SMOLTEK

WHITEPAPER

INTRODUCING SMOLTEK
ELECTROLYZER TECHNOLOGY

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CVD-grown carbon nanofibers in water electrolyzers

Summary

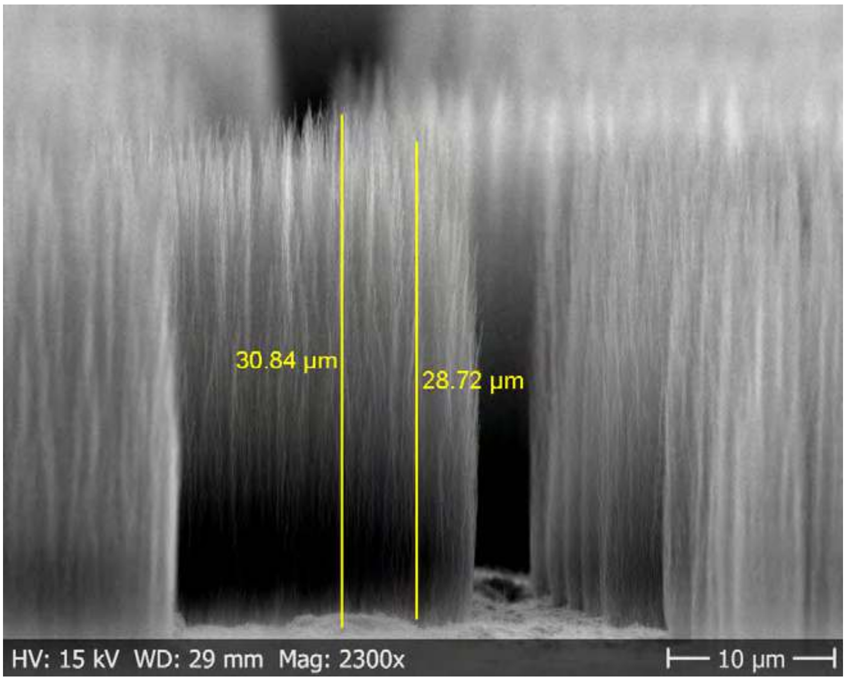
By using carbon nanofibers (CNF) grown by chemical vapor deposition (CVD) as a catalyst support, it is possible to increase the active catalyst surface area in membrane electrolyzers and decrease the required catalyst load. Smoltek, as a technology provider known for nanostructure fabrication technology, is using previous experience and know-how regarding CNF production in this area of application.

The demand for improved water electrolyzer technology can be expected to increase in the near future. Producing hydrogen through electrolysis has been put forward as a key method for storing surplus electricity from intermittent, renewable sources in the form of chemical energy. Simultaneously, the demand for sustainably produced hydrogen is increasing in e.g., the steel industry. In view of this rising demand, there is an urgent need to solve issues related to existing electrolyzer technologies.

Low-temperature membrane electrolyzers, especially those using proton exchange membrane (PEM) electrolytes, are of particular interest as they avoid both the use of a liquid electrolyte as used in conventional alkaline electrolyzers and the high operation temperatures seen in solid oxide electrolyzers. However, PEM water electrolyzers require the use of platinum group metals as catalysts; usually platinum on the cathode side and iridium, in the form of iridium oxide, on the anode side. Ensuring that these expensive catalysts are used efficiently and reducing the necessary catalyst load is a challenge for PEM electrolyzer development.

A key component in this context is the catalyst support, which serves as a scaffolding on which nanoparticle catalysts can be dispersed as well as to electrically connect the catalyst material to the diffusion layer and separator plates. Carbon materials are already used for this purpose on the cathode side of PEM water electrolyzers, but CNF and especially CVD-grown CNF have a number of additional advantages.

The CVD fabrication process enables the production of vertically aligned CNF with a well-defined average spacing, width and height, which gives a high degree of control over the structure of the resulting catalyst support. By selectively coating parts of the fibers with catalyst particles, this also results in improved control of the position of the catalyst particles, which makes it possible to optimize the active catalyst surface area and reduce catalyst load. The regular structure of CVD-CNF is expected to improve mass transport through the catalyst layer and facilitate the application of corrosion-resistant coatings such as titanium, which render the nanofibers more useful also on the anode side of a PEM water electrolyzer.

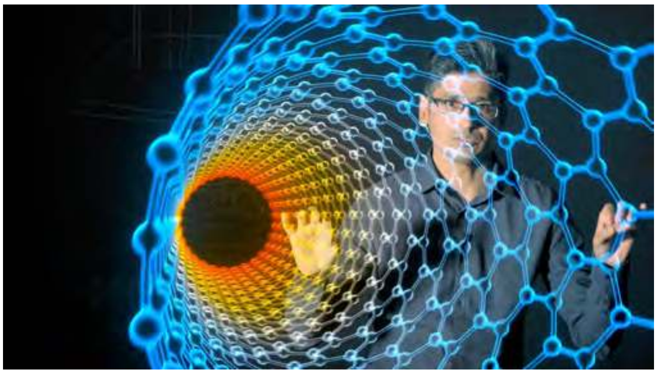


Vertically aligned carbon nanofibers, grown by Smoltek.

Introduction: Green energy, steel, and hydrogen

As countries strive to reduce their dependence on fossil fuels and to lower greenhouse gas emissions, more renewable energy sources such as solar, water, and wind power are being introduced. The intermittent nature of these energy sources creates a demand for energy storage solutions, so that an excess of electricity produced under windy or sunny conditions can be stored and used at a later time. A recent report published by the European Commission mentions storage methods such as batteries and pumped-hydro storage. However, it also proposes that storing the excess as chemical energy through electrolysis of water, producing hydrogen, is important for reaching long-term goals [1]. Fuel cells can then provide an efficient method for converting the stored chemical energy back into electricity.

