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Patent Analysis of the Development of Technologies Applied to the Combustion Process

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Abstract: The use of combustion in industrial activity is of paramount importance for economic and social development. However, combustion reactions are the main sources of atmospheric pollutant emissions. Given this reality, it is necessary to study new combustion techniques, such as the application of oxygen in the process, in order to increase the efficiency and productivity of the burning process and energy production. In addition, studies have reported the use of acoustic excitation, a low-investment technique that can promote higher rates of heat and mass transfer. Thus, the goal of this study was to bring data on the current scenario related to the application of these two technologies to the combustion process where, through the reported results, they can be used as a guide for companies' decisions about new technologies and global trends to be identified. For this, a technological prospection was carried out which focused on patents to investigate the use of oxygen-enhanced combustion and acoustic excitation coupled to the combustion process; a total of 88 documents were found. Few documents applied acoustic excitation for process improvement, indicating that its use is recent; however, according to the literature, it is a promising field to be explored. Siemens AG was the main depositor, and ten primary inventors were identified. Germany and the United States were the countries with the highest number of filings. In the prospected documents, it was possible to identify that there is a need for the further investigation of the joint use of both techniques. These investigations may lead to the development of processes and devices that can provide economic and environmental gains for the energy industry.

Keywords: combustion process; oxygen-enhanced combustion; pulsed combustion; sustainability; patents

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1. Introduction

Combustion is a process of utmost importance for economic and social development and is present in many human and industrial activities. Despite being a technology with a great environmental impact, combustion still is one of the most commonly used energy-release mechanisms because of the energy densification inherent to fuels. As a way to reduce its impact, it is extremely important to study techniques and possible fuels that can contribute to reducing toxic emissions to the environment [1]. Within this context, the study of the energy efficiency of combustion processes, such as the use of burners for energy generation, is necessary, since a large part of the costs of an industry is associated with the purchase of these systems, as well as the operation and maintenance services for the entire system. Thus, besides the economic impact, with the evaluation of the energy efficiency of a system, it is possible to promote a reduction in the environmental impacts caused by the generation and emission of greenhouse gases (GHGs) [2].

Industrial burners are among the main equipment that must have their thermal efficiency increased in order to decrease fuel consumption, as well as to reduce the emission of pollutants and GHGs [3]. Among the techniques used for this purpose, oxygen-enhanced combustion (OEC), characterized by oxygen (O_2) rates higher than those found in atmospheric air [1], can add up to 30% of O_2 without major changes in the equipment to which it is applied. In general, its application in combustion systems can provide several benefits, such as increased productivity, thermal efficiency, lower exhaust gas volume, greater efficiency of heat-transfer processes, and reduced fuel consumption [4,5]. More specifically, its use with burners can promote greater soot formation in certain regions of the flame [6].

Soot is an important component for thermal radiation. The increased production of soot in controlled burning processes by OEC can directly influence the increase in heat transfer from the flames to the heating surfaces through thermal radiation, thus contributing to an increase in the thermal efficiency of the burners and promoting lower emission of toxic gases, such as carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds, and particulate matter [7]. The interaction of O_2 and soot concentration, as well as its amount in the flame structure, was evaluated in a study using OEC in natural gas flames; the results indicated that properly designed burners using OEC can improve the soot formation process by increasing the intensity of thermal radiation by 85% compared to traditional burners using pure O_2 [8]. In another study, when evaluating the effect of the magnetic control of OEC on flame stability, the process allowed the identification of an increase in soot concentration and, consequently, a higher emission of thermal radiation [9]. Moreover, the same efficiency was observed in ethylene flames, where the influence of OEC, ranging from 16.5% to 36.8% in O_2 concentration, allowed increased soot production and promoted effects on other characteristics, such as flame temperature and brightness [10].

Another process that has proven interesting for application in combustion systems, especially for power generation, is acoustic excitation (or pulsed combustion). Acoustic excitation can be defined as a burning process in which some operational parameters can be changed with time, such as the temperature, pressure, velocity, or other variables [11]. The pulsed condition can be achieved by using a device that induces oscillations in the flow, such as a loudspeaker strategically placed on the burner or in the combustion chamber [11,12]. The use of acoustic excitation has been shown to be an attractive technique in combustion systems, mainly in the generation of energy, because it offers several advantages over the conventional combustion process [13,14]. The presence of acoustic oscillations in the combustion process improves the mixing rate between the fuel and oxidizer due to the creation of intense turbulence zones in the flame region. This provides several advantages for this technique, including a higher combustion efficiency with reduced energy consumption and little loss of fuel, increased combustion intensity, increased heat- and mass-transfer rates, low capital investment for implementation, and—more importantly—reduced NOx and CO pollutant emissions [13,15].

One study evaluated the interactions between combustion, turbulence, and acoustic excitation in a premixed flame on a turbulent Bunsen burner. The thermoacoustic interactions were produced by an active system based on speakers, and an acoustically excited and non-excited flame front were compared. The results demonstrated that acoustic excitation changes the pattern of turbulent flow, and by changing this pattern it is possible to actively impact the combustion process, therefore eliminating or reducing combustion instabilities [16]. Acoustic excitation has also been tested on a premixed jet flame (liquid petroleum gaseous flame). In this experiment, acoustic excitation was used to control flame stabilization and perturb its flow. Two external loudspeakers were used for this. The results showed that the flame length and core decreased as the amount of excitation was increased, promoting a good combination characteristic in the flame and thereby allowing a better temperature distribution and burning efficiency, and also reducing the amount of carbon produced [17]. In another study, the interaction of OEC technique with the acoustic excitation of flames was studied, and its effects on the atmospheric emissions of CO, NOx, formaldehyde, and acetaldehyde, as well as the temperature of exhaust gases, in diffusive and confined natural gas flames were evaluated. The results showed a reduction in the emissions of CO and NOx with OEC and acoustic excitation, indicating that both techniques together can reduce pollutant emissions and increase the efficiency of thermal combustion equipment [11].

