gillette (1998)
12 (193)	10 (18)	New roles for cis-jasmone as an insect semiochemical and in plant defense	Birkett et al. (2000)
13 (186)	72 (1)	Air sea gas exchange in rough and stormy seas measured by a dual-tracer technique	Watson et al. (1991)
14 (183)	18 (13)	Near wall flow over urban-like roughness	Cheng and Castro (2002)
15 (179)	23 (12)	Large-eddy simulation of turbulent flow above and within a forest	Shaw and Schumann (1992)
15 (179)	18 (13)	A study on vortex shedding from spheres in a uniform flow	Sakamoto and Haniu (1990)
17 (177)	27 (11)	Study of line source characteristics for 2D physical modelling of pollutant dispersion in street canyons	Meroney et al. (1996)
18 (172)	18 (13)	Stereoscopic digital particle image velocimetry for application in wind tunnel flows	Willert (1997)
19 (171)	4 (31)	AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings	Tominaga et al. (2008)
20 (168)	6 (25)	Experiments on drag-reducing surfaces and their optimization with an adjustable geometry	Bechert et al. (1997)
21 (166)	27 (11)	Characterization of the gent stacked filter unit PM10 sampler	Hopke et al. (1997)
22 (164)	61 (4)	Passive scalar statistics in high-Peclet number grid turbulence	Mydlarski and Warhaft (1998)
23 (163)	41 (7)	Correction of instrumental biases in historical sea surface temperature data	Folland and Parker (1995)
24 (162)	51 (6)	A determination of terminal velocity and drag of small water drops by means of a wind tunnel	Beard and Pruppach (1969)
25 (160)	72 (1)	Respiratory and cardiovascular responses of pigeon to sustained, level flight in a wind tunnel	Butler et al. (1977)
26 (157)	23 (12)	Effects of temperature, wind speed and air humidity on ammonia volatilization from surface applied cattle slurry	Sommer et al. (1991)
27 (154)	41 (7)	Reiterative responses to single strands of odor promote sustained upwind flight and odor source location by moths	Vickers and Baker (1994)
28 (153)	66 (3)	Strategies involved in the location of hosts by the parasitoid *Aphidius ervi* Haliday (*Hymenoptera*: *Braconidae*: *Aphidiinae*)	Powell et al. (1998)
29 (152)	61 (4)	Wind tunnel investigation of rate of evaporation of small water drops falling at terminal velocity in air	Beard and Pruppach (1971)
30 (149)	51 (6)	An improved method of simulating an atmospheric boundary layer in a wind tunnel	Counihan (1969)
31 (148)	58 (5)	Luminescent barometry in wind tunnels	Kavandi et al. (1990)
32 (147)	11 (17)	Emission factors for polycyclic aromatic hydrocarbons from biomass burning	Jenkins et al. (1996)
33 (146)	66 (3)	Relative importance of semiochemicals from first and second trophic levels in host foraging behavior of *Aphidius ervi*	Du et al. (1996)
34 (145)	16 (14)	Saltating particles over flat beds	Nalpanis et al. (1993)
35 (144)	36 (8)	Liquid crystal measurements of heat transfer and surface shear stress	Ireland and Jones (2000)
36 (140)	41 (7)	A note on the overlap region in turbulent boundary layers	Österlund et al. (2000)
36 (140)	41 (7)	A wind tunnel study of air flow in waving wheat: Single-point velocity statistics	Brunet et al. (1994)
38 (139)	27 (11)	Laboratory measurements of axis ratios for large raindrops	Andsager et al. (1999)

Table 2 (continued)

