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Air Conditioning Research Evolution from 2008 to 2019: A Scientometric Analysis

Luis Guillermo Obregon^{1,*}, Guillermo Eliecer Valencia², Jorge Eliecer Duarte²

¹ Research Group on Sustainable Chemical and Biochemical Processes, Chemical Engineering Department, Universidad del Atlántico, Carrera 30 No 8 – 49, Puerto Colombia, Colombia

² Efficient Energy Management Research Group, Mechanical Engineering Department, Universidad del Atlántico, Carrera 30 No 8 – 49, Puerto Colombia, Colombia

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ABSTRACT

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Air conditioning is an essential topic in heat transfer phenomena because it is widely applied in homes and industries. It has an incredible amount of applications ranging from health care to food shelf life. With the enhancement of technology, it is necessary to create new devices that increase the efficiency of air conditioning. Hence, it is required to evaluate the trend of study of this topic to help researchers to get the best research direction that promotes the acquisition of better experimental results. For that reason, it was collected a total of 2431 documents about air conditioning from the Science Citation Index Expanded during the period from 2008 to 2019. Next, it was used HistCite to analyze the yearly output, country, institution, citation impact, and citation relationships in this field of study. Results suggest that the research of air conditioning had an increase during the studied 11-year period. The countries with the highest research output were China, The USA, and Japan, and the institutions with the highest research output were the National Natural Science Foundation of China and the Hong Kong Polytech University. The journals with the largest number of articles were Energy and Buildings with 195 publications and Applied Thermal engineering with 164 papers.

Keywords:

Research output; bibliometric; air conditioning

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1. Introduction

Growth in population has resulted in an extraordinary demand for food and consumer goods [1]. Thus, industries are nowadays using the latest available technologies to meet human needs. Industrial heating and air-conditioning have become a matter of importance worldwide. Typical applications of air-conditioning are found in households, supermarkets, and offices all over the world. Still, for some industries, it is necessary due to the safe production as well as the storage of manufactured goods [2-3]. The global weather variations have further increased the demand for A/C

* Corresponding author.

E-mail address: luisobregon@mail.uniatlantico.edu.co

systems in several industries around the world [4-5]. However, air conditioning and refrigeration are a problem for the environment because of pollution [6-7] and energy consumption, which can be, in some cases, up to 40% of the total energy consumption in the industry. In the specific case of supermarkets, 50% of the electric energy is used annually in refrigeration and 15% in conditioning. The most used air conditioning systems today use the classic thermodynamic cycles that usually use substances that damage the ozone layer [8]. Therefore, some of the conventional processes are being replaced or improved by others with lower energy consumption and lower environmental impact. One way is reducing the condenser temperature using an evaporative cooler in front of the air condenser, which results in more liquid refrigerant in the evaporator [9-12]. This process can be considered as energy-efficient, environment-friendly, and cost-effective method to enhance the performance of air conditioners (ACs) [13]. Although evaporative coolers cannot be used in all countries and at all times, they are generally very much underutilized in places where they can be used successfully. It is a lousy situation for the country and the global environment [14]. Several studies have focused on numerical simulation and modeling to help in finding high efficiency in air conditioners (ACs) [8, 15].

Due to the significant number of studies about air conditioning, it is essential to know the current direction of the new investigations so that researchers follow this trend of research to give the most significant scientific contribution possible. It can be accomplished by using a specific tool named bibliometric analysis [16-17], where a vast amount of data is scrutinized to observe the influence of any field of study regarding the countries, authors, institutions, journals, among others.

This article presents a bibliometric analysis of the research outputs and citations from 2008 to 2019 using the HistCite software to understand research development trends and the current status of this air conditioning. The aim was to make an assessment and comparison of the leading countries, research institutions, authors, and journals around the world with the highest production of articles about the mentioned field of study.

2. Energy Issues with The Air Conditioning Units Worldwide

The technological development of air conditioners (ACs) to improve their efficiency is extremely necessary due to the high worldwide demand for this equipment. The high production of air conditioners (ACs) can have a highly harmful effect on the environment due to greenhouse gases. The highest energy consumers for the use of air conditioners in the world are the USA, the People's Republic of China, and Japan. Although there is an increase in the number of units worldwide, the highest percentage is due to the increase in units in China whose emerging economy makes all of this possible. The combined AC units between Japan and Korea increased from 190 million units in 2010 to 212 million in 2018, representing an increase of 11.58%. The units of ACs in the USA increased from 349 million to 387 million in the same period, representing an increase of 10.89%. In the case of China, its exceptional growth was from 343 to 643 million units, representing an increase of 87.46%. The rest of the world increased from 386 million to 519 million, representing an increase of 34.46% [18]. The difference between China and the rest of the countries is enormous.