It is possible to verify the improvements provided to the combustion process in burners by these techniques, allowing for the characterization of the use of acoustic excitation and OEC methods to reduce the emission of pollutant gases and increase the energy efficiency of the system. However, the number of records evaluating these two processes in combination is still scarce in the literature. For this reason, this study aimed to perform a technological prospection that focused on patents in order to verify the technological panorama evaluating the combustion process coupled to the use of OEC under the influence of acoustic excitation.

2. Materials and Methods

This study was an exploratory search to collect technological information in patent documents. The technological search was carried out on 10 February 2022 in the Derwent Innovation Index (DWPI), Thomson Innovation©, licensed for use by the SENAI CIMATEC University Center. After the refinement (data not shown), keywords and Boolean operators were adopted to build the search strategy used in the prospection:

combustion chamber AND burner AND (acoustic OR thermoacoustic)

In addition, International Patent Classification (IPC) codes were also used. Table 1 indicates the codes used in the prospection, as well as what each code is related to.

Table 1. IPC codes used in the present patent technology prospection.

IPC Code	Related to
F23D 14/32	Burners for the combustion of a gas, e.g., of a gas stored under pressure as a liquid using a mixture of gaseous fuel and pure oxygen or oxygen-enriched air.
G01M 15/04	Testing the static or dynamic balance of machines or structures; testing of structures or apparatus not otherwise provided for testing internal combustion engines

The database was searched in the title, abstract, and claims fields of the patent documents, with no restriction on the period of data collection. For the construction of the graphics, the GraphPad Prism 9.2 (San Diego, CA, USA) software, also licensed for use by the SENAI CIMATEC University Center, was used to report the temporal analysis of the patent documents (year of priority and year of expiration), the main applicants and inventors of the technologies, and the International Patent Classification (IPC) codes assigned to the document indicators. The results pertaining to the geographical distribution of the main applicant countries/regions, the main potential markets for the technologies, and the main technological areas related to the inventions were obtained directly from the DWPI database (with adaptations).

3. Results and Discussion

The use of patents is an important source in the analysis of technologies and innovative activities. In this study, a search for patents was used to evaluate the technology of interest: combustion processes using oxygen-enhanced combustion (OEC) and under the influence of acoustic excitation. Eight-eight documents were found in total. Figure 1 shows the annual distribution of patent applications related to the described technology; the first applications were found in 1997 (Figure 1a). Applications for patent documents were most significant in 1998, reaching a peak of 10 applications, followed by a peak in 2002 with 7 applications. It is important to note that 19 documents were classified as "others", likely because they referred to documents deposited in the years 2021 and 2022. In addition, documents may not have been recovered during the prospection because of the secrecy period, which is usually 18 months [18].

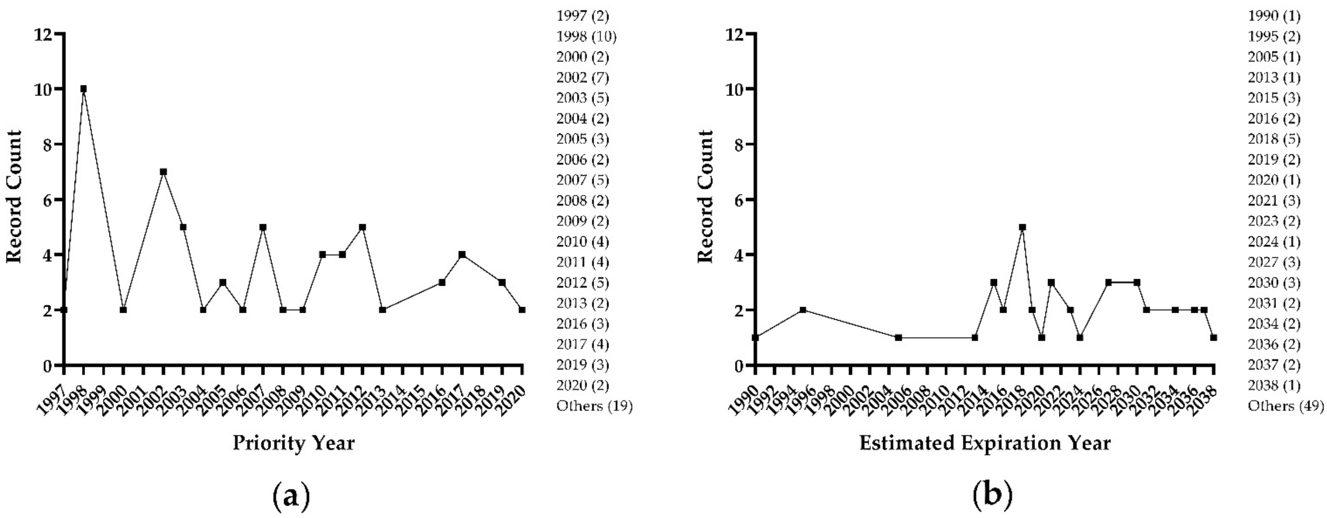


Figure 1. Temporal analysis of patent documents. (**a**) Earliest priority year; (**b**) estimated expiration year.

Starting in the 1980s, global events were focused on the urgent need for efficient generation of electricity, driven by worldwide economic development, an increased environmental consciousness regarding pollutants, and concerns regarding the emission of CO_2, which has been directly linked to global warming [19]. In order to improve both scenarios, the economy, and the environment, in 1997 the Kyoto Protocol was signed by industrial countries and most economies in transition to limit and reduce GHGs by an average of 5.2 percent below 1990 levels in the period from 2008 to 2012 [20,21]. The evolution in the number of patent applications may have been related to these arising concerns with population and economic growth, as well as the environment. According to our results, growth was observed between 1998 and 1999 and between 2002 and 2003 in relation to the number of priority patents related to the proposed theme.