Rank (TC_{2014})	Rank (C_{2014})	Article title	References
39 (137)	14 (15)	An improved method for the estimation of surface roughness of obstacle arrays	MacDonald et al. (1998)
40 (133)	36 (8)	Unconventional lift-generating mechanisms in free-flying butterflies	Srygley and Thomas (2002)
41 (132)	13 (16)	Development and calibration of a resin-based passive sampling system for monitoring persistent organic pollutants in the atmosphere	Wania et al. (2003)
42 (128)	41 (7)	Engineering application of experimental uncertainty analysis	Coleman and Steele (1995)
43 (127)	51 (6)	Wind stress measurements from the open ocean corrected for airflow distortion by the ship	Yelland et al. (1998)
43 (127)	41 (7)	Threshold windspeeds for sand on mars: Wind tunnel simulations	Greeley et al. (1980)
45 (126)	2 (32)	Wind field simulation	Mann (1998)
45 (126)	32 (9)	New microphysics sensor for aircraft use	Gerber et al. (1994)
47 (125)	16 (14)	BUBBLE—An urban boundary layer meteorology project	Rotach et al. (2005)
48 (123)	58 (5)	Feedback control of vortex shedding at low Reynolds numbers	Roussopoulos (1993)
49 (121)	69 (2)	Response of the braconid parasitoid Cotesia (= apanteles) glomerata to volatile infochemicals: Effects of bioassay setup, parasitoid age and experience and barometric flux	Steinberg et al. (1992)
50 (120)	41 (7)	A family of vortex wakes generated by a thrush nightingale in free flight in a wind tunnel over its entire natural range of flight speeds	Spedding et al. (2003)
51 (119)	32 (9)	Effects of dry matter content and temperature on ammonia loss from surface-applied cattle slurry	Sommer and Olesen (1991)
52 (118)	51 (6)	Wind tunnel study of concentration fields in street canyons	Kastner-Klein and Plate (1999)
53 (117)	66 (3)	Behavioral responses of the gypsy moth lepidoptera, lymantridae in a wind tunnel to air-borne enantiomers of disparlure	Carde and Hagaman (1979)
54 (116)	61 (4)	The anisotropy of the small scale structure in high Reynolds number (Rl 1000) turbulent shear flow	Shen and Warhaft (2000)
54 (116)	69 (2)	Pigeon flight in a wind tunnel. II. Gas exchange and power requirements	Rothe et al. (1987)
56 (115)	23 (12)	Temperature-sensitive europium(III) probes and their use for simultaneous luminescent sensing of temperature and oxygen	Borisov and Wolfbeis (2006)
57 (114)	27 (11)	Aerodynamic flow control over an unconventional airfoil using synthetic jet actuators	Amitay et al. (2001)
57 (114)	51 (6)	Wind-blown sand on beaches: an evaluation of models	Sherman et al. (1998)
57 (114)	58 (5)	Field and wind tunnel assessments of the implications of respacing and thinning for tree stability	Gardiner et al. (1997)
60 (113)	61 (4)	A wind tunnel study of gliding flight in pigeon *Columba livia*	Pennycui (1968)
61 (112)	76 (0)	Wingbeat frequency and the body drag anomaly: Wind tunnel observations on a thrush nightingale (*Luscinia luscinia*) and a teal (*Anas crecca*)	Pennycuick et al. (1996)
62 (110)	7 (21)	Experiments with three-dimensional riblets as an idealized model of shark skin	Bechert et al. (2000)
62 (110)	76 (0)	Air side performance of brazed aluminum heat exchangers	Chang and Wang (1996)
64 (109)	61 (4)	Carrying large fuel loads during sustained bird flight is cheaper than expected	Kvist et al. (2001)
64 (109)	36 (8)	Wind tunnel simulation of erosion of soil: Effect of soil texture, sandblasting, wind speed, and soil consolidation on dust production	Gillette (1978)
66 (108)	32 (9)	Large eddy simulation of flow around an airfoil near stall	Mary and Sagaut (2002)
66 (108)	32 (9)	Wind tunnel measurements of concentration fluctuations in an urban street canyon	Pavageau and Schatzmann (1999)
68 (106)	69 (2)	Avian pectoral muscle size rapidly tracks body mass changes during flight, fasting and fuelling	Lindstrom et al. (2000)
68 (106)	18 (13)	Wind tunnel experiments on how thermal stratification affects flow in and above urban street canyons	Uehara et al. (2000)
68 (106)	41 (7)	The role of streamline curvature in sand dune dynamics: Evidence from field and wind tunnel measurements	Wiggs et al. (1996)
71 (105)	23 (12)	Mean flow and turbulence statistics over groups of urban-like cubical obstacles	Coceal et al. (2006)
71 (105)	31 (10)	The origin of accretionary lapilli	Gilbert and Lane (1994)
73 (104)	41 (7)	Wind tunnel experiments relating to supersonic and hypersonic boundary layer transition	Kendall (1975)
74 (102)	72 (1)	Atomic recombination in a hypersonic wind tunnel nozzle	Bray (1959)
75 (101)	72 (1)	Exchange of momentum mass and heat between an artificial leaf and airflow in a wind tunnel	Thom (1968)