China experienced the fastest growth in the world in demand for energy for the cooling of spaces in buildings in the last decade, reaching almost 450 TWh of electricity consumption in 2017. Because the mentioned country is highly dependent on coal, CO₂ emissions increased five times between 2000 and 2017.

In addition to being the country with the highest demand for AC units, its projection remains the same for the following years since around 40% of households still do not have an air conditioner (AC), [19]. It is something that is changing rapidly since as the income levels of its inhabitants continue

growing, the ownership of air conditioners could reach up to 85% by 2030. This effect, along with the increasing number of hot days, will increase the frequency of use of ACs. Consequently, the demand for cooling during the summer months, together with the days of extreme heat, could be even higher. It will undoubtedly lead to increased energy use for space cooling. For this reason, the continuous study of this equipment is necessary to ensure higher efficiency in the future.

Multiple investigations that combine the design of air conditioners with the best control system strategies are being carried out to achieve the highest possible efficiency. These studies are focused on Central units, Ductless, Mini-Split Air Conditioners, Window Units, portable units, Hybrid Air Conditioner, Geothermal Heating, and Cooling.

Yang *et al.*, [20] set up an experimental platform of microwave sterilization in a central air conditioning system. This method avoids the presence of the microorganism in the air, reduce the formation of dirty layers in the heat exchanger area, and maintain their efficiency.

Yang *et al.*, [21] evaluated a patented hybrid air conditioning (HAC) system design to find out the free cooling and humidification performance under hot, dry climate conditions for a comfortable air conditioning.

Cui *et al.*, [22] presented the design of a hybrid AC system using an evaporative-enhanced heat recovery component. The study was done with numerical modeling, an Indirect evaporative heat exchanger combined with chilled water-based cooling coil.

Chen *et al.*, [23] proposed a simple and effective parameter design approach for grid-connected PV AC systems and to explore the suitability of this system for office buildings.

Shen *et al.*, [24] developed a prototype of a window air conditioning unit with high efficiency that integrates compact heat exchangers, advanced compressors and controls, optimized for propane as refrigerant obtaining a 17% higher energy efficiency ratio (EER) than US Energy Star units. Besides, they used simulations using the Heat Pump Design Model to improve the AC design.

Besides the mentioned kind of AC design researches, it has been necessary the research in the area of control and automatization to control the system and work with the optimum conditions.

Tang *et al.*, [25] developed a strategy to obtain the optimal control of central air conditioning systems considering the period of the time in a day, precisely the morning start period. This research study was done with different case studies.

Zhao *et al.*, [26] proposed a novel control method to reduce the power gap between the PV generation for Photovoltaic air-conditioners (PVAC) and the air-conditioning load, enhancing the use of solar energy and decreasing the fluctuation of the Photovoltaic power output. They found that the method can be implemented to traditional air conditioners to reduce indoor temperatures.

One more critical parameter to consider when trying to design the best air conditioner of any kind of building is the degree of insulation of the rooms. Excellent insulation will result in energy saving, causing a decrease in air pollution. Morsy *et al.*, [27] evaluated not only the thermal comfort of all the spaces in a building but also the energy consumption of all the floors in the entire structure. They found that it is necessary to use the thickness of different sizes to achieve their goal. It makes sense because the external contact of all the floors is different, causing a different heat transfer in each of them. It is a situation that must be considered in all the constructions.

As mentioned before, there are many different types of AC design that a consumer can use depending on its needs. It is necessary to have a new mechanism to measure the loss of energy given to the environment, considering the high spent of energy worldwide and its extreme importance due to the environmental impact. With the current new technology, it is feasible to use in the air conditioners a wireless sensor network (WSN) with the capacity to generate a considerable amount of real-time data (RTD) of the working AC. These data are sent to a central location for monitoring and recording the total energy used and wasted. It can be achieved easily with the new

5G wireless technology. However, in order to do that, the system must have inside a computer coding that involves the complete balances of energy and exergy of all the components of the AC.

All elements of the air conditioner must meet the general balances for mass, energy, and exergy, as shown in Eq. (1) to (3), respectively.