The majority of developed technologies found in the patent documents focused on applications in combustion chambers and strategies for improving the combustion process. Patent WO1999056060A1 (1998) [22] refers to a combustion chamber assembly for a gas turbine using a different design for the combustion chambers in order to reduce the natural thermoacoustic instability and promote a more stable combustion process, which consequently leads to a reduction in the emission of harmful gases, such as NOx. Patent WO2000012939A1 (1998) [23] refers to a combustion chamber device with the main goal of reducing the influence of acoustic pressure oscillations, which are generated during the operation of a combustion chamber device. It is important to highlight that the invention patent was designed to allow for the supply flow of O_2-containing gas in order to help the combustion process. Patent EP3742050A1 (2019) [24] refers to an acoustic damper device for a rotary machine with the main purpose of reducing acoustic pressure oscillations during the combustion process. Patent DE102020106329A1 (2020) [25] refers to a method of manufacturing for a cooking appliance burner system and a cooking appliance that produces less noise from the combustion process.

Thermoacoustic instabilities are one of the most challenging fields of combustion studies and are characterized by a large-amplitude oscillation of one or more natural acoustic modes of a combustor arising from resonant interaction between oscillatory flow and unsteady heat-release processes [26]. If uncontrolled, these instabilities can cause undesirable consequences, such as component vibrations, increased heat-transfer rates, flame blow-off, and flashback. In the worst-case scenarios, these oscillations can result in system deterioration of the engine, leading to structural damage [27]. Over the years, different approaches have been studied in order to reduce and/or control thermoacoustic instability during the combustion process [28–31]. Modifying the geometry and configuration of combustion burners, for example, adjusting the fuel-supplying system, and adding acoustic damper devices, such as Helmholtz resonators, are widely used strategies in research [32–34].

Acoustic excitation is a passive control strategy employed to stabilize combustion-engine systems; it uses external excitations, such as a loudspeaker device, for acoustic forcing and fuel modulation to promote energy flow to the system and attenuate combustion oscillations, thus reducing instabilities [29,33,35,36]. The first report on a flame undergoing an acoustic excitation was created by Lovett and Turns. Their group investigated acoustic excitation in a turbulent jet flame for frequency ranging from 2 to 1300 Hz and an oscillating velocity amplitude of 0.13–0.89 relative to the bulk velocity provided by the burner. A notable change in flame structure was observed at a non-dimensional frequency of approximately 0.2 under resonant conditions. Thereafter, the flame was viewed under acoustic excitation, and a decrease in flame height and an increase in flow mixing were noticed upon resonant acoustic excitation of the burner pipe. These findings showed the possible enhancement of combustion performance when the acoustic excitation is used [35].

Tao et al. [28] evaluated the effects of different control strategies on combustion instability by maintaining a loudspeaker interface for acoustic excitation and found that the non-linear controller could effectively suppress thermoacoustic instability. Olivier et al. [30] proposed a new approach to control the operation of a thermoacoustic Stirling electricity generator using an additional acoustic source connected through a feedback loop and demonstrated that the external forcing of thermoacoustic self-sustained oscillations impacted the performance of the engine and improved the efficiency of thermoelectric transduction. Liu et al. experimentally evaluated the non-linear response of the low-swirl flame to acoustic excitation with large amplitude. They used an acoustic excitation system that includes an arbitrary function/wave generator, an amplifier and a loudspeaker set at the base of the test rig. The results demonstrated that vortices were formed and convected downstream along the flame approximately at bulk flow velocity, inducing flame rollup and shear layer instabilities, and also as the perturbation level increases, the high anti symmetric and helical modes are inhibited [36].

Fujisawaa et al. investigated the behavior of a methane diffusion flame under acoustic excitation using simultaneous observations of Mie scattering and schlieren/shadowgraph imaging. They also evaluated the velocity field and temperature distributions in the flame were measured by particle image velocimetry (PIV). The acoustic excitation was provided by a loudspeaker with a diameter of 160 mm driven by a sinewave generator combined with an AC amplifier. The excitation frequency used was 100, 150, 200, and 300 Hz. The results indicated that acoustic excitation promoted changes in flame behavior, where the flame height, oscillation amplitude, and luminosity decreased as the acoustic excitation amplitude increased [37]. The use of acoustics to improve the combustion process is considered a recent development, and possibly for this reason, related patent filings are rare. However, the application of the technology is growing in the literature.

Another strategy documented in the patents and also found in the literature is the use of O_2 to enhance the combustion process. First mentioned by Baukal (1998) [38], OEC is a process that involves enriching the intake air for combustion with O_2; it provides good results, including higher productivity, better thermal efficiency, a lower volume of exhaust gas, greater efficiency in heat transfer processes, reduction in fuel consumption, cost reduction in raw material, and greater flame characteristics, which promote stability and shape control [1,39,40]. Patent EP2284130A1 (2011) refers to a new method of producing mineral wool using a cupola furnace, where the combustion chamber is fed with fuel and O_2 gas. According to the invention, by increasing the O_2 concentration, the flame intensity and temperature increase significantly [41]. Another example, patent WO2000009945A1 (1998), refers to a combustion chamber device with burners of different geometric shapes, where each burner includes a supply for the flow of O_2-containing gas. The main purpose of the invention was to reduce acoustic pressure oscillations without, at the same time, increasing the emissions of NOx [42].

Zhua et al. [43] evaluated the NOx reduction and burnout characteristics of pulverized coal in OEC with a drop-tube reactor, and their results showed the inhibition of thermal and fuel NOx formation with a rise in O_2 concentration under deep-staging parameters. Li and Kuo [44] explored the effect of OEC conditions on torrefied waste wood pellets with the main goal of optimizing the combustion efficiency. The results revealed improved data for both the total fluidized-bed combustion efficiency and volatile combustion ratio when using O_2 enrichment. Silva et al. [1] evaluated the thermal radiation and formation of soot in flames of syngas using the OEC technique under the conditions of poor mixtures. The results demonstrated an influence of lean combustion and OEC on the formation of soot and the thermal radiation of the flame, indicating better control over the formation of soot without a reduction in thermal radiation.

