Research Trends in Superhydrophobic Drag Reduction: a Bibliometric and Visualization Analysis

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Abstract. This study offers a systematic analysis of academic research on superhydrophobic drag reduction. by utilizing two visualization tools named VOSviewer and Bibliometrix of R. We analyzed 407 articles on this area from the web of science database. The authors, journals, organizations and countries in the research on superhydrophobic drag reduction are discerned. In addition, the evolution trend was explored through keyword co-occurrence analysis to find the research focus and to predict the future development in this area. The results conjunctively achieved by VOSviewer and Bibliometrix will enhance understanding of the research on superhydrophobic drag reduction through a comprehensive quantitative analysis and assist scholars with future directions in this area.

Keywords: Superhydrophobicity, drag reduction, Bibliometrix, VOSviewer, research trend

1 Introduction

Superhydrophobic drag reduction is a technology that passively reduces the friction of interfaces between solid surfaces and water [1,2]. A surface is deemed superhydrophobic when it possesses a contact angle larger than 150° and a contact angle hysteresis less than 5°. These surfaces exhibit such unique characteristics as a result of the integration of the special micro-nanostructures and low surface energy of the materials they consist of [3]. Due to superhydrophobicity, air pockets, also called plastron, could be formed at the interface of solid surfaces and water. This provides air lubrication and minimal direct contact of liquid and substrate, which results in the exceptional properties of drag reduction [4–7]. Likewise, many plants and animals in nature present a similar property such as lotus leaves [8], butterfly wings [9], water striders' legs [10], fish scales [11], which has originated early researchers to bring up the idea of hydrophobicity and has also offered new insights into developing artificial superhydrophobic surfaces for drag reduction applications.

Superhydrophobic drag reduction has been of great interest in recent decades due to its potential to reduce the drag or friction force exerted on floating vehicles, underwater

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devices and pipelines and consequently to lower the substantial energy consumption and fuel costs [12–14]. On the other hand, aggregation of seaweed on superhydrophobic surfaces is difficult, thus diminishing the accumulation of biofouling, which may cause severe friction force [15]. As the application scenario presents a tremendous demand for energy saving in marine devices and pipelines, the field of superhydrophobic drag reduction has been continuously developing to face with the common topic of resources and global warming for the human kind [7,16,17]. Given its significant influence, a comprehensive understanding of evolution and trends of superhydrophobic drag reduction empowers researchers and manufacturers to make well-informed decisions. Technology forecasting is crucial in guiding research and engineering, and can therefore minimize the wastage of resources for academia and industries. This could be achieved through qualitative review and quantitative bibliometrics [18]. Related papers have provided an overview of the current status of superhydrophobic drag reduction, focusing on the up-to-date theory optimization and performance improvement. Development and challenges of this area have been discussed from the aspect of qualitative review while prediction through statistical analysis evidence is not yet present in literature. Therefore, bibliometric analysis is adopted in this study to provide quantitative information and could yield predictions on the trend of this research area.

In this work, a comprehensive bibliometric and visualization analysis of superhydrophobic drag reduction is conducted. Previous scientific publications are systematically gathered and the annual publishing distribution is evaluated to identify growth trends. Prominent authors, organizations, countries and journals are then discussed to show the most influential figures and work in this field. Research trends are analyzed through evolution of keywords followed by predictive insights to future directions. This study presents the development of this area in a direct quantitative way, facilitating a clear understanding to trace the origin and development in this field. Additionally, the analysis and prediction of the research trend help guide the readers on the evolution and recognition of new directions.

2 Method

2.1 Data Collection

Web of Science was chosen as the source for obtaining data to implement bibliometric analysis in this study. The search query was the keywords “superhydrophobic” or “superhydrophobicity” and the keywords “drag reduction” applied to “TI (title)”, “AB (abstract)” and “AK (author keyword)”. Preliminary results showed that 619 relevant papers are found to build up the base for the subsequent analysis. The results showed a time frame covering 21 years with no relevant publications existing before 2005.

To ensure the integrity and reliability of the database, the results were screened following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis, the widely acknowledged procedure for database filtering. Three main aspects which were removal of duplicate record and non-English-language documents and inclusion of journal articles and conference proceedings were considered in the initial identification stage. A total of 558 documents underwent this screening stage.

The titles and abstracts were then reviewed to check the relevance to the topic. Some unidentified review articles and unrelated articles in previous steps were excluded and 407 documents remained for the bibliometric analysis.

2.2 Software for Bibliometric and Visualization Analysis

The data analysis and visualization software used in this study was VOSviewer 1.6.20 and bibliometrix of R 4.5.1. VOSviewer was used to investigate authors, journals, organizations and keywords through the co-occurrences. Bibliometrix of R was used to calculate the annual trend of publications and journals and also the frequency and evolution of keywords.