Table 2 (continued)

Rank (TC_{2014})	Rank (C_{2014})	Article title	References
76 (100)	41 (7)	A comparative study of near-wall turbulence in high and low Reynolds number boundary layers	Metzger and Klewicki (2001)
76 (100)	36 (8)	Direct numerical simulation of controlled transition in a flat-plate boundary layer	Rist and Fasel (1995)

TC_{2014} number of citations till 2014, C_{2014} number of citations in 2014

patterns of individual articles, including initially much praised articles, basic recognized work, scarcely reflected work, well-received but later erroneous qualified work, and genial work were reported (Avramescu 1979). Several studies by Ho and co-workers have investigated the life cycles of top-cited articles in specified subjects, for example, adsorption (Fu et al. 2012), wetland (Ma et al. 2013), biomass (Chen and Ho 2015), and thermodynamic (Fu and Ho 2015) as well as research fields of chemical engineering (Chuang et al. 2011) and materials science (Ho 2014b). In this study, the citation life cycles of four highly cited articles related to wind tunnel ranked in both top 10 in TC_{2014} and C_{2014} were illustrated in Fig. 2. These articles were published between 1993 and 2002, with three in 1990s and one in 2000s. The most frequently article entitled "Coherent eddies and turbulence in vegetation canopies: The mixing-layer analogy" by Raupach (1996) showed a fluctuating growth of annual citation number from 1996 to 2014, with most citations in 2008 ($C_{2008} = 42$) and 2013 ($C_{2013} = 41$). This article presented a physical picture for the dominant eddy structure in a plant canopy tested by wind tunnel experiments and proposed that mixing-layer analogy provided an explanation for many of the observed distinctive features of canopy turbulence. The mixing-layer analogy, which is a basic theory, can be applied to many other researches, such as estimating turbulence length and timescales for applied turbulent transport models and predicting behaviors of canopy turbulence in disturbed canopy environments. These possible applications are useful for many aspects of the research, and thus cause high attentions.

The citation frequency of the article "Local isotropy in turbulent boundary-layers at high Reynolds-number" by Saddoughi and Veeravalli (1994) climbed initially to a plateau in 1997 ($C_{1997} = 30$) and then decreased sharply in the following year ($C_{1998} = 18$). But this articles attracted citations again in 2014 ($C_{2014} = 29$). In this work, the world's largest wind tunnel at NASA Ames Research Center was employed to test the local isotropy predictions of Kolmogorov's (1941) universal equilibrium theory. The experimental data has validated