The enrichment of the combustion process with oxygen refers to concentrations ranging from 21 to 90%, where more than 90% O_2 is considered oxyfuel combustion [45]. In order to evaluate three different concentrations of O_2 (21, 25, and 30 volume fraction %) during methane combustion, Melon and colleagues evaluated the stability of a methane−air flame and pollutant emissions, such as CO, CO_2, and NOx. The main results showed that oxygen enrichment promotes large CO conversion into CO_2. CO_2 increases linearly with oxygen addition; the concentration of NOx increases with oxygen addition, mostly because of the increase in the flame temperature; flame stability is enhanced with oxygen addition, even for low concentrations; and also, lift-off heights and their fluctuations largely decrease with oxygen addition [46]. Zaidaoui et al. [47] searched for the effects of exhaust gases recirculation, water vapor, and CO_2, with and without O_2 addition, on non-premixed turbulent flames stabilized by a swirl burner. The O_2 enrichment varied from 21% to 30% (in vol.) and results demonstrated a significant decrease in the liftoff height enhancing the flame stability. They also observed a decrease in NOx emission and exhaust gas temperature and an increase in CO emissions that was directly related to the decreased flame temperature.

The OEC technology can also be applied to others innovative fuel such as hythane as describe by Riahi and colleagues [48]. The group has experimentally and numerically evaluated the combustion of hythane generated in a coaxial burner to assess the efficiency of the process using an oxygen-enriched oxidizer. The results exhibited that oxygen enrichment favors the flame temperature and reduces the hythane flame length, reduces the total volume of combustion products, and minimizes the carbon monoxide production.

Table 2 shows some publications in the scientific literature that address the use of the prospected technologies.

Table 2. Articles that focus on the use of acoustic excitation, OEC, or both technologies in the combustion process.

Title	Technology	Main Findings and/or Conclusions	References
A study on acoustically modulated Bunsen flame and its impingement heat transfer	Acoustic	This study experimentally examined the interaction between an acoustic field and a flame by using a low-power loudspeaker to actuate the oscillation of a Bunsen flame. The results showed a 10% increase in total heat-transfer rate when the optimum nozzle-to-plate distance was coupled with the most effective forcing frequency of 50 Hz.	[49]

Table 2. *Cont.*

Title	Technology	Main Findings and/or Conclusions	References
Soot evolution and flame response to acoustic forcing of laminar non-premixed jet flames at varying amplitudes	Acoustic	The authors evaluated the mechanisms that affect soot evolution in time-varying flames of different burner diameters under both steady and forced conditions. The results showed that by increasing the forcing amplitude from low to moderate (from α = 25% to 50%), the soot volume was increased by 50%. However, for the 5.6 mm-diameter burner, a further increase in the forcing amplitude (from α = 50% to 75%) did not increase soot production significantly. They concluded that the spatial correlation between the soot field and the temperature profile is influenced by the burner diameter and forcing conditions.	[12]
Flame structure changes resulting from hydrogen-enrichment and pressurization for low-swirl premixed methane–air flames	OEC	This study demonstrated how flame dynamics change in response to the systematic addition of hydrogen in a low-swirl lean premixed methane–air burner. They evaluated 0%, 20%, and 40% hydrogen by volume in fuel mixtures in a low-swirl burner at several chamber pressures. The results indicated that increasing the pressure and hydrogen concentration led to an increase in the maximum density of the flame surface.	[50]
Experimental investigation of the natural gas confined flames using the OEC	OEC	This study experimentally evaluated the technique of OEC and its interaction with soot formation and thermal radiation in natural-gas-confined flames. The levels of air enrichment applied were 2% and 4%, and the results suggested that the use of OEC in natural-gas-confined flames produced an increase in thermal radiation coupled with significant reductions in NOx formation.	[40]
Experimental investigation of thermoacoustic coupling using blended hydrogen–methane fuels in a low swirl burner	OEC + Acoustic	The aim of this study was to determine the effect of OEC on combustion instability by examining the flame response to a range of three different blends of hydrogen and methane (93% CH_4–7% H_2, 80% CH_4–20% H_2, and 70% CH_4–30% H_2 by volume) employed as fuel with four different acoustic excitation frequencies (85, 125, 222, and 399 Hz). The flame showed increases in flame base coupling and flame compaction with increasing hydrogen concentration for all conditions.	[51]
Experimental evaluation of CO, NOx, formaldehyde, and acetaldehyde emission rates in a combustion chamber with OEC under acoustic excitation	OEC + Acoustic	This article experimentally evaluated the interaction of the OEC technique with the pulsating combustion technique by the acoustic excitation of flames and the effects of these techniques on atmospheric emissions of CO, NOx, formaldehyde, and acetaldehyde. The results showed that the application of the OEC and acoustic excitation techniques could reduce pollutant emissions and increase the efficiency of thermal combustion equipment.	[11]

Figure 2 shows the main applicants (a) and inventors (b) of the prospected patent documents. The company Siemens AG appears in first place with 11 documents. With operations focused on industry, infrastructure, transportation, and healthcare, in terms of energy, the technology company delivers solutions for the production of oil and gas, power generation, and the transmission and distribution of electrical energy [52]. Compared to the top ten competitors in this set, Siemens AG has 26% of those records. In second place is Alstom Technology, with 10 documents. As a company that is leading societies to a low carbon future, Alstom develops and markets mobility solutions that will provide sustainable foundations for the future of transportation [53]. Asea Brown Boveri, in third place with five documents, is a company working in energy and automation technologies which has various products in its portfolio applicable to electrification, robotics, automation and drive solutions, motors, and generators [54].