3 Results and Discussion

3.1 Time Trend of Publications

The 407 papers used in this study were written by 1360 authors from 321 organizations in 137 journals, citing 8615 papers from 1935 journals. Data regarding the annual production of the papers are presented in Figure 1. Notably, superhydrophobic drag reduction first appeared in 2005 with two papers published. The area really began to develop in 2009 after two years of zero production. The annual volume of the published papers rose gradually and reached a maximum of 49 in 2024, as the record for the year 2025 was not complete. The quantitative examination of the number of papers offers decisive proof that superhydrophobic drag reduction has evolved to a crucial technology.

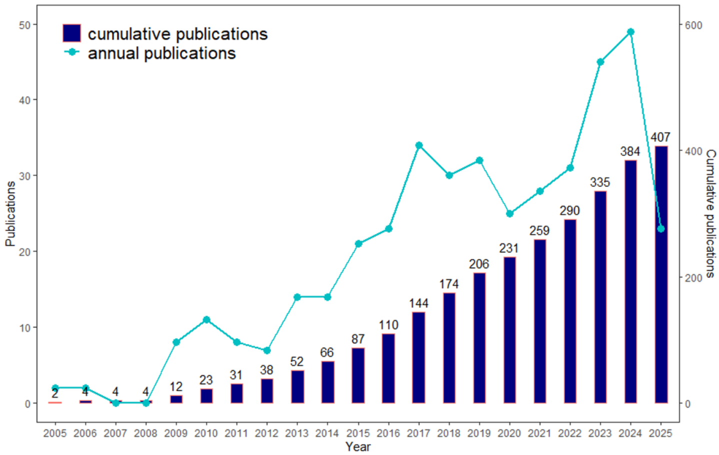

Fig. 1. The production of papers in the field of superhydrophobic drag reduction.

3.2 Publications and Collaborative Networks of Authors, Regions, Organizations and Journals

3.2.1 Bibliometric Analysis of Authors.

Authors' contribution to this area regarding the number of their publications is shown in Figure 2. The size of each node corresponds to an author's number of publications, while connecting lines indicate collaborative relationships, which often arise from shared research interests, teamwork, and significant funding support. Liu XW, Zhang HF, Hu HB and Rothstein J are the most authoritative figures in this area. Liu XW's research interest is in fabrication of biomimetic structure on aluminum or steel for drag reduction. His team has published 13 related papers cited 482 times. Rothstein J has authored 9 influential papers mainly on drag reduction in turbulent flow, cited over 1100 times. Hu HB has published 8 papers cited over 400 times. He has presented work on both micro-nanostructure design/fabrication for superhydrophobic drag reduction and plastron research, which is cutting-edge work in this area.

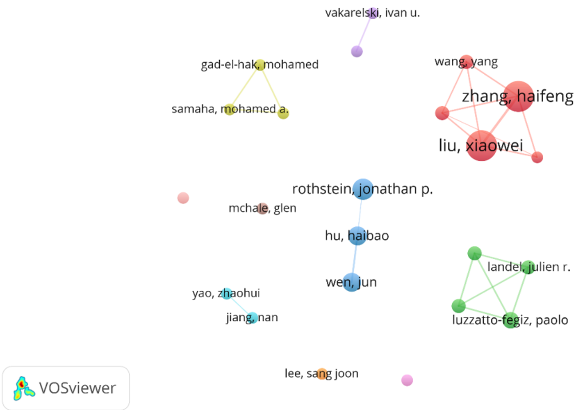

Fig. 2. The most relevant authors in the field of superhydrophobic drag reduction.

3.2.2 Analysis of Countries and Regions.

Figure 3 presents the 10 most productive countries of the corresponding authors. These countries have provided the most publications in terms of superhydrophobic drag reduction. The blue box indicates single-country production and the orange box indicates the multiple production. According to the analysis, China was the most productive country with 192 articles published and cited over 4700 times. USA was the second with 95 articles cited over 5900 times. UK was the third with 24 articles cited over 1800 times. Regarding the number of publications and average citations, these three countries outperformed all other countries, posting around nearly 70 percent of all the articles.

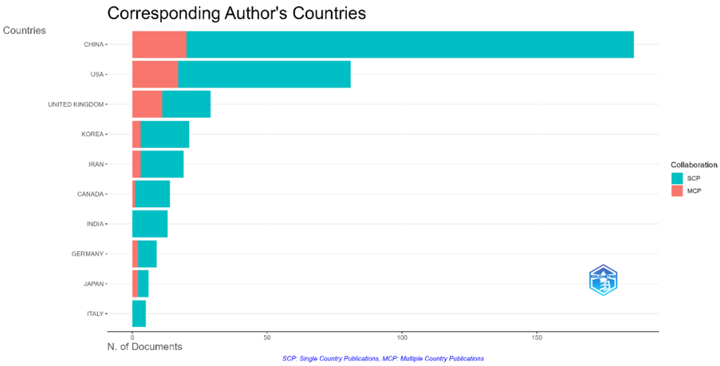

Fig. 3. The most productive countries in the field of superhydrophobic drag reduction.

