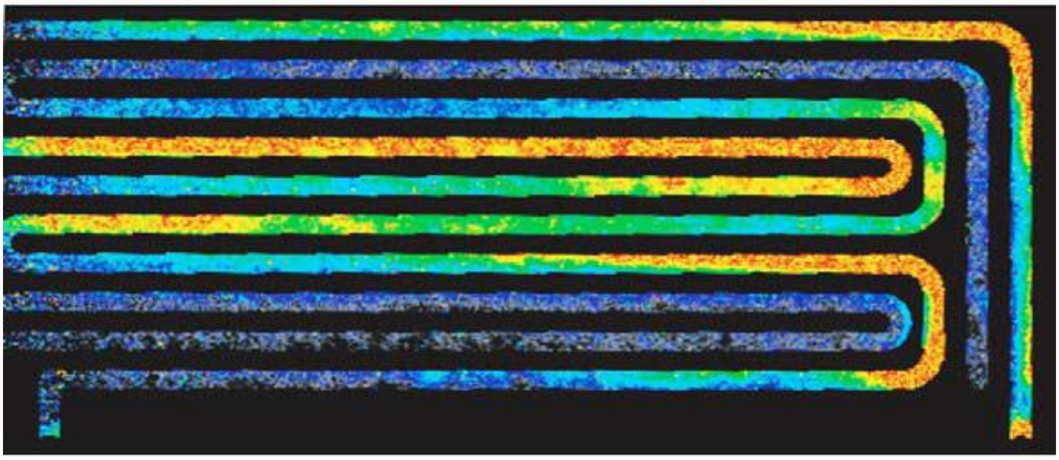
Neutron imaging in fuel cells research

Polymer electrolyte membrane (PEM) fuel cells produce electrical energy directly from hydrogen. With high efficiencies reaching 60% in electrical energy conversion and 80% including thermal energy, the only byproduct of PEM fuel cells is water, leading to a major reduction in pollutant emissions when compared to traditional fuels. Another advantage of PEM fuel cells is that they operate at low temperatures, high power densities, their construction can be scaled up from the lab to industrial scale, and they are fairly light (Wang et al., 2011). No wonder that they are actively researched as an alternative to fossil fuels in transportation, and in fact PEM fuel cells are the choice (see e.g. US Department of Energy) for use in most fuel cell vehicles demonstrated or commercialized.

PEM fuel cells are also used in stationary and portable power supply systems, and in fact in 2014 65% of fuel cell units sold were stationary systems for home use or for larger prime power systems (for instance in critical applications such as power supply of computer systems used in the financial sector), and 31% were portable systems used in a wide range of applications (The Fuel Cell Industry Review 2014). Only 4% were power systems for electrical vehicles, although several major car makers have started selling mass-produced fuel cell electrical vehicles (FCEV) between 2013 and 2015.

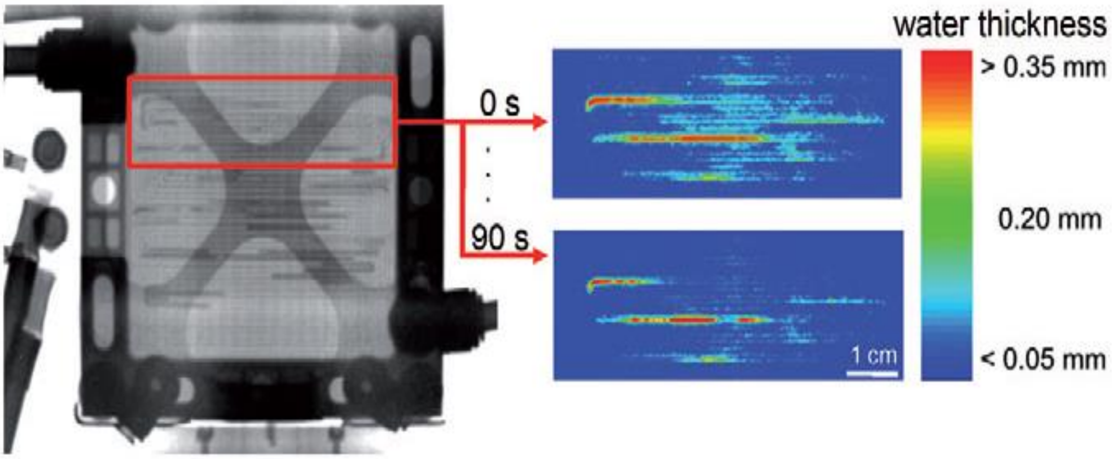
Cost and lifetime of PEM fuel cells are still barriers to their widespread use and commercialization. One of the critical factors for performance and durability of PEM fuel cells is to avoid flooding of the electrodes with the water generated as a byproduct, but fuel, reactant, and byproduct transport is not well understood.

Neutrons are highly sensitive to hydrogen, and therefore to water. X-rays, on the contrary, are almost insensitive to hydrogen and also to oxygen in systems that contain heavier elements such as metals. Satija et al. pioneered in 2004 the use of neutron imaging to perform in situ non-destructive analysis on an operating PEM fuel cell. They collected a real time radiography consisting of 1000 images taken at 2 second intervals, showing water production, transport, and removal through the cell. They observed water forming on the cathode side as expected (see figure below), but also that some water crossed the PEM and was collected at the hydrogen flow channels on the other side. This first use of neutron radiography in the study of PEM fuel cells demonstrated the extraordinary power of the technique.



