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SELECTIVE SURFACE COATINGS: A BIBLIOMETRIC ANALYSIS

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Abstract. *Solar heat conversion has limits when it is designed to reach higher temperatures, limiting applicability. Selective surface coatings for solar radiation absorbing plates, are identified as a way to improve the efficiency of photothermal collectors, changing the gain and loss ratios of energy in the equipment. The performance of the different coatings available, their types and costs, applications and manufacturing parameters should be known, as well as the influence of the coating on the corrosion resistance of the absorbing plate. Bibliometric analysis is a method that uses relevant indicators to study scientific production and the relationships and interactions between its elements. This tool was used to elucidate the most relevant topics that are being addressed in scientific research on solar selective surfaces, as well as the most cited authors and how this technology is being accepted worldwide. The analyses were performed considering the last five years of publication and their results are presented in maps and bibliometric networks.*

Keywords: *Solar energy, Selective Surfaces, Coatings, Bibliometric Analysis.*

1. INTRODUCTION

The world is moving at a fast pace in the consumption of non-renewable natural resources. The implementation of renewable energy is the alternative that provides greater benefits, for its wide variety of energy sources found in nature cyclically (Villalva and Gazoli, 2012). Among these sources, solar energy stands out. Sunlight is readily available and free from geopolitical tensions, and does not pose a threat to our environment. About the use of sunlight as energy source, the simplest, clean and direct way is through its thermal conversion, where heat transmitted by solar radiation is used to heat water for residential use and to generate steam for industrial use, saving other energy resources such as natural gas, coal and electricity (Medeiros, 2020b).

As the emission of heat by radiation is a surface phenomenon, several authors (Shaffer, 1958; Tabor et al., 1961; Kokoropoulos et al., 1980) have proposed that the solar collectors be coated with materials that are good absorbers of radiation and on the other hand emit little heat by this same mechanism. These coatings, which are called solar selective surfaces, are characterized according to their interaction with solar radiation in specific regions of the electromagnetic spectrum (Atkinson et al., 2015).

The use of selective surfaces is one of the alternatives found to increase radiation absorption and, above all, to reduce thermal emission losses (Martins, 2010). In addition to increasing the efficiency of the collectors, surface coatings allow a higher temperature at the equipment outlet, increasing the application horizon and significantly reducing the emission of thermal radiation (Gomes, 2001).

The selective surface is usually composed of a thin film applied on a thermal conductive substrate, and can be proceeded by an antioxidant or antidiffusive layer and followed by an anti-reflective layer, in contact with the environment. The thickness of the selective film can also generate changes, since this can act as a filter at certain wavelengths of incident radiation and that, if the surface thickness is high, the amount of energy emitted by radiation will also be greater (Rebouta et al., 2012).

In addition to the search for the best possible optical selectivity, it is essential that the material has properties that allow its manipulation and adapt to the variety of existing deposition techniques. It is necessary that the deposition of the optically selective coating is performed efficiently, making sure that the solar thermal conversion is homogeneous throughout the collector. It is also desirable that there is a good adhesion between the deposited material and the substrate and that the same coating also acts by protecting the substrate against corrosion, since this is usually composed of a metallic material (Atkinson et al., 2015).

The precursor materials of the coatings, the available deposition techniques, the influence of surface treatments, the best possible parameters and configurations to improve the final efficiency of the photothermal collector, in addition to studies on the aging and behavior of thin films in corrosive environments, are just some of the research variables that are still barriers found for consolidation of photothermal solar conversion in the market. It is of the greatest importance to deepen and follow the academic work developed at the world level to contribute to the evolution of this science.

According to Wolfram (2017) and Pimenta et al. (2017), a bibliometric analysis aims to evaluate and understand the performance of academic production activities, through the analysis of a quantity of data extracted from scientific publications, in a defined period, for the extraction of the necessary information. The bibliometric research can be elaborated starting from some fundamental steps, namely: determination of the research indicators, the database used and how the documents will be selected and standardized (research systematization) (Ferenhof and Fernandes, 2014).