3.2.3. Analysis of Organizations.

The most pertinent affiliation indicates how one institute has excelled in the particular area. The research expertise and the apparatus are the reason the institutes can specialize. Figure 4 shows that the number of most publications from a single affiliation is 21, achieved by Harbin Institute of Technology and Tsinghua University affiliation number. Chinese Academy of Sciences and Northwestern Polytechnical University are also active organizations that are in collaboration with the previous top two. Other affiliations that are productive in this area include University of Massachusetts, University of Alberta, University of California, Los Angeles and Virginia Commonwealth University.

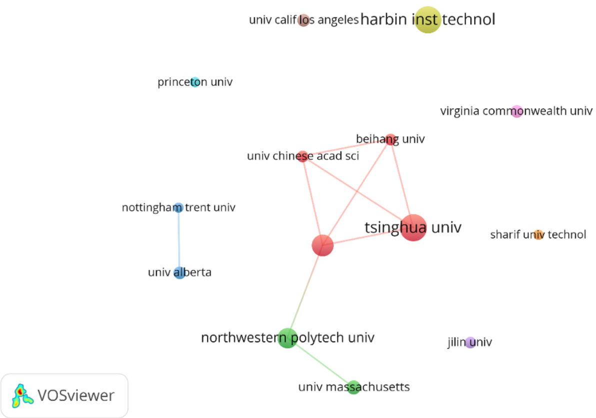

Fig. 4. The co-occurrence of organizations of the corresponding researchers.

3.2.4 Analysis of Journal Publications and Impact.

In this section most relevant sources of publisher in superhydrophobic drag reduction are presented to analyze how the journal is empowering the specific research areas. The top 10 journals are shown in Table 1. Considering the number of published articles and total citations, Physics of Fluids and Journal of Fluid Mechanics are the dominant journals in this area. The most relevant sources indicate how recent journals have emphasized superhydrophobic drag reduction and contributed sufficient publications in this domain.

Table 1. Top 10 journals with the highest number of publications.

Rank	Journal	IF(2024)	JCR(2024)	Article	Citation
1	Physics of fluids	4.3	Q1	47	3008
2	Journal of Fluid Mechanics	3.9	Q1	28	1594
3	Langmuir	3.9	Q2	19	697
4	Colloids and Surfaces A-Physicochemical and Engineering Aspects	5.4	Q2	18	441
5	Applied Surface Science	6.9	Q2	17	712
6	ACS Applied Materials & Interfaces	8.2	Q1	14	628
7	Physical Review Fluids	2.8	Q2	13	271
8	Chemical Engineering Journal	13.2	Q1	12	426
9	Surface & Coatings Technology	6.1	Q1	11	321
10	Microfluidics and Nanofluidics	2.5	Q2	9	311

3.3 Statistics of Keywords and Trends of Topics

3.3.1 Growth and Trends of Topics.

Figure 5(a) represents the evolution of the top keywords in superhydrophobic drag reduction. The vertical axis indicated the cumulative occurrences and the horizontal axis indicates the publication year. The term “drag reduction” showed an excellent performance curve, indicating continuous development in this area. The keyword appeared most is “drag reduction” (184 out of 407 occurrences) and “superhydrophobic” (85 out of 407 occurrences), reflecting the core topics in this field. The second-most frequent terms are “turbulent” “plastron” “slip” “bioinspired”, etc., which are key directions addressed in literature. Other available keywords, though not that frequent, highlight additional topics within the discipline.

The trend of research topics of superhydrophobic drag reduction could be more specifically visualized through time distribution in Figure 5(b). In this visualization, the navy blue indicates lower frequency of discussion in early stages, transitioning into light yellow as the topics record more occurrences. The term “slip” emerged early in this research area, inferred from conventional experiments including particle image velocimetry and pressure drop analysis to quantify drag reduction effect. The keyword “laminar flow” appeared before “turbulent flow”, reflecting a shift of research focus from simpler to more complex flow conditions. Subsequently Later the keywords “plastron” “robustness” appeared, indicating the rise of research interest into the long-term stability of the superhydrophobic surfaces. This implies that research attention is more concentrated to practical performance. Other keywords are about the fabrication methods and diverse functions of superhydrophobic surfaces. The keyword “laser ablation”

(10 occurrences) indicates that it has become the most widely studied and adopted fabrication route. Additional keywords such as "anti-icing," "anti-corrosion," "anti-fouling," and "wear resistance" point to a growing trend toward developing multifunctional superhydrophobic surfaces. Anti-corrosion (11 occurrences) appears most frequently among these topics, while anti-fouling specifically addresses applications in water vehicles - both topics primarily corresponding to marine device applications. Research on anti-icing (5 occurrences) properties emerged later with less frequency, indicating technological innovations extending to other industries.