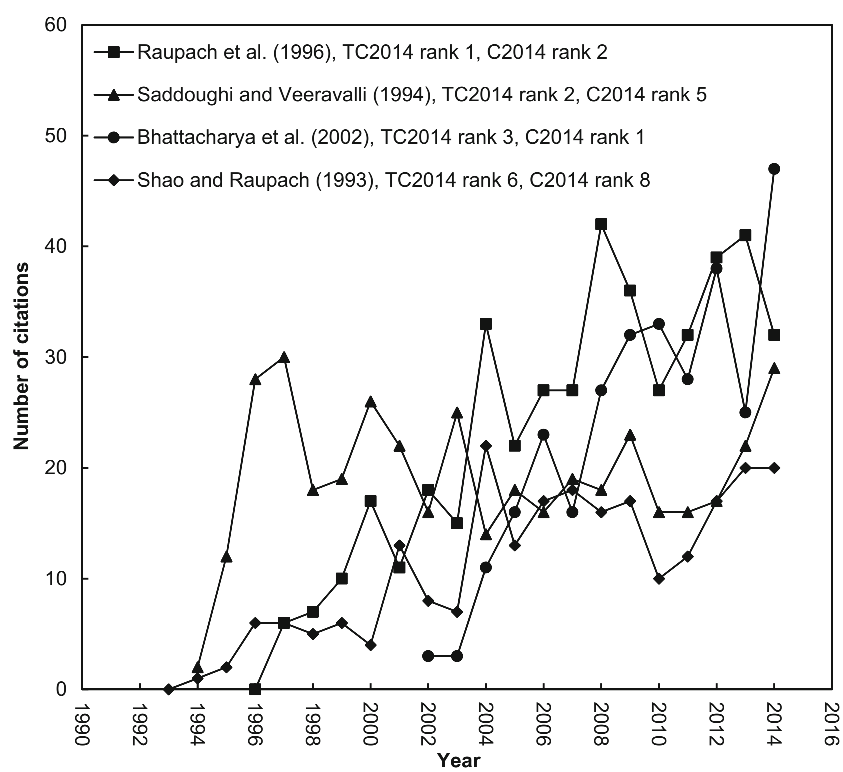

Fig. 2 The four articles ranked in both top 10 TC_{2014} and C_{2014}

the local isotropy hypothesis, and cited by numerous researches. If direct numerical simulation (DNS) on super computers cannot meet the high Reynolds number requirement to study the turbulence, the experimental data obtained in such a large wind tunnel facility, which achieved the high Reynolds numbers, will be still valuable and irreplaceable nowadays.

The third most cited article "Thermophysical properties of high porosity metal foams" by Bhattacharya et al. (2002) was the youngest one among the four articles, but has the highest number of citations in the most recent year ($C_{2014} = 47$). This article showed a rapid increase of citation in spite of a fall in 2013. However, the number of citations has climbed back on top in 2014 ($C_{2014} = 47$). This article presented a comprehensive analytical and experimental investigation for the determination of the effective thermal properties of high porosity metal foams, while most of studies on low porosity media such as packed beds and granular media. The wind tunnel was used to conduct fluid experiments on a number of metal foam samples with different porosities and pore densities. Several models were proposed to determine these thermal parameters, which agreed well with the measured data. This work pioneered in measuring thermophysical properties of high porosity fibrous metal foams, which was seldom reported previously. Thus, this paper was reasonable to attract high citations since its time of publication.

The corresponding author of "Effect of saltation bombardment on the entrainment of dust by wind" (Shao and Raupach 1993) was M.R. Raupach who was also the first and corresponding author of the most cited articles (Raupach et al. 1996). This article showed a relative slow growth trend of annual citations. The highest number of citations occurred in 2004 ($C_{2004} = 22$), over 10 years after its publication time. After a subsequent decline in 2005 ($C_{2005} = 13$), the number of its citations reached 20 in 2014, showing that this article still attracted attentions in recent years. This article derived theoretical explanation of the experimental results from wind tunnel investigation on dust emission by saltation bombardment. The theoretical hypothesis and measured data were accordingly basic for further study on the mechanism of saltation bombardment.

From the above analysis, we found that these highly cited articles were almost earliest reports of wind tunnel measurements on their own research specialty, and the wind tunnel experimental data provided validation of the theoretical models and hypothesis, which is basic information for next-step research.

Publication performances: countries, institutions, and authors

In order to improve bias in Web of Science, all hard copies of highly cited wind tunnel-related articles were collected and checked information in Web of Science. It has been noticed that the corresponding author is most likely to appear first and then last (Mattsson et al. 2011). In a multiauthor article where authorship is unspecified, the first author is classified as the corresponding author (Ho 2014a). Articles from Germany and Federal Republic of Germany (Fed Rep Ger) were, after manual inspection, reclassified as being from Germany (Ho 2012).