In bibliometric analysis are used several indicators to study scientific production, relationships and interactions between its elements (Maricato, 2011). In general, these indicators are intended to measure productivity, develop relationships, identify collaboration and co-occurrence of items in a sample of documents. The role of the academic area, especially the postgraduate courses Stricto Sensu, is fundamental in the production and dissemination of knowledge, aiming to meet the emerging demands of organizations and society (Machado Junior et al., 2016). Scientific articles, dissertations and Phd theses present, in addition to theoretical surveys based on other scientific documents, rigid standards of methodology and research standards based on technical standards, being considered reliable sources for information extraction from bibliometric methodologies.

Bibliometric analysis is therefore a powerful tool capable of indicating the currently relevant topics within the study of selective solar surfaces, materials and methods that have advanced the most in the quality of absorbing films and which authors and respective countries are contributing to the consolidation of this knowledge.

2. SELECTIVE SURFACE COATINGS

The concept of selective surface appeared in 1955, when H. Tabor used it on his black nickel surface, formed by NiS and ZnS and produced by the electrodeposition method.

These surfaces are characterized by the following properties: high absorbance in the range of solar radiation 220 nm $< \lambda <$ 2500 nm and low emittance in the range of thermal irradiation 2500 nm $< \lambda <$ 25000 nm (Lee et al., 2000). Moreover, it is necessary that these surfaces do not degrade significantly from the optical point of view during the life of the collector and are resistant to stagnation temperature, corrosion and humidity.

Surfaces with solar selection may be homogeneous or contain composite materials whose optical properties are dependent on the materials used and their structure (Duffie and Beckman, 2006). Several techniques have been developed for the production of these surfaces, such as electrodeposition, chemical vapour deposition (CVD), sputtering, spraying, chemical conversion and pyrolysis (Jeeva et al., 2016), with different materials used as coating, like black chrome, black nickel, black copper, molybdenum, among others. Table 1 shows a number of materials used as coatings of thermal collectors and their respective deposition processes.

Table 1. Some solar selective surface impact materials and their respective deposition techniques. Adapted from Kennedy (2002).

Material	Substrate	Deposition Techniques	Absorbance (%)	Emitance at 100º C (%)
$Cr:SiO_2$	Cu Al	DC (Direct Current) Sputtering	90-96	3-14
$NiCrO_x$	Steel	Sputtering	80	14
Black Chrome	Ni-Cu Cu Steel	Electrodeposition Method	97	9
$CuFeMnO_4$ /Silica	Glass Si	Sol-gel	60	29-39
PbS	Al	Pyrolysis	93-99	10-21
Cr, Fe, Mo, SS, Ta, Ti, W	Cu	DC Sputtering	84-90	3,5-6
Ge Si PbS	Cu SS	Painting	91 83 96	7 7 7
TiN	Al or Cu	CVD	87-93	8-14

The optical selectivity of an absorbing surface varies as a function of the wavelength of the incident radiation. An ideal selective surface can be defined as one to which absorptivity can be represented by a step function where the maximum value occurs at the wavelength in the visible region and the minimum value occurs at the infrared region.

According to Gomes (2001), an ideal selective surface must have an abrupt transition between the regions of high and low reflectivity, around 2500 nm, which is approximately the upper limit of the solar spectrum. The selectivity factor is a parameter used to characterize a selective surface and is defined as the ratio of absorptivity in the visible range and emissivity in the infrared range. The selectivity factor of a solar plate should not be confused with energy efficiency, as selectivity applies only to the absorbent plate and not to the entire solar collector.

A selective surface for photothermal purposes must present the minimum selectivity factor of 5.67, solar absorbance greater than 85% and emittance less than 15%. When the selectivity factor is greater than 10 the selective surface is considered highly selective (Xiao et al., 2011).

Different types of coatings have been studied, but in all of them has been sought the improvement of the absorption/emission ratio from: (i) use of materials that have intrinsically favorable properties to the absorption of radiation; (ii) superposition of various matter coatings to obtain a gain in the absorption of solar radiation from effects of destructive optical interference inside the film; (iii) texturing of the film, creating optical traps for incident radiation; (iv) construction of films with composite material, combining the thermal stability of ceramic materials with the high thermal and electrical conductivity of metals; and (v) combinations of all the aforementioned ways (Kennedy, 2002).