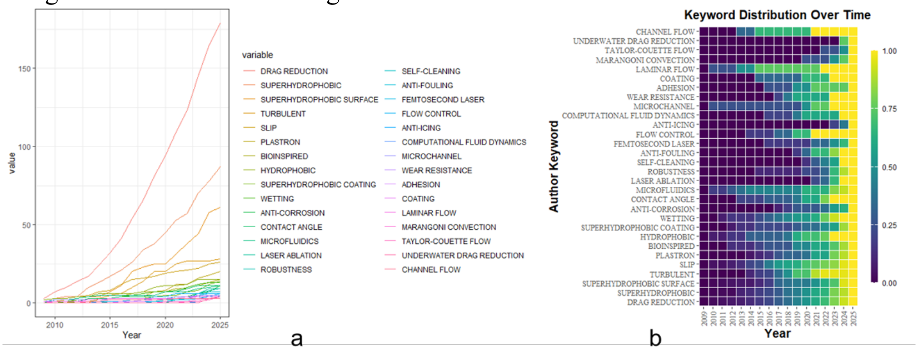

Fig. 5. (a) An outgrowth of top 30 keywords and (b) keyword distribution over time.

The most recent research topic is “underwater drag reduction”, while in comparison “microchannel” frequently appeared in early research work, indicating that researchers’ view turns into practical use of superhydrophobic surfaces in real waters instead of lab-based experiment setup. Considering previous research focus in this field, the topic “underwater drag reduction” is believed to be a highly promising direction. Recent advances in understanding plastron and robustness have laid some groundwork for underwater implementation. Meanwhile, progress in fabrication methods supports the development of superhydrophobic surfaces of underwater devices and vehicles. Additionally, investigations into multifunctional surfaces could provide possible solutions to adapting to complicated real-world conditions. This also suggests that interdisciplinary collaboration will play a key role in the field, driving important advancements in areas such as renewable energy, ocean engineering and environmental engineering through superhydrophobic technologies. All these developments are paving the way to yielding a breakthrough in underwater drag reduction applications, which is the ultimate objective in this field.

3.3.2 Socio-economic Impacts.

As previously noted, the topic superhydrophoic drag reduction is closely related to energy conservation and environment protection. Multifunctional surfaces were developed to address the need for energy and environment from different perspectives. Related keywords such as drag-reduction, self-cleaning, anti-fouling, anti-corrosion were examined and quantified to explore trends how such surfaces are designed to yield the energy and environment benefits. The academia has consistently focused on energy saving challenges with the core topic drag reduction addressed throughout full stages. Later, research focus expanded to self-cleaning, anti-fouling and anti-corrosion with 24 occurrences in total, aiming to develop multifunctional surfaces to better realize energy savings in practical applications. However, the integration of these functions remains in its early stages; although interest has surged in recent years, the volume of publications is still limited. Judging from section 3.2.3, most author affiliations are universities and academic institutions. Participation from industries are rarely seen. This shows that there is still a long way to go before the technologies are fully implemented in industries and generate economic benefits.

4 Conclusions

Superhydrophobic drag reduction is a topic that has been intensively studied over the years with numerous articles contributing to its development. While the understanding of this area is presented by some highly-rated review papers, a comprehensive quantitative analysis remains lacking, which could show an essential perspective in the research evolution. This study uncovers the development of superhydrophobic drag reduction from 2005 to 2025 by bibliometric and visualization analysis using a combination of VOSviewer and Bibliometrix. According to the 407 articles collected from the Web of Science, important publications, authors, journals and affiliations are identified and the network is analyzed. Hot topics and research trends are subsequently predicted. This study achieves some insights from the literature and summary of the existing studies with quantitative results. This will assist scholars to better understand the development in this field and to find the key journals, authors and publications they are interested in. Last but not least, predictions concluded from the bibliometric analysis present current focus and can provide possible ideas for future research.

This study is helpful for providing a comprehensive framework that can inform future inquiry. Nevertheless, some limitations should be acknowledged. First, the samples in this study are captured from a single database. Although WoS covers a wide range of journals, it does not encompass all relevant work in the field. Work from some journal and conferences providing more insights and latest findings in the field is not included currently. Second, although the bibliometric analysis conducted through specialized software is objective, the interpretation of the results involves subjectivity. Different researchers may have different recognition on even the same data. By multiple discussions among authors and larger amount of related publications to be analyzed, the subjective interpretation may be overcome. Addressing these two aspects would enhance the study in the future.

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The authors declare that they have no conflict of interest.

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