Of all the 77 highly cited wind tunnel-related articles in SCI-EXPANDED, 61 (79%) articles were single-country articles from 10 countries and 16 (21%) articles were internationally collaborative articles from 16 countries. The USA published the most articles with 29 articles (38% of 77 articles), followed by the UK (24 articles), Germany (12), Sweden (6), Australia (5), Netherlands (5), Denmark (4), Canada (3), Japan (3), France (2), Italy (2), and 1 for each of Belgium, Brazil, Bulgaria, Ireland, Singapore, Switzerland, and Taiwan, respectively. The seven major industrial countries (G7: USA, Japan, the UK, Germany, France, Canada, and Italy) published 67 highly cited articles (87% of 77 articles). Domination in highly cited articles from the G7 was not surprising since this pattern occurs in the materials science field (Ho 2014b). It can be also found that the earlier wind tunnel-related researches were published by the USA (Munk 1923) and the UK (Rosenhead 1930). The USA was the most frequent partner accounting for 50% of 16 internationally collaborative articles followed by Sweden (6 articles; 38%), Germany (5; 31%), the UK (5; 31%), France (292; 14%), Japan (291; 14%), China (235; 11%), Switzerland (152; 7.4%), Netherlands (4; 25%), Australia (2; 13%), and Italy (2; 13%). There is no doubt that the USA was the most productive and dominant country in wind tunnel research, because most of the large wind tunnel facilities were constructed in the USA. For example, Ames Research Center of NASA has operated over 20 wind tunnels of varying sizes and purposes. Three major are used at Ames to support civilian and military model tests, including the National Full-Scale Aerodynamics Complex (NFAC), The Unitary Plan Wind Tunnel, and The 12-Foot Pressure Wind Tunnel (Baals and Corliss 1981). The leadership of USA in wind tunnel research indeed depended on ready access to technologically advanced, efficient, and affordable test capabilities. They also established large-scale projects such as Aeronautics Test Program (ATP) to perform and participate in the research (Marshall 2010), which well explained their dominations in wind tunnels studies.

In total, 40 articles (52% of 77 articles) were single-institution articles, and 37 (48%) were inter-institutionally collaborative articles. Table 3 shows the top 10 productive institutions and displays the rankings and numbers of six indicators including total number of articles and numbers of first-author, corresponding-author, single-institution, inter-institutionally collaborative, and single-author articles (Ho and Kahn 2014). Four of the 10 most productive institutions were in the USA, 3 institutions were in the UK, and 1 each was in each of Australia, Germany, and Sweden. Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia and Lund University in Sweden published four highly cited articles, topping in the list of institutions. CSIRO ranked first in first-author articles ($FP = 4$) and in corresponding-author articles ($RP = 4$). This means that all the highly cited articles from CSIRO were written by the authors who were first and corresponding author at the same time, which illustrated their leaderships and dominant positions in these articles. Lund University have most inter-institutionally collaborative articles ($CP = 4$), indicating its strong corporations with other institutions. All the other eight institutions, including Cornell University, DLR, IACR, NASA, University of Bristol, University of California Davis, University of California Los Angeles, and University of Southampton, published three highly cited articles. Specifically, Cornell University and University of California Los Angeles ranked top in single-institution articles ($IP = 3$). This suggested that these two institutions had good capability of independently conducting research. What is more, NASA, which has more wind tunnels than any other groups (Saddoughi and Veeravalli 1994), did not publish many highly cited articles though they were dominated in total publication output of wind tunnel field.

Citations are of course an imperfect means of measuring an author's impact on the field (Stern and Arndt 1999). The highly cited articles were published not only in journals with high impact factors as expected but also in low impact factors (Hsu and Ho 2014). It was reported that how often one's work is cited as a better measure of the impact of an individual's works than how many papers a person has authored (Stern and Arndt 1999). The first author is the person who contributed most to the work and writing of the article (Gaeta 1999). The corresponding author is perceived as the author contributing significantly to the article independently of the author position (Mattsson et al. 2011). In addition, the first-author contribution of highly cited articles was studied more in research field (Stern and Arndt 1999). In recent years, the *Y* index has been presented and applied to characterize highly cited articles of authors (Ho 2012, 2013). The *Y* index is related to important positions which are the numbers of first-author articles (*FP*) and corresponding-author articles (*RP*). The *Y* index with two parameters (*j*, *h*) assesses both the publication quantity and characteristics of contribution as a single index. The *Y* index is defined as