3. METHODS

The systematization of the research consisted in the search for keywords supported on the theme and based on the bibliography in the Web of Science Main Collection, in the last six years of publication. We used the terms "Selective" and "Surface*", connected by the Boolean operator AND, and "Coating*" connected by the Boolean OR, because they represent significantly the theme of the research. By filtering the results by type of examination document and article, at these stage 2216 files were obtained for the search terms.

The complete record and the resulting cited references were exported to a spreadsheet and imported into the VOSviewer software, a tool used to build bibliometric networks based on citation, co-citation or co-authorship relationships, also offering the functionality of creating co-occurrence maps of relevant terms taken from references.

Two works are said to be co-cited when a third document cites them together, and the relationship of co-citation between these two works is greater the greater the number of works in which both are co-cited (Lima and Leocádio, 2018). To build the co-citation network, the alternative of creating a map based on bibliographic data was selected by importing the references, analysing them by co-citation. We set a minimum of 5 citations for each author and opted for networked viewing. Only papers whose titles (or abstracts) were connected with the research theme were considered, totaling 79 papers.

Data analysis was conducted in accordance with the laws of bibliometrics. Bradford's law (1934) deals with the productivity of journals, allowing an evaluation of the works published in that journal. It is understood that as the papers are submitted, evaluated and approved by the journal, this will attract new papers to be submitted during the development of that subject. Bradford (1934) states that when journals are organized in descending order of article productivity on a specific subject, they can be distributed in a debate network containing the same number of articles.

Lotka's law (1926), known as the Inverse Square Law, deals with the authors' productivity with the premise: the number of authors who have published exactly (n) works is inversely proportional to (n^2). It should be said that the more it is published, the easier it is to publish a new work and these researchers who publish more interesting results gain more recognition and access to resources to improve their research.

The law of Zipf (1949) permits to evaluate the presence of words of a certain text, using the principle of least effort. Zipf suggests that the most cited words are also the shortest, because long or compound words are harder to assimilate.

4. DATA ANALYSIS

Figure 1 shows the co-citation network developed in the VOSviwer software. This keyword analysis is intended to highlight the blocks that identify the structure of a research field, their relevant points and the relationships between them. For this identification, the size of the circle and letter is used as a parameter, indicating that this keyword was often used by authors in publications. This means that the more times that word has been quoted, the size of the circle and letter gets bigger. According to bibliometric researchers, the formation of clusters with different colours represents references that are generally cited together. This type of relation reveals similar lines of research and, after looking at the map becomes clear the existence of four areas of research on the subject of selective surfaces.

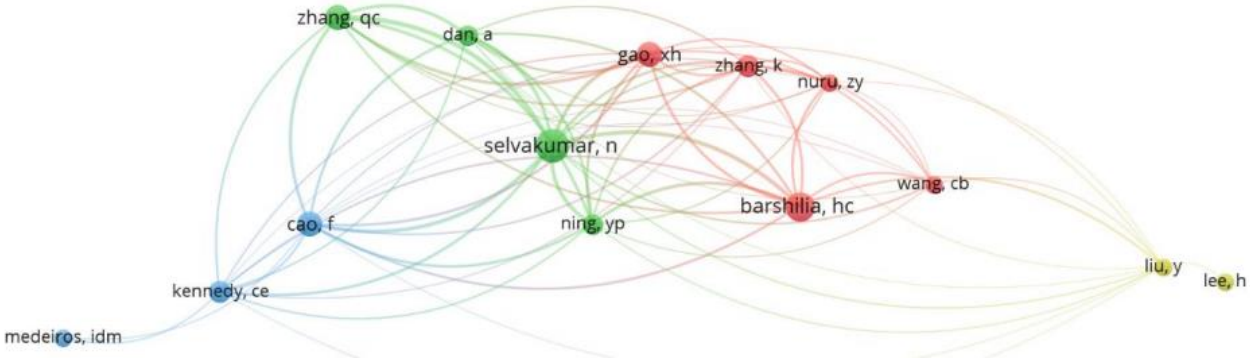

Figure 1. Co-citation network.