Production of hydrogen through electrolysis of water, rather than from fossil fuels, is also important for reducing the carbon footprint of industries such as steel production. Replacing current production methods with direct reduction of iron ore using hydrogen gas could reduce greenhouse gas emissions by as much as 90 % [2], but requires significant amounts of sustainably produced hydrogen. Companies around the world are dedicating research and development efforts to implementing this method [3], [4]. For example, in Sweden the steel production company SSAB, the mining company LKAB and state- owned energy company Vattenfall collaborate on technology development in the HYBRIT project [5], [6].



Together, the demand for energy storage solutions and the need for hydrogen gas in industry point towards an increasing demand for water electrolyzer technology in the near future. However, existing electrolyzer technology is associated with issues relating to corrosive electrolytes and the need to reduce the amount of expensive noble-metal catalysts. Due to these issues, innovations in electrolyzer technology are very likely to be of high interest.

Among existing electrolyzer types, proton exchange membrane (PEM) electrolyzers typically show the highest production rates per unit area with current densities of 1-2 A/cm2, and current densities between 6 and 10 A/cm2 have been demonstrated in experimental cells even with low catalyst load [7], [8].

As a technology provider known for cutting-edge nanostructure fabrication technology, Smoltek has previously developed devices for the semiconductor and electronics industries [9]. Now, we reuse the same technology with the aim of modernizing hydrogen gas production and using carbon nanostructures to improve electrolyzer productivity. Carbon nanostructures enable a higher degree of control over the position of the catalyst particles and allows for optimization of the active surface area, leading to increased productivity and/or reduced need for expensive catalysts.

Structure of the whitepaper

The first section of this whitepaper provides an introduction to water electrolysis and an overview of available electrolyzer technologies. Some challenges associated with existing methods are also discussed, particularly those that are relevant to membrane electrolyzers. (pages 4-10)

The last section introduces carbon nanofibers and discusses some of the fabrication techniques developed by Smoltek, as well as expected outcome in terms of the properties of the grown carbon nanofibers. This is followed by a discussion of how carbon nanofibers can be used in electrolyzers and how they can be expected to improve on existing solutions. Finally, the last section offers a summary and outlook. (pages 11-15)

Water electrolysis

On a basic level, all water electrolyzer cells include two electrodes, a positively charged anode and a negatively charged cathode, as well as an electrolyte. The electrodes are connected to a DC power source that maintains an electrical current through the cell, thereby supplying the energy that drives the reaction. The overall electrochemical reaction taking place in a water electrolyzer is

$$\mathbf{H_2O \rightarrow H_2 + \frac{1}{2}O_2,}$$

with hydrogen gas being generated at the cathode and oxygen gas at the anode [10]. The cathode reaction is also frequently referred to as the hydrogen evolution reaction, or HER, while the anode reaction is referred to as the oxygen evolution reaction, OER.

Water electrolyzers can be divided into traditional alkaline electrolyzers and ion exchange membrane electrolyzers. The electrolyte and the materials used in the electrodes differ depending on the type of electrolyzer and at what pH and temperature the electrolysis is performed. In most electrolyzers, electrocatalysts are used to lower the energy barrier for the electrochemical reactions.

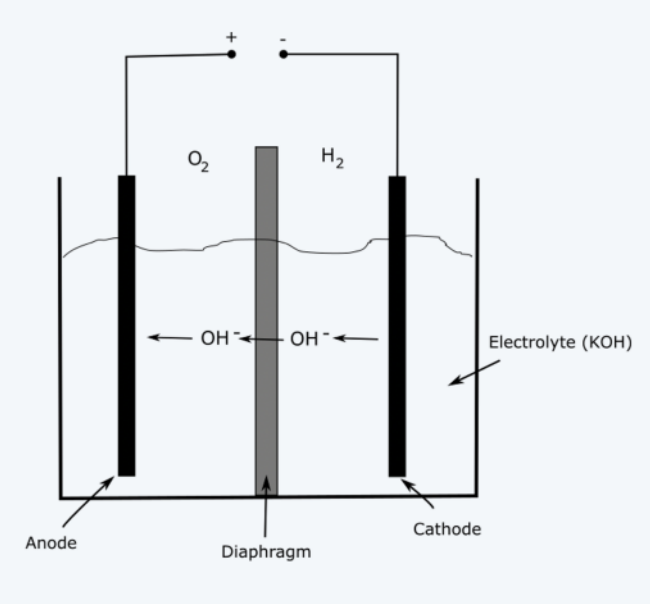


Figure 1: Schematic of an alkaline electrolyzer.

Alkaline electrolyzers

Alkaline electrolysis has historically been the most common water electrolysis method [10]. Alkaline electrolysis uses a liquid electrolyte, typically a solution of water and potassium hydroxide or sodium hydroxide, in which the electrodes are submerged as illustrated in figure 1. The electrochemical reactions take place at the electrode surfaces, with the cathode reaction being