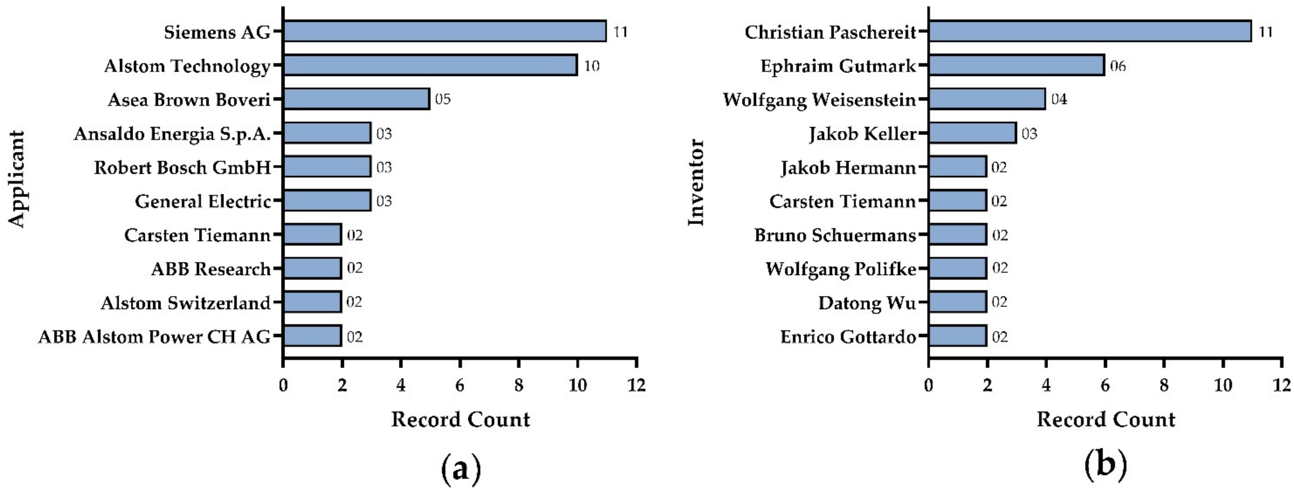


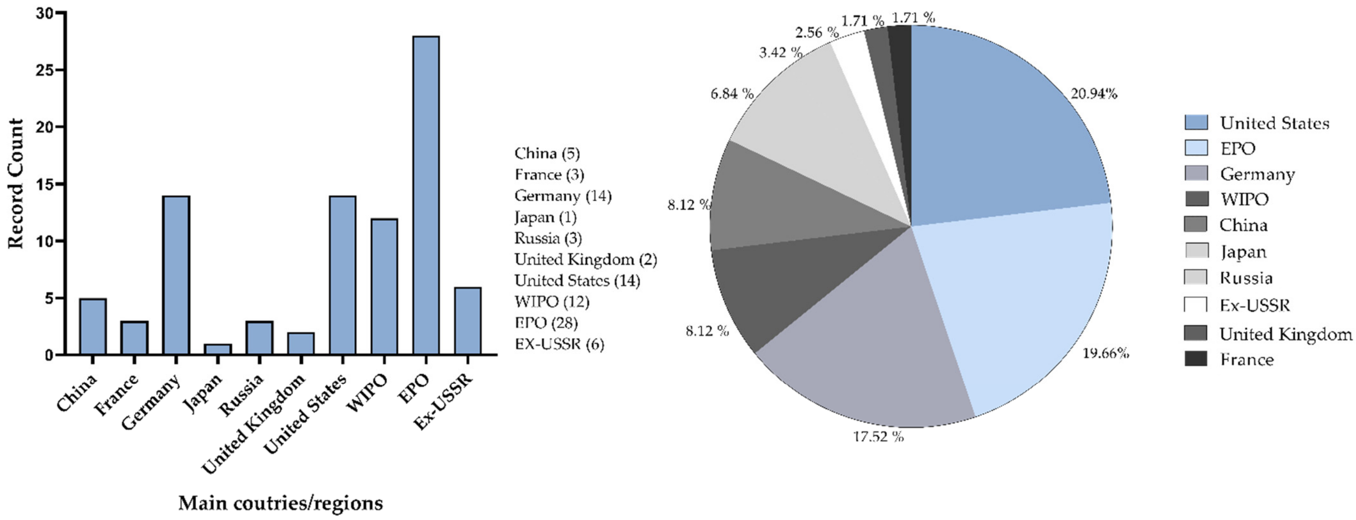
Figure 2. Analysis of the main (**a**) applicants and (**b**) inventors of the prospected technologies.

It can be seen from Figure 2a that not only companies appear among the main applicants, but also the inventor Carsten Tiemann. This reflects the possibility of patent applications not only by companies, but also by individuals. One of the patents that can be cited in which Tiemann was both the inventor and applicator of the technology is publication number US20010018173A1, applied in 2001. The invention concerns a process related to the operation of a hybrid burner [55]. Figure 2b shows the top ten inventors of the prospected technologies, most of whom are associated with the companies found.

When analyzing the main countries that deposited these technologies (Figure 3a), it is possible to observe that Germany and the United States are the primary countries, with a total of 14 documents each. Germany plays an important role in the development and export of technologies involving combustion processes that are mainly applicable to vehicle construction. In 2019, Germany exported an equivalent of USD 7.04B in combustion engines, placing it in second position as one of the largest exporters of this type of technology in the world. This range includes diesel engines for motor vehicles as well as propulsion engines [56].

In recent years, Germany has been adopting more climate-friendly policies in the field of burner production. The large combustion plants in the German energy and industrial sectors are part of the European Union (EU) Emissions Trading System (ETS), since Germany is a member of the EU and is guided by the EU's energy and climate policy framework. Thus, reducing GHGs is one of the main points of the climate policy that has been adopted by the country. In March 2019, Germany adopted the Climate Action Programme 2030 in order to take a clear step in the direction of producing technologies that promote lower GHG emissions. Assigned to various sectors, but primarily related to the energy sector, the measures include increasing renewable energy, modernizing fossil fuel power plants, and developing more cogeneration plants (the combined production of heat and power) [57].

