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## Review of cell performance in anion exchange membrane fuel cells

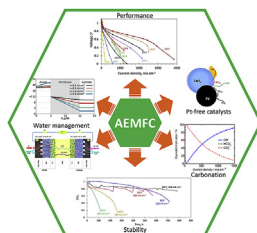
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### HIGHLIGHTS

- AEMFC performance reported in the literature is reviewed and summarized.
- New high records in AEMFC performance were achieved in the past three years.
- High power densities of 0.5 and  $>1 \text{ W cm}^{-2}$  (Pt-free and Pt catalysts) were achieved.
- Wide range of fuels exhibit promising cell performance in direct fuel AEMFCs.
- Performance stability is the major remaining challenge in AEMFCs.

### GRAPHICAL ABSTRACT



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### ABSTRACT

Anion exchange membrane fuel cells (AEMFCs) have recently received increasing attention since in principle they allow for the use of non-precious metal catalysts, which dramatically reduces the cost per kilowatt of power in fuel cell devices. Until not long ago, the main barrier in the development of AEMFCs was the availability of highly conductive anion exchange membranes (AEMs); however, improvements on this front in the past decade show that newly developed AEMs have already reached high levels of conductivity, leading to satisfactory cell performance. In recent years, a growing number of research studies have reported AEMFC performance results. In the last three years, new records in performance were achieved. Most of the literature reporting cell performance is based on hydrogen-AEMFCs, although an increasing number of studies have also reported the use of fuels others than hydrogen - such as alcohols, non-alcohol C-based fuels, as well as N-based fuels. This article reviews the cell performance and performance stability achieved in AEMFCs through the years since the first reports in the early 2000s.

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### 1. Introduction

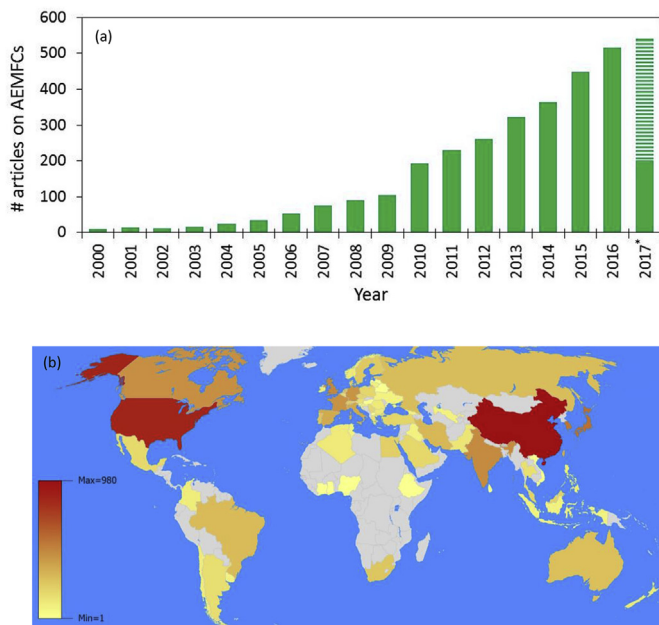
Anion exchange membrane fuel cells (AEMFCs) have been referred to in various ways in the research community. Most common terms found in the literature are alkaline membrane fuel cells (AMFCs) [1–7], solid (or solid-state) alkaline fuel cells (SAFCs)

[8–13], hydroxide exchange membrane fuel cells (HEMFCs) [14–15], alkaline polymer electrolyte fuel cells (APEFCs) [16–18], and polymer electrolyte alkaline fuel cells (PEAFCs) [19]. AEMFCs have recently gained significant interest and are a current focus in the fuel cell research community [20]. This is well illustrated in Fig. 1, which shows the number of publications in the AEMFC field since the year 2000. A continuous and rapid increase in the number of publications can be seen, particularly since 2010. More than 2000 publications were reported on this technology over the years, while