$$\mathbf{2H_2O + 2e^- \rightarrow H_2 + 2OH^-,}$$

and the anode reaction being

$$\mathbf{2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-.}$$

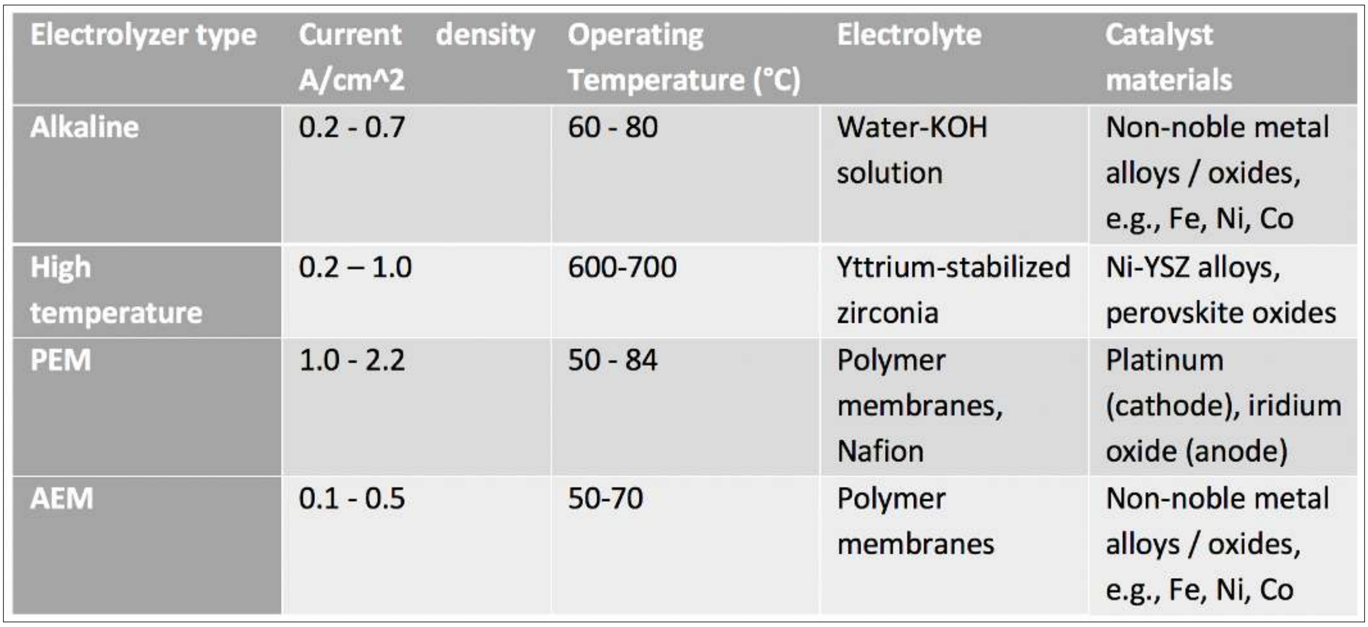
In alkaline electrolyzers it is possible to use cheap and abundant materials such as nickel and stainless steel in the electrodes, sometimes coated with additional electrocatalysts that facilitate the chemical reactions taking place at the electrode surface. The catalysts are usually also based on non-noble metals such as nickel, iron or zinc, often in the form of alloys or oxides [11] [12]. The electrolyzer cell is divided into an anode side and a cathode side by a diaphragm that separates the hydrogen and oxygen gases produced in the reaction, while still allowing passage of hydroxide ions from the cathode to the anode. The diaphragm often consists of a porous ceramic or polymer material [11].

Alkaline electrolysis is a mature technology, but it also has some known drawbacks. For example, the liquid electrolyte is associated with losses connected to its specific conductivity. Lately, this problem has been mitigated by using so-called zero-gap designs, where the electrodes are situated in contact with either side of the diaphragm [12]. Alkaline electrolysis also requires the handling of substantial amounts of strongly alkaline electrolyte.

Ion exchange membrane electrolyzers

In ion exchange membrane electrolyzers, the liquid electrolyte is replaced by an ionically conducting solid electrolyte or membrane. Rather than merely being a porous material, like the diaphragm in an alkaline electrolyzer, the membrane selectively conducts one type of ion, which allows for a more efficient separation of the two sides of the electrolyzer and of the product gases [10]. Additionally, although in some ion exchange membrane electrolyzers the reactions still occur at a high pH, the required volume of alkaline solution is reduced and the electrolyzer design can be made more compact.

Ion exchange membrane electrolyzers can be categorized according to their operation temperature and according to which ionic species is conducted by the membrane. Operation temperatures in existing electrolyzers fall either in the high-temperature range above 600 °C, where oxides such as yttrium-stabilized zirconia can be used as ionic conductors, or below 100 °C where hydrated polymer membranes such as Nafion® can be used.



Electrolyzer type	Current density A/cm^2	Operating Temperature (°C)	Electrolyte	Catalyst materials
Alkaline	0.2 - 0.7	60 - 80	Water-KOH solution	Non-noble metal alloys / oxides, e.g., Fe, Ni, Co
High temperature	0.2 – 1.0	600-700	Yttrium-stabilized zirconia	Ni-YSZ alloys, perovskite oxides
PEM	1.0 - 2.2	50 - 84	Polymer membranes, Nafion	Platinum (cathode), iridium oxide (anode)
AEM	0.1 - 0.5	50-70	Polymer membranes	Non-noble metal alloys / oxides, e.g., Fe, Ni, Co

Table 1: Summary of electrolyzer types. Data from [13], [14], [15]

High temperature electrolyzers have the advantage of being less dependent on efficient catalysts, as the increased operation temperature reduces the activation potential for the electrolysis reactions.

However, the high temperature leads to degradation of the component materials and longer startup times, making this type of electrolyzer less well suited for applications that makes use of intermittent power sources [10], [16]. Here, the focus will therefore be on low temperature electrolyzers. However, it should be noted that water electrolysis in the intermediate temperature range, between 100 and 600 °C is a topic of ongoing research [10], [17]. So far, no electrolyzers in this temperature range appear to have been commercialized.

Proton exchange membrane electrolyzers

Proton exchange membranes (PEM) are well established as electrolyte materials for low-temperature fuel cells. The most well-known is sulfonated tetrafluoroethylene, also known as Nafion® [10], although alternative polymer membranes are commercially available and also a topic of research (see, e.g., [18]). Generally, PEM become proton-conducting upon absorbing liquid water, which limits the operation temperature to below 100 °C.