$$j = FP + RP \quad (1)$$

$$h = \tan^{-1}\left(\frac{RP}{FP}\right) \quad (2)$$

j indicates publication potential with first and corresponding-author articles only. It was calculated by using numbers of first-authored articles and corresponding-authored articles as the Eq. (1). When one had larger *j*, it means its *Y* index located far away from origin of the polar coordinates. It indicates that one published more articles as "important author." In order to determine the location of *Y* index in the polar coordinates, another parameter *h* is necessary. *h* is a publication characteristic constant, that differentiates its nature of leadership role. It introduces the distribution of the numbers of the first-authored articles and the corresponding-authored articles. When the number of the first-authored articles and the number of the corresponding-authored articles are the same, *Y* index is located in the 45° (0.7854 rad) line. Thus, *h* could be calculated by using Eq. (2). Then, when $h > 0.7854$, it means one published more corresponding-author articles, and when $h < 0.7854$, it means one published more first-author articles. When $h = 0$, j = number of first-author articles, and $h = \pi/2$, j = number of corresponding-author articles (Ho 2014a).

A total of 77 highly cited articles in wind tunnel-related research were contributed by 222 authors from 18 countries. In wind tunnel-related research field, corresponding author

Table 3 Top 10 institutions with no less than three highly cited articles ($TP \geq 3$)

Institution	R (*TP*)	*R* (*IP*)	*R* (*CP*)	*R* (*FP*)	*R* (*RP*)	*R* (*SP*)
Commonwealth Scientific and Industrial Research Organization, Australia	1 (4)	3 (2)	2 (2)	1 (4)	1 (4)	N/A
Lund University, Sweden	1 (4)	N/A	1 (4)	10 (1)	7 (2)	N/A
Cornell University, USA	3 (3)	1 (3)	N/A	2 (3)	2 (3)	N/A
DLR, Germany	3 (3)	3 (2)	14 (1)	2 (3)	2 (3)	1 (1)
IACR, UK	3 (3)	3 (2)	14 (1)	2 (3)	2 (3)	N/A
NASA, USA	3 (3)	8 (1)	2 (2)	10 (1)	12 (1)	N/A
University of Bristol, UK	3 (3)	3 (2)	14 (1)	2 (3)	2 (3)	1 (1)
University of California Davis, USA	3 (3)	8 (1)	2 (2)	7 (2)	7 (2)	N/A
University of California Los Angeles, USA	3 (3)	1 (3)	N/A	2 (3)	2 (3)	N/A
University of Southampton, UK	3 (3)	8 (1)	2 (2)	10 (1)	12 (1)	1 (1)

TP total number of highly cited articles, *IP* single-institution articles, *CP* inter-institutionally collaborative articles, *FP* first-author articles, *RP* corresponding-author articles, *SP* single-author articles, *R* rank, *N/A* not available