Analyzing the patent documents filed by Germany, according to the search strategy used, only two of them are recent, from the years 2019 and 2020. Before these, the last filing dated back to the year 2011. The patent number DE102019114788A1 (2019) entitled "Method for monitoring a burner and a device therefore" refers to a burner monitoring system for the exhaust system of vehicle engines that acts via air and fuel injection. It can be seen that the technology uses air (not specifically O_2) and, although it does not present an acoustic excitation application in the process, it makes use of an acoustic sensor for combustion noise control purposes [58].



(a) (b)

Figure 3. Geographical distribution of the analysis of the (**a**) main countries/regions of the depositors of the prospected technologies with their number of patent documents and (**b**) main markets for these inventions. EPO—European Patent Office; WIPO—World Intellectual Property Organization; USSR—Union of Soviet Socialist Republics (The others 9.4% not highlighted in the figure refers to other countries found in the search).

Industrial burners are widely used in industry processes that need to reach high temperatures to process materials in closed systems. In this context, developed countries, such as those identified in Figure 3a, stand out in the production of these technologies, which are being increasingly improved to meet current environmental demands. The control of the fuel/air reaction is one of these applicable processes, as well as technologies that promote the reduction of toxic gases, such as NOx, during combustion [59]. Thus, market growth in the field of industrial burners is expected by the year 2029, with compound annual growth rate (CAGR) projections of 4% during this period. According to research conducted by Persistence Market Research, this growth will be associated with the stimulus for the adoption of technologies that promote the increased efficiency of the process and the reduction of toxic gases, including the processes of OEC and acoustic excitation, since the control of environmental footprints is receiving increasing importance [60].

It is possible to notice that not only countries are highlighted in the results, but also institutions, including the European Patent Office (EPO), with 28 documents, and the World Intellectual Property Organization (WIPO), with 12 documents. Filing through the EPO occurs when the applicants want to protect their technologies in the EU [61], and filing through the WIPO occurs when the applicant wishes to make several international applications through a single application. An example is filing through the Patent Cooperation Treaty (PCT) of the WIPO [62]. Protection through international applications via WIPO is carried out in order to reduce costs associated with the patenting process and simplify it, protecting the technology simultaneously in several countries [63]. The data show that the application of patent documents via the EPO or WIPO suggest a greater preference on the part of applicants in filing internationally or covering a particular region, indicating that such a developed technology is of interest not only to one location, but to several.

North America is a predominant market for these inventions, and is expected to maintain its dominant position in the global industrial burner market, both in terms of volume and associated value, until at least 2029 [60]. This assumption can be evidenced by the current prominence of the United States both as one of the main developer countries and as one of the main markets for use of the inventions (Figure 3b). Figure 3b gives an analysis of where the main developing countries in the prospective technologies have protection, as well as where the potential markets for these inventions are. It is possible to observe that the United States occupies one of the main positions, with a market share of 20.94%. The United States is a pioneer in the production of oil and natural gas with the application of combustion processes, leading the way in the use of fossil fuels for energy production. Its strong market for new technologies is reflected in the fact that, besides being a major producer, this country is also a leader in imports of combustion technologies, mainly in terms of combustion engines. In 2020, the United States imported more than USD 4 billion worth of combustion engines, mainly from Mexico (USD 1.44B), Japan (USD 961M), Germany (USD 712M), the United Kingdom (USD 361M), and Italy (USD 360M) [64].

After the United States are Germany with 17.52% of the market share and China with 8.12%. In addition, it is possible to identify the participation of the EPO (19.66%) and the WIPO (8.12%). This result may indicate that the absorption of technologies in the European market ranks the region in second place as a market for inventions. In the case of WIPO, this result may indicate the participation of the technologies in 8.12% of the world markets. According to the DWPI database, overall, 2% of companies have filed in more than four countries. A global filing strategy may demonstrate the increased market potential in this space.

Other data extracted from the DWPI database indicate that 59% of worldwide filings in these results are granted, which indicates protection for active (alive) patents in the relevant markets. Furthermore, 41% of this result set is pending applications. The higher percentages of applications point to a new or growing market, whereas lower application rates can point to already established markets or low-growth areas. A general analysis considering high percentages as above 50% can indicate that the market for the production of combustion processes may be establishing itself because of the recurrent use of combustion processes for energy, and the high amount of information and technologies that associate OEC with this process. However, it is important to mention that the search for methodologies involving processes with lower GHG emissions, for example, may be one of the factors why high percentages were not observed. This may strengthen the idea that new technologies, besides OEC, applied to the combustion process are characterized as a potential area of exploration, such as the involvement of acoustic excitation in the processes that, although the technological prospection itself has not been found in many patent applications, have shown good results in the scientific literature, indicating the possibility of their application to combustion processes, with the aim of reducing the negative effects of the process and potentializing the market with new technologies that can be patented [65–70].

In terms of the technological areas of the prospected inventions (Figure 4), 10 technology classifications were found. According to the DWPI database, the number of technologies indicates recent innovations and can provide an overview of the "state of the market" and how it is segmented. The top three technologies in last 5 years presented and highlighted in the charts account for 68% of patent applications. The number of technology area assignments to patent applications can speak to a diverse portfolio or a specific technical focus. As can be seen, the three companies leading development in these technological areas are Siemens AG, Alstom Technology, and Asea Brown Boveri, and they account for 80% of all records in the entire results set.

The technological area (a), in red, refers to "combustor, gas turbine engine, fuel nozzle, heat shield, cooling hole, turbofan, impingement". Here, Siemens AG and Alstom Technology have 33% of their patent applications classified in this area, while Asea Brown Boveri has 29%. Overall, 91% of the depositors highlighted in Figure 4 have filings classified in this technological area, which totals 33 records. The technological area (b), in pink, refers to "gas turbine engine, combustor, turbocharger, compressor, turbomachine, bleed, spool", and (c), in purple, refers to "burner, combustion, fuel, gas, flue, fluidized bed reactor, coal".