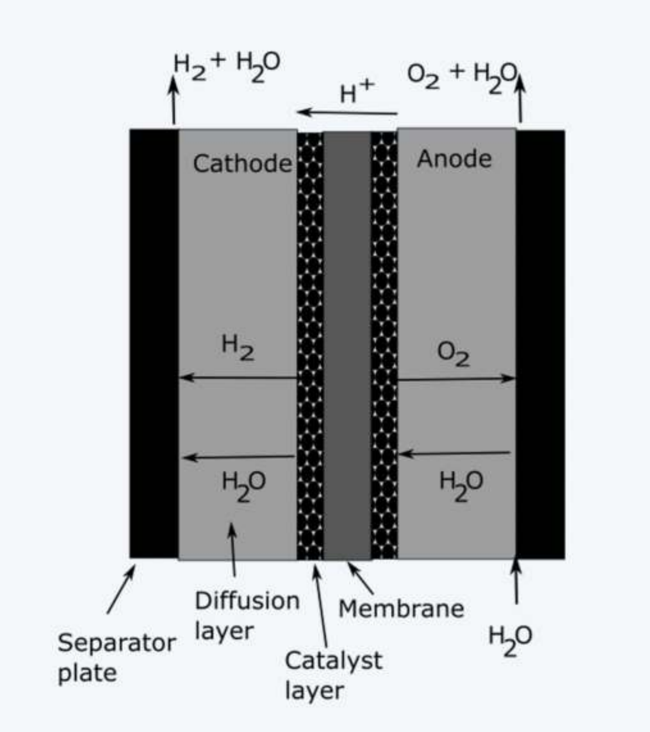


Figure 2: Schematic of a PEM electrolyzer.

In a PEM electrolyzer, illustrated in figure 2, the electrolysis reaction takes place under acidic rather than alkaline conditions. Under these conditions, the anode reaction becomes:

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^-.$$

The protons traverse the membrane and undergo the cathode reaction:

$$4H^+ + 4e^- \rightarrow 2H_2.$$

Electrolysis under acidic condition is associated with a higher potential barrier compared to electrolysis under alkaline conditions. Thus, for the reaction rate to be high enough, more efficient catalysts need to be used. The catalysts also need to be chemically stable in the acidic environment. Currently, the most common anode-side catalyst is iridium oxide, IrO2, while platinum is typically used on the cathode membrane electrolyzers (see summary in Table 1), but platinum and iridium are also more expensive than the catalyst materials used in other electrolyzer types. Thus, a significant amount of research and development effort in both academia and industry is directed to reducing the necessary catalyst load and/or finding alternative catalysts [19], [20].

Anion exchange membrane electrolyzers

Anion exchange membrane (AEM) electrolyzers, illustrated in figure 3, can also be considered as alkaline electrolyzers with a zero-gap design, using a membrane that selectively conducts hydroxide ions instead of a conventional diaphragm. The AEM is typically a polymer membrane, consisting of e.g., polysulphones or polyphylene oxides, with cation groups attached to the polymer chain backbone. As is the case for PEM, the AEM needs to absorb liquid water in order to act as ionic conductors [15].

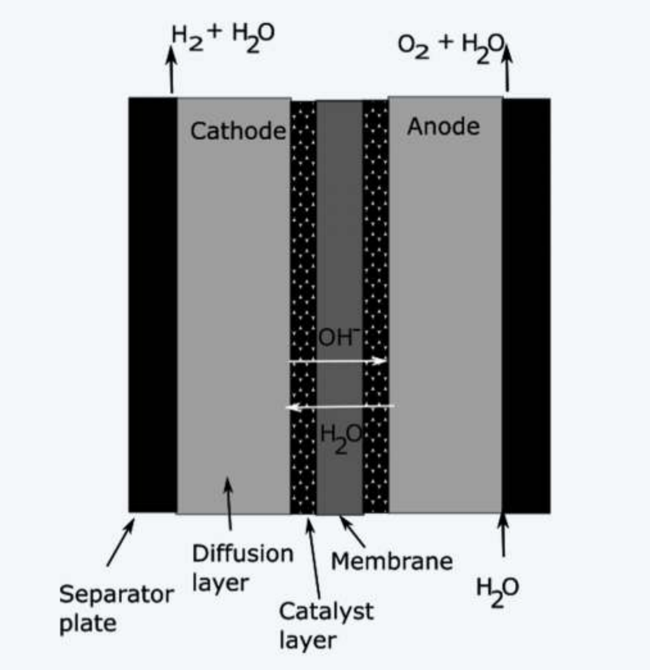


Figure 3: Schematic of a AEM electrolyzer.

AEM electrolyzers retain many of the advantages associated with alkaline electrolysis, such as the possibility of using alloys or oxides of non-noble metals as catalysts, with the additional advantage of improved separation of the product gases that comes with using an ionically conducting membrane in the place of a liquid electrolyte [10]. However, existing AEM materials are not sufficiently chemically stable for long-term use, limiting the lifetime of electrolyzer cells to only around 1000 h [15]. Compared to proton exchange membrane electrolyzers, which operate at similar temperatures, AEM also show lower current densities (see Table 1).

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Membrane electrolyzer cell design

The use of a membrane rather than a liquid electrolyte requires changes to the design of the electrolyzer cell. Examples of this can be seen in figure 2 and figure 3, which show schematic depictions of PEM and AEM electrolyzers, respectively. In both cases, the membrane is in close contact with catalyst layers on both the anode and the cathode side. Further away from the membrane there is a material known as the current collector, porous transport layer, or gas (and/or liquid) diffusion layer. This is followed by the conducting plates, which are also sometimes referred to as separator plates or flow plates. In systems where multiple electrolyzers are connected in series the conducting plate serves as part of the cathode for one electrolyzer cell and part of the anode for an adjacent electrolyzer cell, in which case it is often referred to as a bipolar plate [15], [21].