The blue cluster has as main authors co-cited Cao F. and Kennedy C.E., bringing work focused on the development of new precursor materials for thin films for applications in medium and high temperatures. The green cluster has as main authors Selvakumar and Barshilia (2012) being thermal stability, physical deposition PVD and Magnetron Sputtering some of the terms most cited in the titles and abstracts of these works, according to the VOSviewer. The red cluster covers subjects such as coating adherence, optical properties, layering and spectral selectivity. And the yellow cluster includes more recent studies looking at the corrosion resistance of coatings. We note that the research areas are not very remote from each other, only different approaches are identified. Figure 2 shows the number of citations per country.

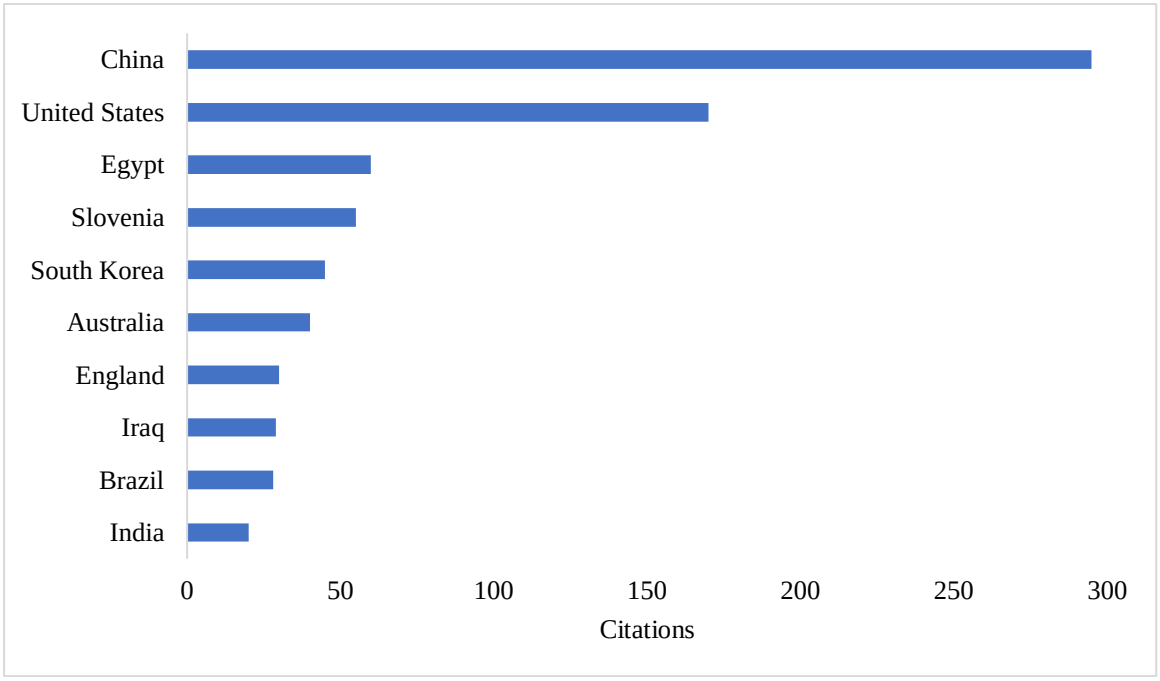

Figure 2. Citation counts per country.

China seems to be at the top of the list of publications cited in this area, followed by the USA, Egypt, Slovenia and South Korea. Brazil has made progress in scientific research into selective solar surfaces. Among the most co-cited authors represented by VOSviwer in Figure 1, the Brazilian Medeiros (2016a) and Medeiros (2020b), developed relevant studies in the area of selective solar surfaces with black chromium coatings produced by electrodeposition, and the ash of the sugarcane bagasse sintered and applied as anti-reflective coating.

With respect to institutions that have had more publications over the past 6 years, Chinese universities have dominated this ranking. The Chinese Academy of Sciences received 204 publications, followed by 61 from the Nanjing University of Aeronautics and Astronautics. The second most reported country was the US, highlighting Northeastern University and Stanford University, both with 73 publications.

In the building of the co-occurrence of words map, a minimum number of three occurrences per term was established and the overlay map visualization option according to the years of publication was selected. Figure 3 shows the bibliometric map of co-occurrence of words, elaborated in the VOSviwer software. Clusters are arranged in colder colours for articles published from 2017 onwards, and warmer colours for articles published in late 2022 and early 2023.