Water in the cathode side of a fuel cell.
Figure credit Satija et al., 2004.

Manke et al. (2008) used the difference in neutron attenuation by hydrogen and deuterium, its heavier isotope: deuterium (D) interacts much more weakly with neutrons than hydrogen, and so, heavy water (D_2O) is almost transparent to neutrons, while normal water is a strong neutron absorber. By switching the fuel supply from hydrogen to deuterium, the cell starts to produce heavy water, and water exchange processes inside the fuel cell can be followed. This provides unique information, useful to develop water transport and diffusion models.



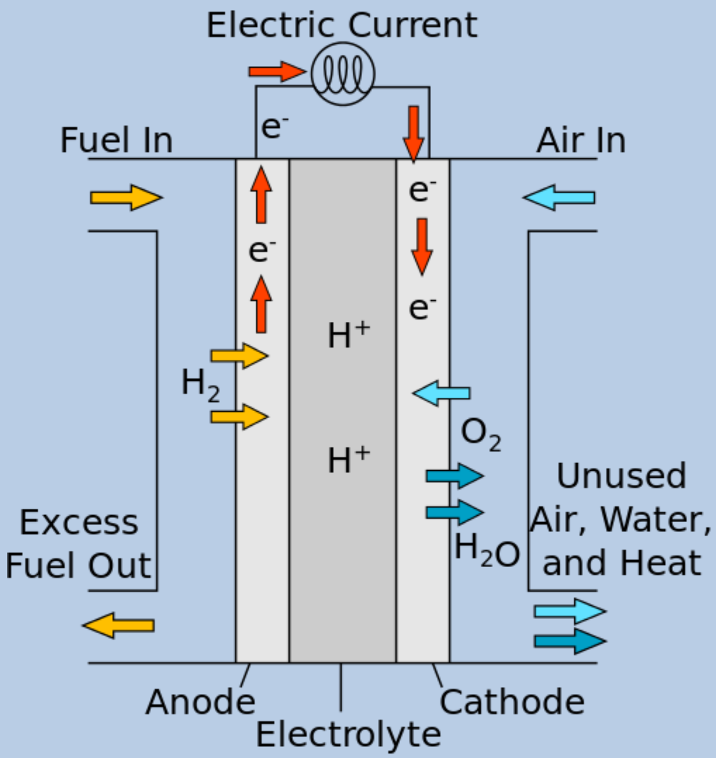
Water distribution in a fuel cell. At 0 s the fuel was changed from hydrogen to deuterium.
Credit: Manke et al., 2008.

The same group overcame the issues with X-ray radiography by using synchrotron radiation (C. Hartnig et al., 2009). Choosing carefully the X-ray energy the sensitivity to water can be optimized, depending on the materials of the fuel cell components. They obtained better spatial resolution (3 to 7 μm) than with neutrons (≈15 μm), at the cost of a somewhat lower contrast between water and the fuel cell.

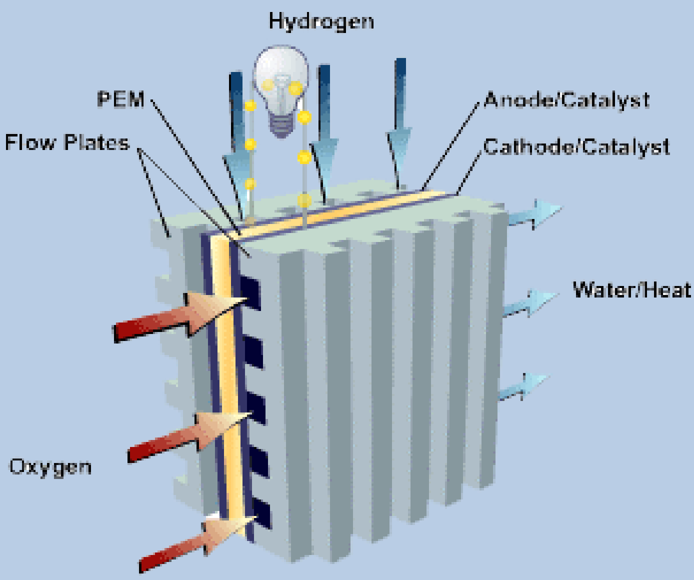
Current designs of PEM fuel cells incorporate the information first derived with neutron radiography, including the transport of water in the cathode side and its diffusion to the fuel injection channels and wetting of the membrane on the anode side. Research is on-going to understand these processes, using both neutrons and synchrotron X-rays, as well as other imaging techniques. But neutrons have played an essential part from the beginning in this line of research for hydrogen-fueled power supply.

How do PEM fuel cells work?

Molecular hydrogen (H_2) is injected on the anode side, where it is catalytically split into two protons (H^+) and two electrons (e^-). The protons are transported to the cathode through the PEM electrolyte, while the electrons generate electric current - the electricity used to move cars. The protons combine with oxygen in the cathode side to form water, which is expelled together with unused air. Some heat is also generated, that could be recovered for heating in home applications.



The system can be easily scaled by having flow plates with multiple hydrogen channels on the anode side, and multiple air channels on the cathode side.



Pictures credit: Wikipedia.