The electrochemical reactions in the cell take place at the catalyst surface and optimizing the reaction rate therefore places a number of requirements on the catalyst layer and its connection to other parts of the cell. Firstly, water must be able to reach the anode-side catalyst and gases (hydrogen or oxygen depending on the electrode) must be electrically connected to the power source, which among other things requires the contact resistance between catalyst layer and the diffusion layer and between the diffusion layer and the separator plate to be low.

The electrochemical reactions take place at the catalyst surface but depending on the structure of the catalyst layer only part of the catalyst surface may contribute. For the reactions to proceed efficiently the catalyst surface must be in contact with both the membrane, allowing ion transport to or from the catalyst, and the surrounding water and gas that allows for transport of reactants and products. This is sometimes described as the reaction occurring at the three-phase boundary between membrane, water, and catalyst. The surface area where these conditions are met is the active catalyst surface area, and the catalyst layer needs to be structured to make it as large as possible. Like all components of the electrolyzer cell, the catalyst layer must also be chemically stable [15], [19], [21].

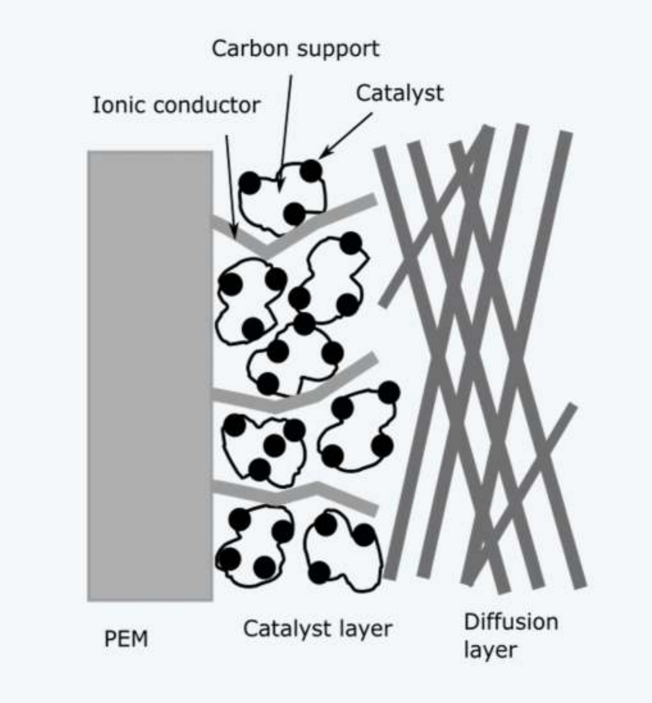

Figure 4: Catalyst particles on carbon support.

In practice, catalyst layers often contain nanoparticles of the catalytically active material, such as platinum or iridium oxide, either unsupported or dispersed on a porous, electrically conducting catalyst support such as carbon black or a titanium mesh [19], [21]. Thin films of catalytically active material sputtered onto nanostructured supports may also be used [20]. The catalyst is often mixed with an ionically conducting polymer in order to improve the transport of ions to and from the catalyst particles. Usually, the membrane and the catalyst layers are fabricated together in what is known as a membrane-electrode assembly (MEA).

Catalyst supports used today, such as carbon black, typically have an irregular porous structure (see Figure 4). However, more regular nanostructured supports made from nanowires, nanowhiskers, nanofibers, and nanotubes have been considered [19], [20], [22]. A catalyst support with a more regular structure can enable better control over the placement of the catalyst, leading to better contact between the catalyst and the membrane.

The layer between the conductive plate and the catalyst layer, known as the diffusion layer or the current collector, faces a similar set of requirements, except for the need for ionic conductivity. The diffusion layer serves to connect the catalyst layer to the conductive plate in order to allow electric current to flow between the power source and the catalyst, while also allowing mass transport of the reactants and products of the electrolysis reaction, i.e., water, oxygen, and hydrogen. It can also serve as a heat conductor and as a mechanical support for the MEA. Carbon paper or carbon felt are often used on the cathode side, while porous metal structures are more often used on the anode side due to the harsher chemical conditions. In PEM cells this often means a titanium mesh, while in AEM cells the anode-side diffusion layer may be a nickel foam [15], [21].

As previously mentioned, the contact resistance between the diffusion layer, the conductive plate and the catalyst should be kept low in order to reduce Ohmic losses in the cell. This can particularly be a problem on the anode side of PEM electrolyzers, as the titanium used in the diffusion layer forms an electrically insulating oxide layer on the surface. The oxide layer protects the remaining metal from the harsh environment but also increases the contact resistance. Attempts to mitigate this problem include both altering the structure of the diffusion layer and introducing new surface treatments for the porous titanium structure [23], [24], [25].

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For PEM and AEM electrolyzers, the mass transport problem is compounded by the fact that the incoming water is a liquid, while the produced hydrogen and oxygen are gaseous. Thus, gas bubbles may form in the catalyst and/or diffusion layers on the anode side, and conversely water droplets may form on the cathode side. Gas bubbles in particular can block mass transport and, if they remain on the catalyst surface, reduce the amount of available catalyst surface area in the cell [26], [27].

The void fraction and pore size of the catalyst support and gas diffusion layer strongly influence the formation and movements of bubbles. It has also been observed that the pore shape is important for bubble transport, leading to a tradeoff between maximizing the surface area in the catalyst support and ensuring pore size and shape do not interfere with bubble transport [28]. Recently, catalyst layers containing 1D nanostructures such as nanowires, nanorods or nanofibers have been found to offer more efficient mass transport than conventional structures, particularly when it comes to gas bubbles [29], [30]. Periodic catalyst layers formed from 1D nanostructures can be designed with more efficient channels for gas transport compared to conventional porous materials.