Figure 4. Analysis of the three main technological areas related to the inventions. Comparisons between the top filing company, Siemens AG, and other companies, wherein (**a**, red) refers to combustor, gas turbine engine, fuel nozzle, heat shield, cooling hole, turbofan, and impingement; (**b**, pink) refers to gas turbine engine, combustor, turbocharger, compressor, turbomachine, bleed, and spool; and (**c**, purple) refers to burner, combustion, fuel, gas, flue, fluidized bed reactor, and coal. In the center of the larger donut chart is the number of patent documents of the main applicant for a given technology and, in the smaller donut charts, the percentage of companies involved in the production of inventions related to this technology.

The patent applications identified in these technology areas most often cite the use of OEC (or the injection of another type of gas) in the processes identified. Nevertheless, the use of acoustic excitation seems to be a more recent process. Proof of this is that, given the search strategy used and the other strategies investigated during the methodological design (data not shown), only a few patent documents made use of acoustic excitation to promote a pulsation condition during the process, increasing mixing rates between the fuel and oxidizer and promoting greater energy-efficiency with lower GHG emissions [13]. Furthermore, according to the literature, there are not many reports demonstrating the successful application of acoustic excitation under conditions of reducing flue gas compositions [71]. In the patent documents found, the scarce use of acoustic excitation could be evidenced and, contrary to what is positive about its application to combustion processes, many patent documents described approaches for the control of pulsation in the process, since the noise generated ends up being a problem. However, that can be dampened to acceptable levels by the use of acoustic decouplers and sound insulation [72].

Thus, studies involving both OEC and acoustic excitation applied to the combustion process are recent. An example is the investigation of the confined combustion of synthesis gas (or syngas) in poor mixture conditions with acetylene doping associated with OEC and acoustic excitation, a project that is under development by the authors of this manuscript. As previously mentioned, the use of OEC can promote the adequate control of soot formation, taking advantage of its energetic potential with the control of its emissions. As a form of potentiating this process, and taking into consideration the environmental concerns surrounding the emission of GHGs, the association of techniques such as acoustic excitation to OEC was taken into account for the evaluation of the related energy aspects and the impacts of the emissions in the combustion of synthesis gas, which has been increasingly arousing industrial interest with the increase in biomass in the energy matrix. Previous results have shown that the combined use of the effects of these two techniques presents a promising opportunity to provide improvements to the combustion process, such as increased energy efficiency and reduced emission of pollutants in industrial plants [11]. One patent application was filed with the Brazilian National Institute of Industrial Property (INPI), a Brazilian federal agency responsible for improving, disseminating, and managing the system of granting and securing intellectual property rights for industry [73]. The application (BR1020160229014) relates to a natural gas combustion device for controlling the correlations between thermal radiation, soot formation, and CO and NOx emissions using OEC and pulsed combustion (acoustic excitation) techniques [74].

In Table 3, other prospected patent documents that relate the use of these two techniques to combustion processes are presented.

Table 3. Patent documents involving technologies that associate the use of OEC and acoustic excitation with the combustion process.

Priority Number	Title	Refers to	References
CN207019906U	A measuring acoustic transmission relation of rotational flow burner device.	Rotary flow burner in which an air and fuel premix is fed by means of an acoustically excited sonic vibrator measured by a device for determining the thermoacoustic transfer ratio with the burner.	[75]
CN103244958A	A pulse metal wire net catalytic combustion apparatus and combustion method.	Catalytic combustion device that has a pulsating metal wire mesh arranged in an acoustic decoupling chamber connected to a heat radiation duct and a Rijke tube.	[76]
CH2007964A	Method for determining thermoacoustic transfer function of burner of combustion system, particularly combustion chamber of gas turbine, involves forming transfer function by two partial transfer functions.	Method that performs and evaluates the application of a thermoacoustic transfer function of a burner of a combustion system, more particularly the combustion chamber of a gas turbine.	[77]
US6211617B1	Acousto ionic radio antenna.	Plasma antenna that uses an acoustic mechanism to accelerate plasma ions, causing them to radiate electromagnetic energy into a fuel/air-based burner.	[78]
EP1429004A2	Method and device for affecting thermoacoustic oscillations in combustion systems.	A burner and a combustion chamber are used to effect modulated fuel injection into a recirculation zone formed in the combustion chamber in order to improve the influence of thermoacoustic vibrations.	[79]

As the last indicator of the patent prospection we performed, Figure 5 presents the main International Patent Classification (IPC) codes assigned to the patent documents found. The IPC was established in 1971 and is based on a hierarchical language of independent symbols for the classification of patents and utility models according to the different areas of technology to which they pertain [80]. Of all the documents, 24 were classified with the code F23R 3/28, which is the code most commonly used for patent classification. In addition, all documents were classified in the technological area F, which refers to "mechanical engineering, lighting, heating, weapons, blasting". It is important to mention that the same document can be assigned more than one code. Descriptions of the 10 main codes are presented in Table 4.

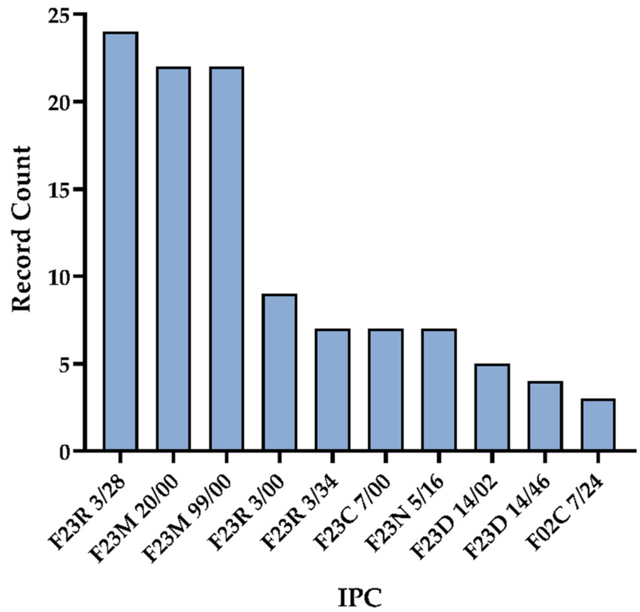


Figure 5. The major IPC codes used in the classification of the patent documents.