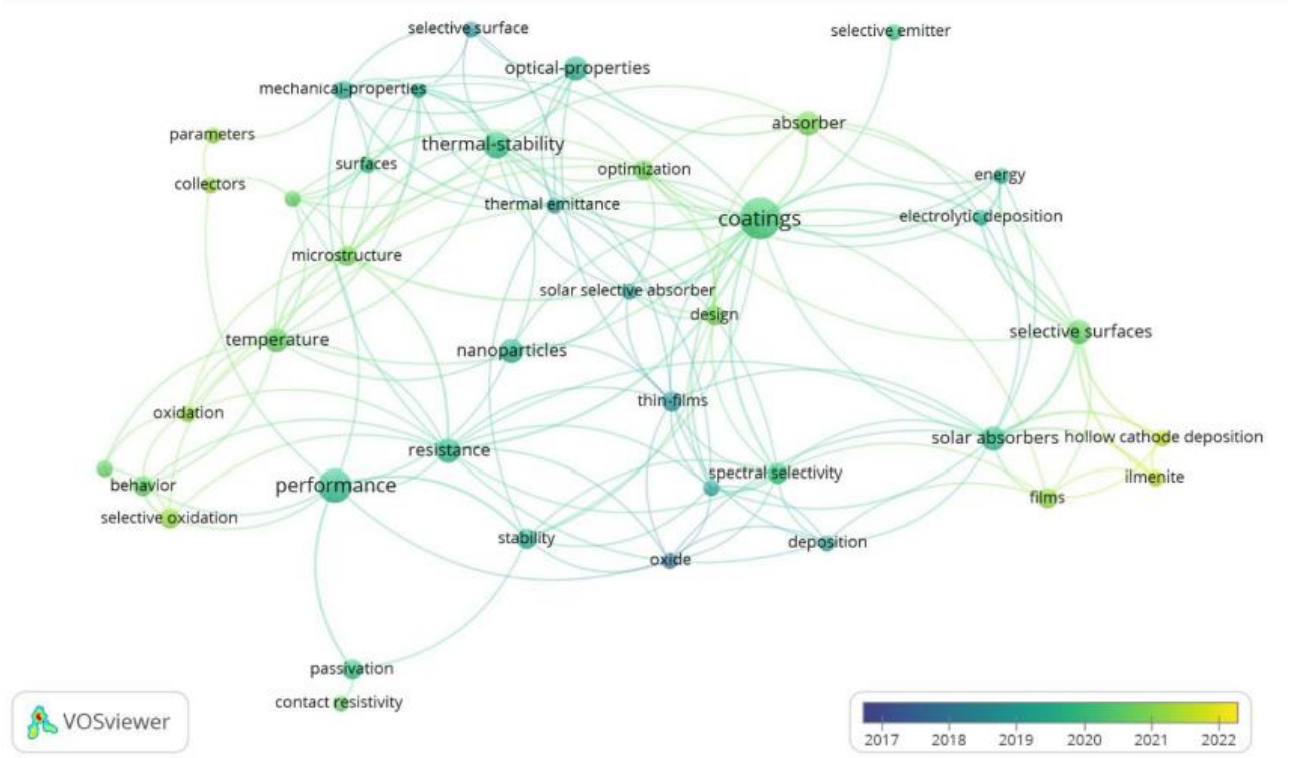

Figure 3. Map of co-occurrence of words.

The larger the size of the font and circle, the higher the number of repetitions of that word in abstracts and article titles. Therefore, the words "coatings", "performance" and "thermal stability" are those with a greater number of occurrences. This means that during the last 6 years, articles on selective surfaces are focused on producing coatings with good thermal stability at medium and high temperatures. However, the last published works analyze the oxidation and resistance of the films, the parameters used in their manufacture and techniques and materials that can reduce the cost of production of these coatings. It is also noticeable little research intensity in relation to corrosion of coatings, despite all the potential to be explored, given the relevance of this theme for a healthy operation of photothermal solar collectors.

In total, 660 journals published a minimum of one article. Table 2 presents the 10 most sought-after journals for the publications of works involving selective surfaces based on the Web of Science database, the journal Solar Energy Materials and Solar Cells with 127 published documents and the work of Li et al. (2017) with 385 citations in the journal ACS Applied Materials & Interfaces.

Table 2. Top 10 most published journals in the last 6 years.