Challenges in low-temperature membrane electrolyzers

PEM and AEM electrolyzers are promising alternatives in the search for a way to convert excess electrical energy into a more easily stored form, such as hydrogen. However, there is room for improvement in today's systems. For AEM, the main obstacle appears to lie in the chemical stability of ion exchange membranes, while for PEM the main challenge is tackling the need for expensive catalyst materials either by reducing the necessary catalyst load or by finding alternatives. In both PEM and AEM electrolyzers, it is also important to develop catalyst and diffusion layers that allow for improved mass transport while maintaining good electrical conductivity and low contact resistance between components.

Developing better catalyst supports is crucial both to reducing the necessary catalyst load in PEM cells and for improving mass transport. Nanostructured catalyst supports with a regular structure could both improve control over the position of the catalyst relative to the membrane and the gas and water transport properties of the catalyst layer.

Carbon nanofibers in water electrolyzers

As seen in the previous section carbon materials such as carbon black and carbon paper are used in catalyst and diffusion layers, especially on the cathode side of electrolyzer cells, due to their electrical conductivity and relatively low price. To solve the remaining problems related to electrolyzer electrodes, however, a different type of carbon material may be needed.

Carbon nanofibers (CNF) are elongated carbon nanostructures with diameters between 1 and 100 nm and lengths from 0.1 to 100 µm [31]. Although CNF can be produced in multiple different ways, such as through electrospinning [32] or from bio-carbon, the focus here will be on vertically aligned CNF grown through chemical vapor deposition (CVD). Smoltek has previously developed and patented cutting-edge CVD-based CNF production methods [9].

CVD-grown carbon nanofibers

Chemical vapor deposition is a fabrication method where a precursor, typically a gas, is deposited on a substrate. On the substrate, it undergoes a reaction to form the fabricated material. One type of CVD that is particularly suitable for growing CNF is plasma-enhanced CVD or PECVD. In PECVD, a carbon-containing gas such as methane or acetylene, known as the process gas, is introduced into the reactor along with an inert gas [33]. In the reactor gases are converted into a plasma, e.g., using AC or DC discharge between two electrodes as shown schematically in figure 5. From the plasma, carbon is deposited on the substrate.

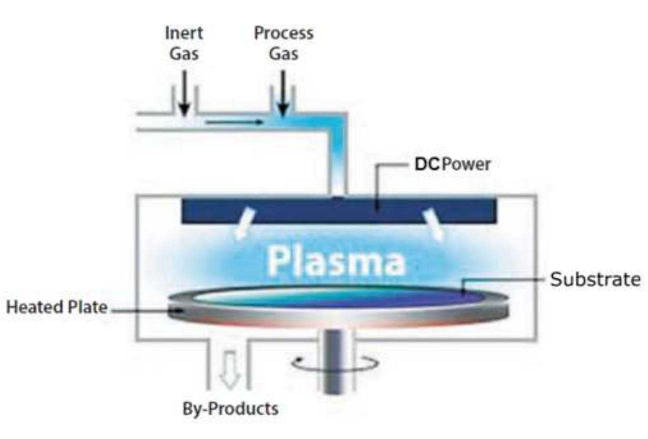


Figure 5: Schematic depiction of PECVD reactor.

In order for CNF to form, a catalyst must be present on the surface of the substrate. Common catalyst materials are nickel, iron, cobalt, and palladium. The catalyst can be deposited in the form of a uniform layer, or it can be patterned using lithographic techniques. The catalyst may also be deposited in the form of nanoparticles, e.g., through spin-coating. If the catalyst is not already in the form of nanoparticles as it is deposited, it will form nanoparticles on the substrate through a process known as de-wetting (see Figure 6). During the CVD process, carbon will be deposited on the catalyst particles and diffuse across the surface, eventually forming nanofibers. Depending on parameters such as the size of the catalyst particle and the interaction between the catalyst and the substrate, the CNF will display either base growth or tip growth. During base growth, the CNF will grow upwards from the catalyst particle, which remains on the substrate. During tip growth the CNF will grow underneath the catalyst particle as illustrated in figure 6 [33].