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \frac{dm}{dt} \quad (1)$$

$$\sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} - \sum \dot{Q} + \sum \dot{W} = \frac{dE}{dt} \quad (2)$$

$$\sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{out} ex_{out} + \dot{Q} \left(1 - \frac{T_0}{T}\right) - \dot{W} - \dot{E}x_D = \frac{dEx}{dt} \quad (3)$$

Where E is the energy within the control volume, \dot{m} is the mass flow of the refrigerant, h is the specific enthalpy of the refrigerant, \dot{Q} is the heat transferred and \dot{W} is the power, ex is the exergy per unit of mass of the streams of each component, T_0 is 298.15 K, $\dot{E}x_D$ is the destroyed exergy associated with each element, $\frac{dE}{dt}$ and $\frac{dEx}{dt}$ are the time rate of change of energy and exergy contained within the system.

Following the importance of the energy and exergy balances, it is necessary to consider the Exergo-environmental analysis, which considers the impact of each of the components of the system in the environment, see Eq. (4).

$$\sum \dot{B}_{out} = \sum \dot{B}_{in} + \dot{Y}^{Tot}_k \quad (4)$$

where B is determined by Eq. (5).

$$\dot{B} = b \cdot \dot{E}x \quad (5)$$

$\dot{E}x$ is the rate of exergy, b is the specific environmental impact per unit of exergy, and \dot{Y}^{Tot}_k is the total environmental impact of the component k .

3. Methodology

All the research on air conditioning was gathered through the online-based scientific citation indexing database Web of Science. HistCiteTM was the software used to put together all the information of the papers about air conditioning (authors, journals, titles, countries, dates, author affiliations, references, etc.)

The search was done using phrases like "air conditioning." The search yielded 2431 documents that came from several document types, including journal articles, conference proceedings, reviews, editorial materials, and letters. The number of documents per year, most productive countries, institutions and authors, and leading journals were organized and analyzed in tables using a spreadsheet of Excel. The main variables used to make the analysis were the number of publications or the number of publications, and the Total Local Citation Score (TLCS).

4. Results

4.1 Publication Output

There were nine different types of documents identified from a total of 2431 documents. Most of them were articles representing 89.8 % of the total documents, indicating that these are the primary mode of scientific communication regarding air conditioning. Proceeding papers (3.8%) and Reviews (3.2%) were the next two other important manners to publish articles in this field of research. Papers were written in 13 languages where English dominated, embracing 97.1 % of the total documents. It might happen because English is accepted as the international language for researchers around the world.

Figure 1 shows the research output each year from 2008 to 2019. During these 11 years, the number of documents maintained an increase between 2008 and 2017, then a small decrease in 2018 to again increase the last year 2019. Broadly, the number of publications had continuous growth with a slope of approximately 25 documents per year. This field of study had an increment in the number of documents of 212% from 2008 to 2019. It shows the importance of this field of study in the scientific community. With the increase in technology around the world, new researches about air conditioning surge to make more efficient this process where heat transfer is the target of optimization, and therefore the energy saving.

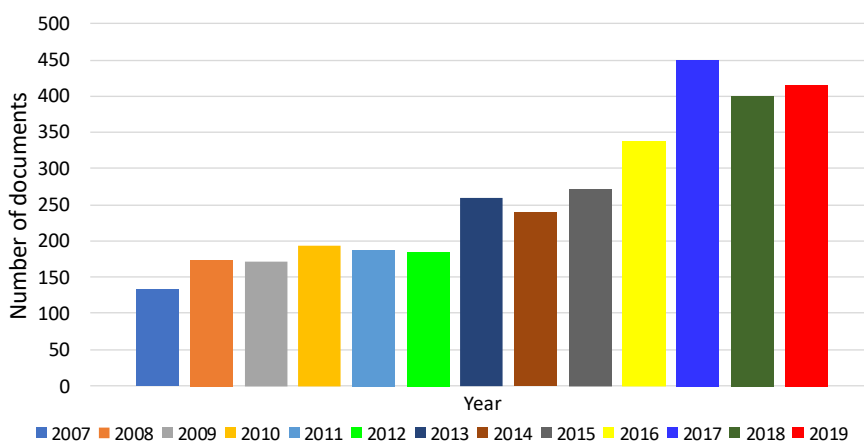


Fig. 1. Number of published documents about A/C from 2008 to 2019

4.2 Country-Based Distribution of Research Output and TLCS

The distribution, shown in Figure 2, illustrates the capacity of research of a country. A total of 89 countries contributed to the research output of air conditioning, indicating that this topic attracted lots of attention from most researchers around the world. Figure 2(a) shows the top ten countries with the highest number of publications, where the People's Republic of China was the country with the best production of documents (36.9% of the total output). The USA and Japan followed it with 20.9% and 8.4%, respectively. These countries have high participation in the industrial sector worldwide and have been part of various programs that looks for reducing energy consumption to promote environmental care.