Journals	Publications	Citations
Solar Energy Materials and Solar Cells	127	2.372
Journal of Alloys and Compounds	88	1.723
Solar Energy	86	1.057
ACS Applied Materials & Interfaces	77	3.120
Applied Surface Science	56	1.171
Optics Express	49	864
Journal of Materials Science-Materials in Electronics	47	329
Ceramics International	41	633
Solar RRL	35	437
Materials Research Express	34	284

5. CORROSION OF COATINGS

The bibliometric analysis conducted on selective solar surfaces suggested that the study of corrosion of these coatings should be explored. Service life and thermal stability are closely linked to the corrosion of absorber films. The interest here is to understand what is being published with scientific relevance in the study of corrosion in the last five years within Mechanical Engineering.

The systematization of the research consisted in searching for keywords in the main collection of the Web of Science, and filtering the research only for articles in the category Mechanical Engineering of the Web of Science. The word 'corrosion' was used to identify the most recent research in this field. By filtering the results based on review document and article type, 881 records were obtained for the searched terms in this phase.

The complete document and its cited references were sent to a spreadsheet, which was then imported into VOSviewer to create word co-occurrence maps based on text data from article titles and abstracts. It was established a minimum number of five occurrences put to an end, totaling 62 keywords, and it was decided to display in networksFigure 4 shows the bibliometric map of co-occurrence of words, developed in the VOSviwer software.

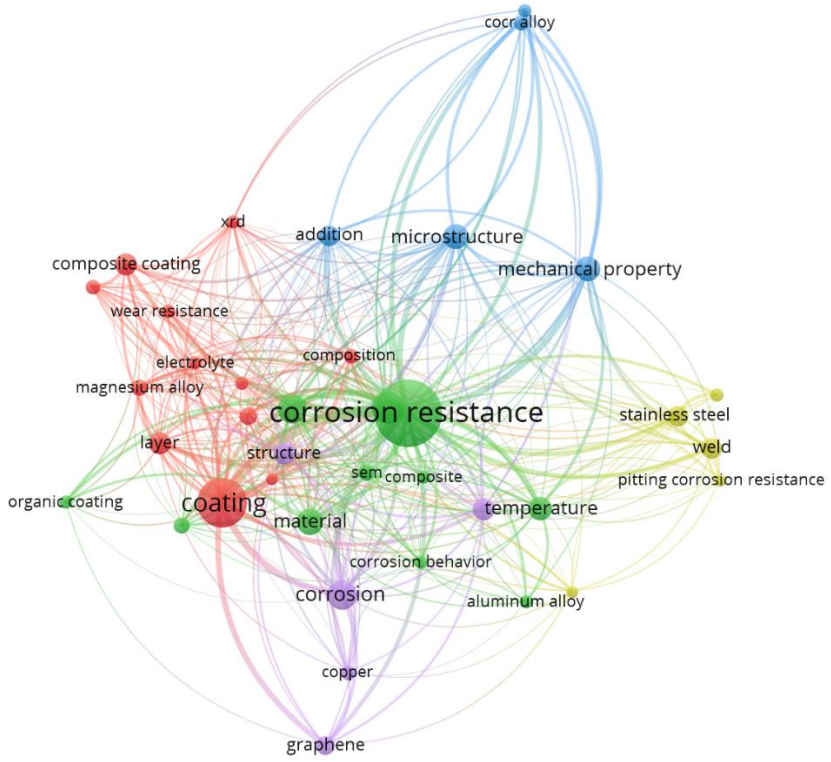

Figure 4. Cooccurrence of words in the study of corrosion in Mechanical Engineering.

It is observed that the larger the font size and circle, the greater the number of repetitions of this word in the abstracts and titles of the articles. The most frequently used words in articles on corrosion published between 2018 and 2023 are 'corrosion resistance' and 'coating'. Which implies that in the last 5 years, the study of corrosion resistance of coatings has been gaining strength in scientific research.

From the association by clusters, it is possible to observe in Figure 4 that it is a concern of the green cluster to study the behavior and corrosion resistance of different materials at different temperatures. Characteristics that are also strongly evaluated in the design of coatings, which justifies the intensity of the network between the green and red clusters. The most relevant articles of the purple cluster work with inhibitors of corrosive action from graphene. Since these inhibitors are usually acquired with coatings, it is justified the strong binding of the purple cluster with green and red. The blue and yellow clusters highlight more defined areas of study in the mechanical properties of structures and specific corrosion failures.