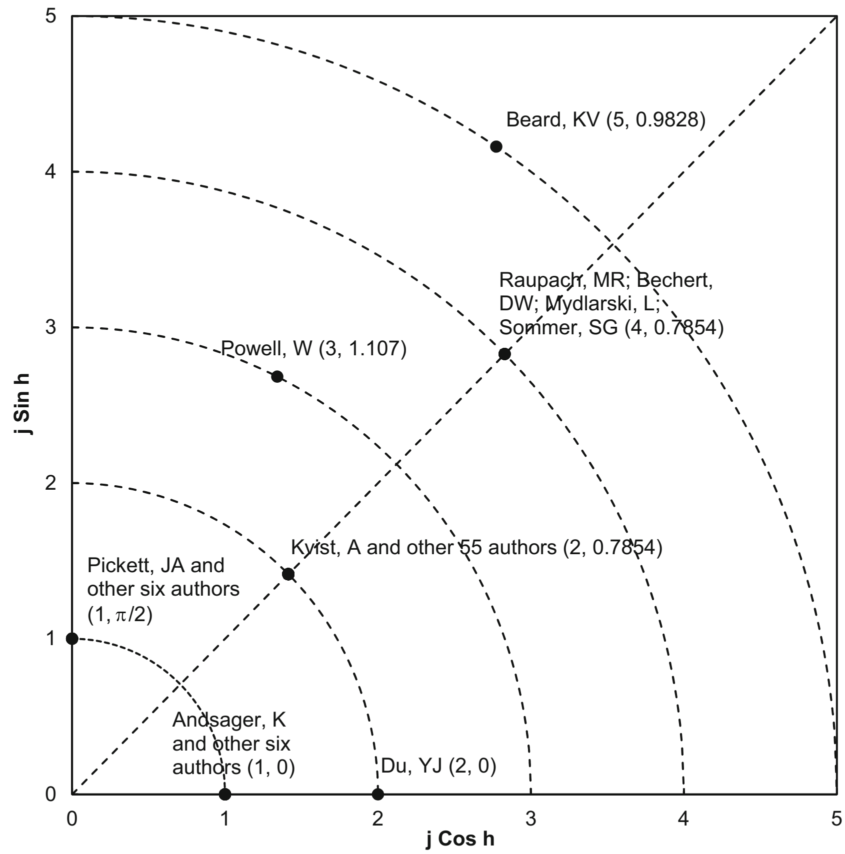

Fig. 3 Top 78 authors with *Y* index ($j \geq 1$)

preferred to be the first author in highly cited articles. Sixty-eight articles (88% of 77 articles) published by authors who were both first author and corresponding author. Only 63 authors (28% of 222 authors) had both first and corresponding-author articles, while 151 (68%) authors had no first-author article, 152 (68%) authors had no corresponding-author article, and 144 (65%) authors had not either first-author articles or corresponding-author articles. Of the 63 authors, only two authors (3.2% of the 63 authors) had $h > 0.7854$ and no authors had $0 < h < 0.7854$, while 61 (97%) authors had the same numbers of first-author and corresponding-author articles ($h = 0.7854$). In addition, eight authors published only first-author articles ($h = 0$) and seven authors published only corresponding-author articles ($h = \pi/2$). The *Y* index (j, h) for 78 authors who published at least one first or corresponding-author article is presented in Fig. 3. Each dot represents one set of *Y* index value that could be one author or many authors. K.V. Beard had the highest j of 5, who published four highly cited articles including two first author and three corresponding author with *Y* index (5, 0.9828), followed by M.R. Raupach, D.W. Bechert, L. Mydlarski, and S.G. Sommer who had the same value of $j = 4$. Y.J. Du and A. Kvist had the same value of $j = 2$ located in the same curve in Fig. 3, but they had different publication characteristics. h of A. Kvist was 0.7854, and Y.J. Du was 0. A. Kvist had greater proportion of corresponding-author articles to first-author articles. Furthermore, within these 78 authors, Y.J. Du, K. Andsager, A. Bhattacharya, R.B. Srygley, S. Steinberg, N.J. Vickers, M.A. Birkett, and S.M. Borisov published only first-author articles ($h < 0$). J.A. Pickett, L.J. Wadhams, T.C. Baker, M. Dicke, R.L. Mahajan, A.L.R. Thomas, and O.S. Wolfbeis published only corresponding-author articles ($h = \pi/2$).

Conclusions

Highly cited articles in wind tunnel-related research were identified and analyzed basing on the Science Citation Index Expanded (SCI-EXPANDED) database from 1900 to 2014. A total of 77 highly cited articles were published between 1959 and 2008, with most articles occurring in 1990s. English was the only one language used. The 77 highly cited articles were distributed in 37 journals, with the *Journal of Fluid Mechanics* topping the list. The USA contributed most to the total highly cited articles and internationally collaborative articles, which dominated in wind tunnel research. Of the top 10 most productive institutions, most were located in the USA, followed by the UK. Authors were in important positions including first and corresponding author. *Y* index analysis suggested that K.V. Beard was distinguished in the wind tunnel research. Four articles ranked top 10 on both total citations and citations in the latest years, indicating their important statue in this research field. These influential articles were almost earliest wind tunnel experimental data and reports on their own research specialty, which still attracted much attention nowadays. It was also found that wind tunnel research were rapidly developed and obtained great achievements in 1990s, with most classical works. However, the development of CFD model might slow down the research of wind tunnel.

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