On the other hand, citations reflect the academic impact of published papers in this study. It was selected the total location citation score (TLCS) as the indicator to measure the quality of the documents and the academic influence among these countries. China, which had the highest number of published papers, also had the highest TLCS with a total of 1451 citations. The countries that

followed China occupied the same position in the number of published documents, and TLCS. The USA was the second with 507 documents and 330 citations. Japan was the third country with 205 documents and 166 citations. It is a measure that indicates that the first three countries have unique technology and training to do excellent research in the field of the study mentioned. The three countries have proven to be economic powers worldwide as well, which is evidence of the productivity and quality of the documents mentioned above.

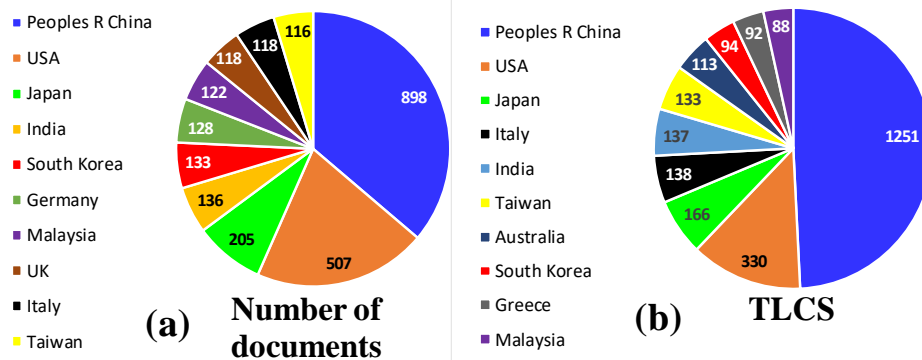


Fig. 2. Top 10 countries with a) highest number of publications b) highest TLCS

4.3 Institution-Based Distribution of Research Output and Citations

Table 1 identifies the leading institutions regarding air conditioning research around the world. There were a total of 2119 institutions with documents in this field of study. The research institution with the highest paper productivity was the National Natural Science Foundation of China, with 330 publications. The next two institutions were the Hong Kong Polytech University with 114 documents, and the Shanghai Jiao Tong University with 69 papers. Table 1 shows that five of the ten top institutions are from China, which can be explained because this country has a considerable increase in technology as well as in the economy. It lets the government make an excellent capital investment in research in many areas of study, e.g., air conditioning. Besides, air conditioning is a process that is linked to pollution, which is a problem that China is dealing with, implementing an aggressive plan to reduce the contamination. Because of this reason, many of its institutions have focused their research on this issue that afflicts its population in general.

Table 1

Top ten research institutions with the highest number of publications, TLCS, and TLCS/publications

Institution	Publications	Institution	TLCS	Institution	TLCS/publications
National Natural Science Foundation of China	330	Hong Kong Polytech Univ	383	China Acad Bldg Res	8.75
Hong Kong Polytech University	114	National Natural Science Foundation of China	314	Natl Tsing Hua Univ	3.78
Shanghai Jiao Tong Univ	69	Shanghai Jiao Tong Univ	197	Hong Kong Polytech Univ	3.36
Chinese Acad Sci	40	Tsinghua Univ	41	Shanghai Jiao Tong Univ	2.86
Unknown	37	Univ Tokyo	37	Univ Tokyo	1.61
Tsinghua Univ	36	City Univ Hong Kong	36	Univ Maryland	1.48
Southeast Univ	28	Southeast Univ	36	City Univ Hong Kong	1.38
Univ Illinois	27	Univ Illinois	36	Univ Illinois	1.33
City Univ Hong Kong	26	China Acad Bldg Res	35	Southeast Univ	1.29
Indian Inst Technol	25	Natl Tsing Hua Univ	34	Tsinghua Univ	1.14

4.4 Distribution of Core Journals and Citations

There were 803 journals where 2431 documents in the area of air conditioning were published. All journals were sorted in descending order by their respective number of published articles. Table 2 shows the top 10 core journals with the highest productivity of papers, and the one with the highest number of publications was Energy and Buildings (195), followed by Applied Thermal Engineering (164) and Advanced Materials Research (145). The Journals where the largest number of articles were published would not necessarily be a guarantee of the highest Total Local Citation Score (TLCS). However, in this particular case, the top 5 journals with the highest productivity were the same top 5 journals with the highest TLCS. It means that the researchers consider the mentioned journals of high quality, where they can publish their results and have the guarantee that the scientific community will more see them.