For the construction of the co-citation network, the alternative of creating maps based on bibliographic data was selected by importing references exported from the Web of Science database. A minimum number of 10 citations per author was established, totaling 36 relevant authors in the network. Figure 5 shows the co-citation network developed in the VOSviwer software.

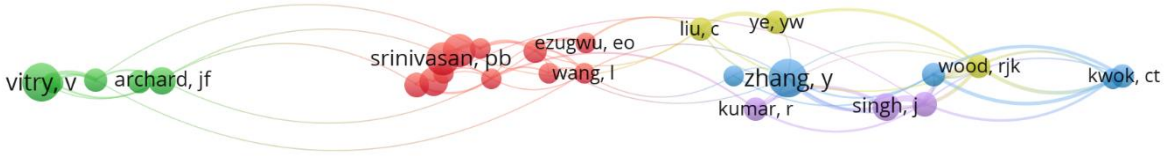

Figure 5. Co-citation map.

From the network of co-citations created by researchers in the field of corrosion, five lines of research have been identified. The green cluster has as main author Vitry et al. (2008), with more than 113 works of authorship and co-authorship, relevant in the area of coatings for corrosion applications, with special emphasis on her work on the mechanical properties and wear resistance of nickel-boron coated aluminum alloy after heat treatments and his latest work on improving the corrosive performance of a nanocomposite coated aluminum alloy by sol gel process.

The red cluster is where corrosion research is most concentrated. Srinivasan, P. B. stands out with more than 87 articles published in the field of welding and surface engineering focused on the mechanical properties of structures and specific corrosion failures. In the yellow cluster stand out Chao Liu, with 21 articles, his most relevant work being carried out in 2017, in which he mentions the effects of the thickness of the electrolytic film on the availability of cathodic current in a galvanic pair; and R. J. K. Wood with his research on electrochemical reactions that occur in a system exposed to a corrosive environment.

The purple cluster behind Raman Kumar with 17 works with theoretical and experimental studies on corrosion inhibitors; and the blue cluster, with Y. Zhang bringing work on the synergistic effect of cavitation erosion and corrosion of various engineering alloys (2000) characterization and analysis of the corrosive behavior of coatings manufactured by electrophoretic deposition (2009), and its most recent study on the remarkable synergistic effect in nitride nanosheets for electrochemical separation of water. A study that examines the corrosion resistance of selective coatings falls within the green cluster.

6. CONCLUSION

Bibliometric analysis is a tool that can be used to map and organize scientific research from indicators of interest. The VOSViwer software proved to be efficient in creating the maps of indicators and in organizing the database, elucidating each line of research through the clusters and varying the size of the source and the circle on the map, according to the relevance of the themes or works.

Selective materials have been used to coat solar panels of photothermal collectors with good results in recent years. Photothermal solar collectors with selective coatings provide a minority of thermal losses by emissivity while providing a significant gain in the absorption of solar radiation. This relationship considerably increases the selectivity of the solar plate, increasing the final temperature of operation of the collector and increasing the possibilities of application of this form of use of solar energy.

Brazil was identified by bibliometric analysis as a country that has made significant scientific contributions to the study of selective coatings. Brazil has great energy potential because it has continental dimensions and is inserted in the intertropical region of the planet. Basically, the less sunny region of Brazil is about 40% sunnier than the sunniest region of Germany, a pioneer country in the development of solar collectors. It is essential to keep studying ways to harness solar energy to turn all this research potential into energy potential, making Brazil a global power in the generation of energy from sunlight.

According to the occurrence map of words, scholars of selective solar surfaces are concerned with producing coatings that have good thermal stability at medium and high temperatures. Corrosion problems are common and can occur in various activities. The equipment in the solar collector is exposed to a chemical environment that can cause corrosion, which can result in a loss of efficiency and decreased heat transfer through corrosion products. It is therefore important to consider corrosion as a factor of great importance in the design phase to avoid or minimize future corrosive processes. Confirming the research potential of corrosion resistance of selective coatings.

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