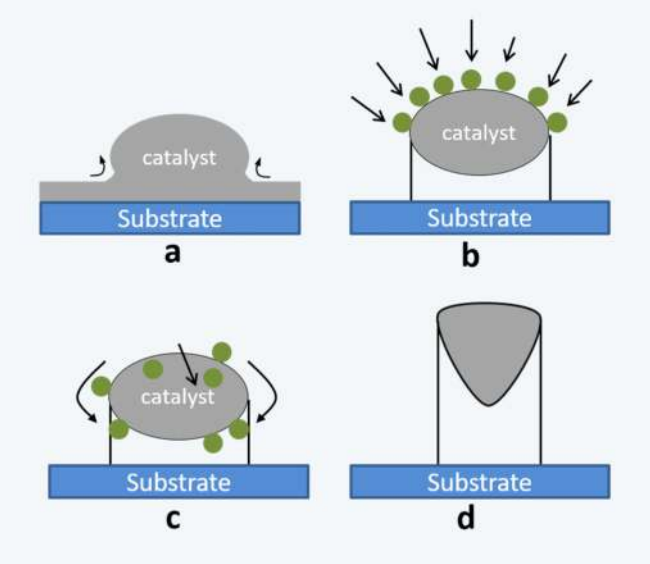
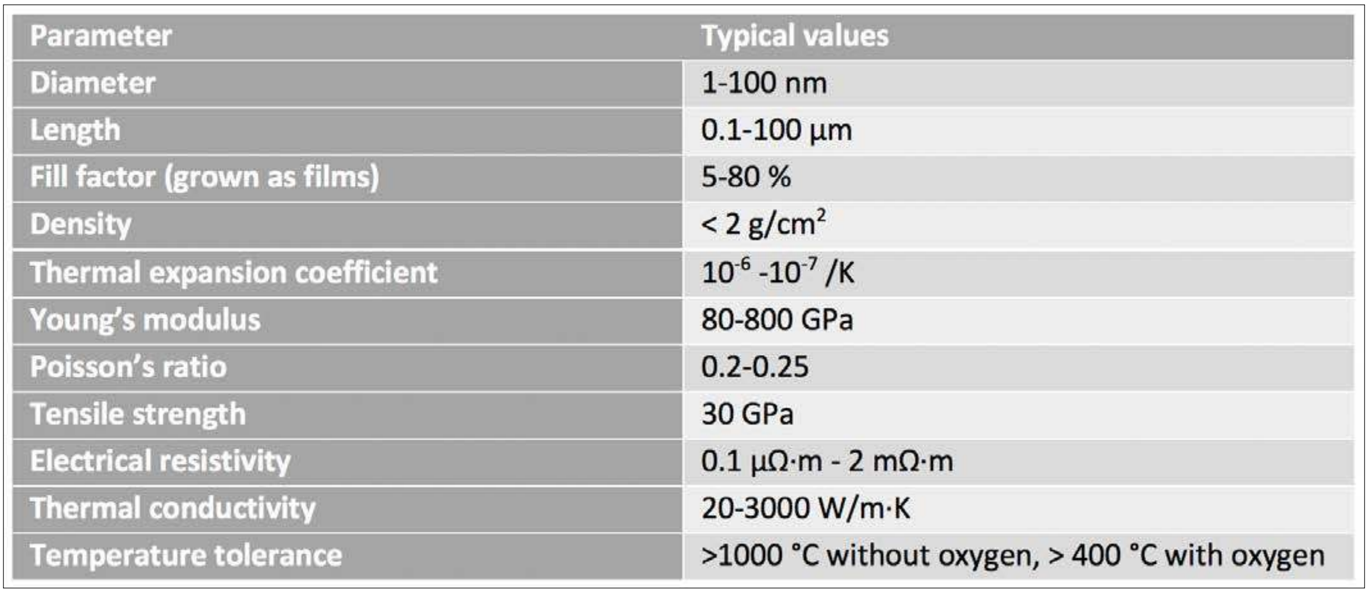


Figure 6: Tip growth of CNF. The catalyst layer forms nanoparticles (a), upon which carbon adsorbs (b) and diffuses (c), finally forming a CNF with the catalyst particle at the tip (d). Image from [31].

Using PECVD to grow CNF has several advantages. Unlike many other types of CVD, PECVD can be performed at temperatures down to around 350 °C, making it possible to grow CNF on substrates that cannot tolerate higher temperatures. PECVD can be used to produce vertically aligned CNF, which extend mostly perpendicularly from the substrate as seen in figure 6. Also, by using a patterned catalyst it is possible to control the spacing between the nanofibers. Thus, it is possible to grow an array of nanofibers with relatively well-defined widths and heights and a desired spacing between the fibers. Other properties of CVD-grown CNF, such as mechanical properties and electrical resistivity, will vary depending on the exact growth conditions (see Table 2).



Parameter	Typical values
Diameter	1-100 nm
Length	0.1-100 µm
Fill factor (grown as films)	5-80 %
Density	< 2 g/cm^2
Thermal expansion coefficient	10^{-6} -10^{-7} /K
Young's modulus	80-800 GPa
Poisson's ratio	0.2-0.25
Tensile strength	30 GPa
Electrical resistivity	0.1 µΩ·m - 2 mΩ·m
Thermal conductivity	20-3000 W/m·K
Temperature tolerance	>1000 °C without oxygen, > 400 °C with oxygen

Table 2: Typical properties of PECVD-grown CNF, from [31].

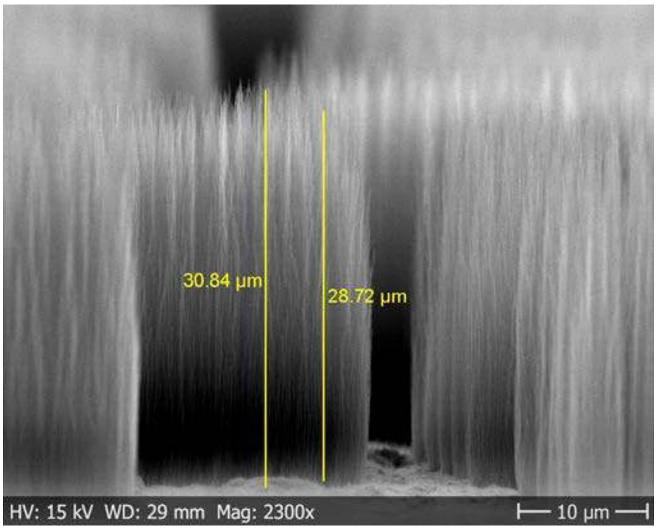


Figure 7: SEM image of vertically aligned carbon nanofibers, around 30 µm in length, grown by PECVD.

The rate of growth of CNF also depends on a number of growth parameters and on the catalyst used. The CNF length, choice of materials and geometrical precision also influence the production rate. Increased focus on process development for scale up are expected to further speed up the growth.

Application in electrolyzers

Comparing the properties of PECVD-grown carbon nanofibers with the previous discussion on membrane electrolyzers, it is clear that carbon nanofibers fulfil several of the requirements of good catalyst support and diffusion layer materials.