The Energy and Buildings journal was the number one because, currently, the constructions are trying to be friendly to the environment to improve the energy efficiency of the buildings.

Table 2
Top 10 journals with largest number of publications in air conditioner

Journals	Publications	TLCS
Energy and Buildings	195	376
Applied Thermal Engineering	164	292
Advanced Materials Research	145	231
Applied Mechanics and Materials	141	166
International Journal of Refrigeration	119	149
Applied Energy	87	135
Energy	76	116
Energy Procedia	73	40
SAE Technical Papers	70	138
Procedia Engineering	68	20

Table 3 shows the most cited articles from 2008 to 2019, where GCS refers to the Global Citation Score. It is obvious that the oldest papers have to be those with the highest number of citations. However, number four of the top five is from 2013, being an indication of the degree of importance of this article compared with the others. Considering that it is a review, it means that many researchers have been looking for the different advances in research in this area, with the purpose to continue doing new studies to enhance the current technology to make more efficient devices. It is evidenced with the highest GCS of the second paper of Table 3, which indicates that changes must be done as the weather variates over time. It makes imperative the research in this area, mainly in overpopulated regions where the highest efficiency has to be obtained to decrease in the lowest possible way the air pollution.

Although it is not shown in the table of global citation score (GCS), Shiming Deng from the Department of Building Services Engineering (BSE) in The Hong Kong Polytechnic University is the researcher who has the highest number of publications in the area of study. Also, he is the researcher with the highest TLCS concerning the time range studied. It means that it is recommended to read his researches or make contact with him to go further in this area of research.

Table 3

Top 5 most cited documents

#	Author / Title / Journal	GCS
1	Henning HM, "Solar assisted air conditioning of buildings - an overview" APPLIED THERMAL ENGINEERING. 2007 JUL; 27 (10): 1734-1749, [28]	252
2	Isaac M, van Vuuren DP, "Modeling global residential sector energy demand for heating and air conditioning in the context of climate change" ENERGY POLICY. 2009 FEB; 37 (2): 507-521, [29]	193
3	Balaras CA, Grossman G, Henning HM, Ferreira CAI, Podesser E, et al. "Solar air conditioning in Europe - an overview". RENEWABLE & SUSTAINABLE ENERGY REVIEWS. 2007 FEB; 11 (2): 299-314, [30]	189
4	Chua KJ, Chou SK, Yang WM, Yan J, "Achieving better energy-efficient air conditioning - A review of technologies and strategies", APPLIED ENERGY. 2013 APR; 104: 87-104, [31]	171
5	Rathnam RK, Elliott LK, Wall TF, Liu YH, Moghtaderi B, "Differences in reactivity of pulverised coal in air (O ₂ /N ₂) and oxy-fuel (O ₂ /CO ₂) conditions", FUEL PROCESSING TECHNOLOGY. 2009 JUN; 90 (6): 797-802, [32]	149

5. Conclusions

Regarding the area of study of air conditioning, an analysis of the number of publications, main journals, most productive countries, best research institutions, and highest quality documents was done using a bibliometric analysis through the data from 2008 to 2019 obtained with the software HistCiteTM. The number of publications had continuous progress with a slant of approximately 25 documents per year. This trend implies that air conditioning has an important research area that addresses climate change. As the global climate change and pollution problem still exist, it can be predicted that air conditioning research will continue in a raise. This area of research had a rise in the number of publications of 212% in the period from 2008 to 2019. The People's Republic of China was the country with the best production of documents (646), followed by the USA (364) and Japan (147). These countries occupy the same position regarding the TLCS, The People's Republic of China (1451), The USA (507), and Japan (330). The top three institutions with the highest number of published documents were the National Natural Science Foundation of China with 330 publications, the Hong Kong Polytech University with 114 documents, and the Shanghai Jiao Tong University with 69 papers. The top five journals in the number of documents had the same position in TLCS; Energy and Buildings (195 docs, 376 TLCS), Applied Thermal Engineering (164, 292), Advanced Materials Research (145, 231), Applied Mechanics and Materials (141, 166), and International Journal Of Refrigeration (119, 149). Shiming Deng from the Hong Kong Polytechnic University is the researcher who has the highest number of publications in air conditioning, as well as the one with the highest TLCS.

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