Table 4. IPC codes used in this patent technology prospection.

IPC Code	Related to
F23R 3/28	Continuous combustion chambers using liquid or gaseous fuel characterized by the fuel supply.
F23M 20/00	Details of combustion chambers not otherwise provided for.
F23M 99/00	Baffles or deflectors for air or combustion products; flame shields.
F23R 3/00	Continuous combustion chambers using liquid or gaseous fuel.
F23R 3/34	Continuous combustion chambers using liquid or gaseous fuel of the fluid-screen type.
F23C 7/00	Combustion apparatus characterized by arrangements for air supply.
F23N 5/16	Systems for controlling combustion using noise-sensitive detectors.
F23D 14/02	Burners for the combustion of a gas, e.g., of a gas stored under pressure as a liquid; premix gas burners, i.e., in which gaseous fuel is mixed with combustion air upstream of the combustion zone.
F23D 14/46	Burners for the combustion of a gas, e.g., of a gas stored under pressure as a liquid;
F02C 7/24	Features, component parts, details, or accessories, not provided for in or of interest apart from air intakes for jet-propulsion plants; heat or noise insulation

The combustion process is already a well-established process in terms of industrial application, and the associated use of OEC can already be found in the form of considerable research conducted in the area, as well as in technological development, such as the production of patents. Although newer and with little technological record, acoustic excitation can also improve the combustion process. Future trends in the use of acoustics associated or not with OEC have already been found in recent works that study its influence on the combustion of different gaseous and liquid fuels, e.g., jet flame, hydrogen–methane mixtures, biodiesel fuel blends, and other biofuels [17,65].

New energy routes can also be identified as potential energy sources, such as ammonia, known as "the other hydrogen" and, more importantly, industrial waste [81]. Biomass is another example of waste that already has relevant importance in the energy matrix, especially in the use of sugar and ethanol, paper, and cellulose production chains. Biomass residues are abundant in the agribusiness sector and can be used as energy sources subjected to the combustion process associated with OEC and acoustic excitation. Through gasification of biomass, synthesis gas (or syngas) is produced; its combustion is of interest in research because of its low GHG emissions. However, it also has a low energy-efficiency because of the reduced propensity to soot formation and, consequently, the low heat-transfer in the flame by thermal radiation [1]. Thus, this type of gas may be among the future fuel trends for which the application of OEC and acoustic excitation may benefit for possible technological applications.

The estimation through patents can also be identified, which reflects the novelty brought in this work in assisting companies and/or organizations in making decisions regarding technological development in this area. Based on the information presented, companies can identify opportunities and examine the risks associated with the development of new inventions in the area of combustion processes. Using information extracted from the patent research, along with marketing surveys, consumer analysis, and evaluation of internal production capacity, it is possible to boost the research and development process for the conception of new products to assist this industry [82].

With the exception of PCT protection, patents can only be protected at the place of registration, so countries that have not requested protection for a particular invention can make use of patent documents as a knowledge base to enhance their own processes. In addition, they can be used to find technological gaps, which can then be investigated, possibly leading to new discoveries [83]. For example, Germany and the United States were indicated in this prospection as the main depositing countries for the prospected technologies. Thus, this may direct other countries to base themselves on the technologies produced by them—either by absorbing the methodology or by identifying gaps that may be transformed into new opportunities—or even to consider them as potential markets for protection of their inventions, in view of the fact that these countries were also identified as the main markets for the prospected technologies. Companies can also make use of this information to monitor technological trends, such as in the areas identified in Figure 4, directing them to attend to technological areas that need greater investments and production of new technologies to improve combustion processes.

In general, the analysis and extraction of patent data can help obtain information to analyze and predict future trends of technological development, assisting in the decision making of companies [84,85].

4. Conclusions

The combustion process is a technique that is widely used in industrial sectors to obtain energy, and it can be measured by its participation in the world energy sector using different sources, including oil, natural gas, coal, or biomass. Based on the findings of this work, it was possible to observe that the OEC and acoustic excitation processes are relevant for promoting improvements in the combustion process, pointing to an important existence of technologies involving OEC and identifying acoustic excitation as a promising field to be explored. This is affirmed considering that, of the 88 patent documents found, most brought the application of OEC to the combustion process, and few brought the application of acoustic excitation to the process. However, the scientific literature points to the growth of research involving the study of this type of process, characterizing it as a trend for future patent filings.

The results also identified the main applicants of the technologies, as well as the main inventors, highlighting the company Siemens AG and Christian Paschereit, respectively. Besides these, the identification of other main players placed Germany and the United States as the main countries that deposited the technologies, as well as the main markets of application, with a total of 14 documents each and with market shares of 17.52% and 20.94%, respectively.

In terms of technological areas, the main highlights to which the technologies are directed were identified. These data in particular can contribute to the direction of investments in research on these processes associated with combustion, with identification of areas that may or may not be saturated, as well as those that present themselves as technological trends. Taken together, the information extracted from this technological research can be used in decision-making by companies that can direct their production based on the identification of the main areas and countries of interest. From this and other reported information, companies can be guided on the identification of technologies of interest and their use as a technological knowledge base for the development of their own inventions, as well as identifying gaps that can be transformed into new discoveries; moreover, it can contribute to the identification of market needs, which can be the focus of research and development of new inventions based on the application of OEC and acoustic excitation to the combustion process of different types of fuels, especially taking into consideration the importance for socioeconomic and sustainable development worldwide.

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