Resistivity and contact resistance

As can be seen in Table 2, PECVD-CNF have low electrical resistivity, as is required for both catalyst support and diffusion layer materials. Additionally, they may be useful for reducing the contact resistance between adjacent components in the electrolyzer cell. Previous studies on separator plates in fuel cells, which face similar requirements, have shown that CVD-grown carbon nanofibers can reduce contact resistance [34]. PECVD-CNF grown on either a separator plate or the material of the diffusion layer may thus improve the electrical contact between the catalyst and the power source.

Surface area, catalyst placement, and mass transport

An existing application of PECVD-CNF is in supercapacitors, where they function as electrodes with high surface area as previously demonstrated by Smoltek [31], [33], [35]. High surface area is also relevant in the context of electrolyzer electrodes, particularly for the catalyst support. In membrane electrolyzers, the catalyst particles and catalyst support are frequently mixed with ionically conducting material to improve ion transport as previously described [19], [21]. With PECVD-CNF as catalyst support, the tips of the CNF can be embedded in the ion exchange membrane, resulting in a large active surface area or three-phase boundary, where the catalyst is in good contact with the membrane (see Figure 8). This can aid in reducing the necessary catalyst load, particularly on the anode side of PEM water electrolyzers where high catalyst loads are common.

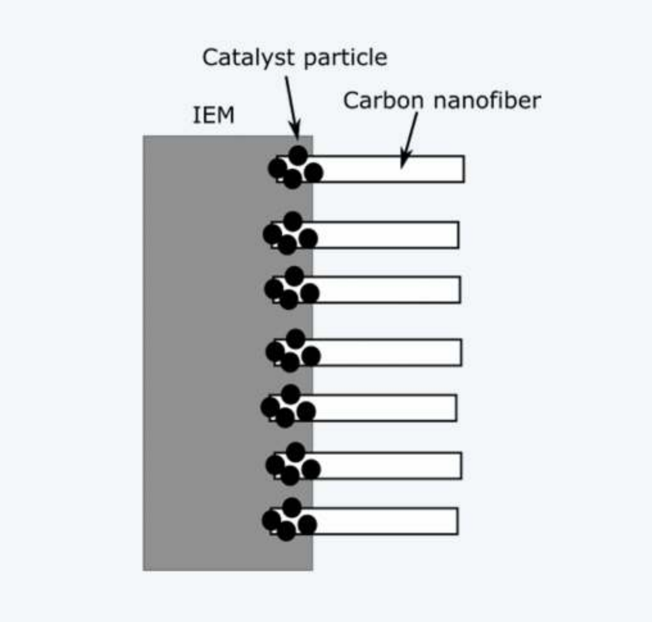


Figure 8: Schematic of carbon nanofiber tips embedded in ion exchange membrane (IEM).

Using vertically aligned PECVD-CNF as catalyst supports also gives better control over the position of the electrocatalyst particles. If the tips of the CNF are selectively coated with catalyst particles, or even if the catalyst used for growing the CNF is also useful as an electrolysis catalyst, positioning the tips of the CNF either at the surface of the ion exchange membrane or embedded in the ion exchange membrane ensures good contact between the catalyst and the membrane. This leads to an efficient use of the available catalyst and enables the use of a lower catalyst loading (patent pending, see [36]).

The regular structure that can be achieved with a catalyst support made from vertically aligned PECVD-CNF may also improve mass transport. As previously mentioned, recent studies have shown improved mass transport in catalyst supports with regular structures made from nanowires or nanofibers [29], [30], particularly on the anode side where the problem of gas bubbles in water blocking the transport may occur. PECVD-CNF form such a regular structure, with the advantage that the nanofiber spacing can be precisely controlled during manufacture. This makes it possible to optimize both the void fraction and the size of the voids in such a catalyst support material.

Corrosion resistance and coatings

One reason for carbon materials such as CNF being used in catalyst supports is their chemical stability even under harsh conditions [10]. PECVD-grown CNF can be expected to show adequate chemical stability under conditions where carbon cloth or carbon black are used today, such as at the cathode side of an electrolyzer cell [19], [21].

PECVD-grown CNF can also be coated with layers of even more chemically stable materials such as titanium, for example through atomic layer deposition [35], [37]. This enables the use of PECVD-CNF structures also on the anode side of water electrolyzer cells, where the chemical conditions typically require using metals or metal oxides in catalyst supports and diffusion layers [19], [21].

Conclusions

Although electrolyzer technology is of high interest in the search for efficient energy storage solutions, there are improvements to be made to lower initial investment costs and render the technology more efficient in terms of produced hydrogen per cell area. This is especially the case for low-temperature membrane electrolyzers such as PEM electrolyzers, which thanks to their low operating temperature are suitable for handling of excess electricity from intermittent power sources.

Such improvements to electrolyzer technology are likely to require innovation regarding the materials used. CNF are attractive for electrolyzer applications due among other things to their electrical conductivity and the high degree of control over their orientation and spacing provided by the PECVD production method. In particular, PECVD-CNF show promise when used as a catalyst support, where they can provide improved control over catalyst placement and a large active catalyst surface area.

Smoltek as a company possesses both technology and know-how regarding CNF production and experience from industrialization of nanofabrication technologies in the semiconductor and electronics industries and is therefore well placed to realize the promises of PECVD-CNF in electrolyzer technology.

For PEM electrolyzers, a main challenge is improving the efficiency of the anode-side catalyst. PECVD-CNF are promising in this regard, provided that they can be rendered sufficiently chemically stable. Thus, future efforts will include demonstrating the efficacy of titanium and other coatings in achieving this, as well as showing the hydrogen and oxygen production rate achievable with a PECVD-CNF catalyst support.

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