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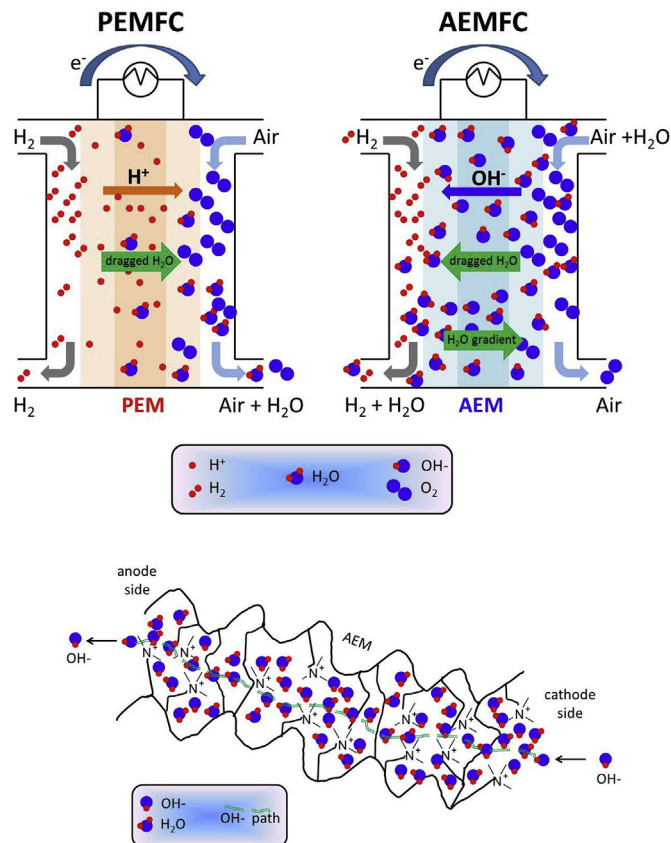
**Fig. 1.** Number of research articles published on AEMFCs (a), and their distribution according to their countries of origin (b). (Source: Web of Science. 2017\* is an estimation based on the number of articles published in the first months of the year).

the majority of them was recently published in just the past 5 years, showing that this technology is currently a blooming research area in fuel cell technology. Most of the studies in the AEMFC field have been carried out in different countries around the world, with the highest number of reports originating from China and the USA (see Fig. 1).

The increased number of studies in the past few years indicates a growing interest in the research community, driven by the several advantages of the AEMFC technology over the currently commercialized proton exchange membrane fuel cells (PEMFCs). Technically, AEMFCs are similar to PEMFCs, with the main difference being that the solid membrane is an alkaline AEM instead of an acidic PEM. With an AEM in an AEMFC, the  $\text{OH}^-$  anion is transported from the cathode to the anode, opposite to the  $\text{H}^+$  conduction direction in a PEMFC (see Fig. 2). Although in principle both technologies are similar, the use of an AEM creates an alkaline pH cell environment, and therefore, the AEMFC offers several potential advantages over the mature PEMFC technology. Among them, the following are particularly noteworthy:

- Enhanced oxygen reduction catalysis, allowing for the use of less expensive, Pt-free or precious group metal (PGM)-free catalysts;
- Extended range of cell and stack materials stable in the fuel cell environment;
- A wider choice of fuels in addition to pure hydrogen; and
- A wider range of less expensive polymer chemistry (fluorinated raw materials are not necessary).

As mentioned before, the use of an AEM in the fuel cell creates an alkaline environment inside the cell. Therefore, the AEM is the key differentiating element in the AEMFC device. AEMs are solid polymer electrolytes that conduct anions, such as  $\text{OH}^-$  and carbonate anions, as they contain positively charged cationic groups bounded to (or part of) a polymer backbone (see Fig. 2). Recent years have seen extensive research on the preparation and properties of AEMs. Numerous studies on new chemistries have been



**Fig. 2.** Schematic of an AEMFC as compared to a PEMFC (top scheme), and of an AEM based on a quaternary ammonium pendant functional group (bottom scheme).

reported. The different cationic functional groups and polymer backbones used in typical AEMs for fuel cells are well summarized in the literature [20–22]. Initially, most studies on AEMFCs focused on the development of suitable AEMs, and only a small subset of them reported data on cell performance and performance stability.

Before reviewing the state of the art in cell performance and performance stability, it should be remarked that in an AEMFC, ions and water are not transported in the same directions as in PEMFCs. During the operation of an AEMFC, when ambient air is used, several anions are present in the cell:  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ , and  $\text{OH}^-$ . However, in an AEMFC operated at high current densities, the most common anion species present across the membrane is the  $\text{OH}^-$  [23], generated according to the electrochemical oxygen reduction reaction (ORR) at the cathode:



The  $\text{OH}^-$  is transported to the anode where, if hydrogen is used as fuel, the following oxidation reaction takes place:



In the overall reaction, both PEMFC and AEMFC produce water as a byproduct. However, in contrast to PEMFC technology, in an AEMFC water is generated at the anode (twice as much as in a PEMFC, per electron), while at same time water is a reactant at the cathode. This distinctive water transport scenario, together with the high alkaline medium in AEMFCs, represent a unique feature of AEMFCs. Fig. 3 shows a schematic drawing of these transport characteristics in an AEMFC.

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