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Original Research

The use of metal hydrides in fuel cell applications☆

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ABSTRACT

This paper reviews state-of-the-art developments in hydrogen energy systems which integrate fuel cells with metal hydride-based hydrogen storage. The 187 reference papers included in this review provide an overview of all major publications in the field, as well as recent work by several of the authors of the review. The review contains four parts. The first part gives an overview of the existing types of fuel cells and outlines the potential of using metal hydride stores as a source of hydrogen fuel. The second part of the review considers the suitability and optimisation of different metal hydrides based on their energy efficient thermal integration with fuel cells. The performances of metal hydrides are considered from the viewpoint of the reversible heat driven interaction of the metal hydrides with gaseous H_2. Efficiencies of hydrogen and heat exchange in hydrogen stores to control H_2 charge/discharge flow rates are the focus of the third section of the review and are considered together with metal hydride – fuel cell system integration issues and the corresponding engineering solutions. Finally, the last section of the review describes specific hydrogen-fuelled systems presented in the available reference data.

1. Introduction

Radical changes in energy policy are necessary in order to reduce the consumption of conventional hydrocarbon energy carriers, *viz.* oil, natural gas and coal. Such changes would not only provide benefits for mankind (relating to the climate and environment), but also economic and political advantages for the countries importing these hydrocarbon fuels. The solution to this problem envisages: (i) higher priority of the development and implementation of energy-saving technologies, and (ii) structural changes in the energy sector with the aim to increase the contribution of power generation without the consumption of hydrocarbons which release CO_2 emissions into the atmosphere [1].

A promising option for small- and medium-scale distributed renewable energy systems is electrochemical energy storage, for example rechargeable batteries or hydrogen and fuel cells. These technologies directly convert chemical energy into electricity and are characterised by overall electrical efficiencies of 50–75% [2]. A distinct advantage of electrochemical energy storage systems is that in comparison to conventional combustion heat engines they are not limited by the Carnot efficiency and, therefore, such efficiencies can be achieved at near ambient temperatures. Advanced hybrid energy storage systems which include fuel cells and batteries are particularly promising [3].

Overall, this review summarises the literature data on fuel cell applications which use metal hydrides (MH), mostly, for the storage and supply of gaseous H_2 fuel. For ease of understanding, the review is broken down into several sections to provide the reader with a full insight into developments in the field of fuel cells and metal hydrides. This is achieved by firstly introducing the existing types of commercially available fuel cells and the potential for metal hydride storage for the different systems. Issues surrounding the thermal integration of different types of metal hydrides and their performance in terms of the reversible heat driven interaction with gaseous hydrogen are then discussed. Heat exchange systems and engineering solutions for controlling hydrogen charge/discharge flow rates for integrated metal hydride – fuel cell systems are covered in the subsequent section. Finally, the last section of the review presents reference data on integrated metal hydride-fuel cell systems from the available literature.

1. An overview of fuel cells and the potential of using metal hydrides.

A fuel cell is an electrochemical device which generates electricity

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Table 1
Types of fuel cells and their main characteristics.

Electrolyte	Fuel	Oxidant	Anode reaction	Cathode reaction	Type of FC	Operating temperature [°C]	Electrical efficiency [%]	Unit power range [kW]	Applications
OH^- conductive alkaline solution	H_2	O_2 Air[a]	$H_2+2(OH)^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2}O_2+H_2O + 2e^- \rightarrow 2(OH)^-$	AFC	65–220	45–60	1–100	Space Naval
OH^- conductive alkaline solution OH^- conductive polymer membrane Na^+ conductive polymer membrane	$NaBH_4$	O_2 Air[a] H_2O_2	$BH_4^-+8(OH)^- \rightarrow BO_2^-+6H_2O+8e^-$	$2O_2+4H_2O + 8e^- \rightarrow 8(OH)^-$ $4H_2O_2+8e^- \rightarrow 8(OH)^-$	DBFC	20–85	30–40	10^{-3}–0.5	Portable
H^+ conductive polymer membrane	H_2	Air	$H_2 \rightarrow 2H^++2e^-$	$\frac{1}{2}O_2+2H^++2e^- \rightarrow H_2O$	LT PEMFC	60–80	40–50	0.05–100	Portable Vehicular Stationary
	H_2	Air			HT PEMFC	150–180	45–50	up to 200	Stationary
	CH_3OH	Air	$CH_3OH + H_2O \rightarrow 6H^++6e^-+CO_2$	$\frac{3}{2}O_2+6H^++6e^- \rightarrow 3H_2O$	DMFC	50–130	20–30	up to 5	Portable
H_3PO_4	H_2	Air	$H_2 \rightarrow 2H^++2e^-$	$\frac{1}{2}O_2+2H^++2e^- \rightarrow H_2O$	PAFC	150–220	40–45	5–200[b]	Stationary
CO_3^{2-} conductive molten carbonate	H_2 CO	Air	$H_2+CO_3^{2-} \rightarrow H_2O + CO_2+2e^-$ $CO + CO_3^{2-} \rightarrow 2CO_2+2e^-$	$\frac{1}{2}O_2+CO_2+2e^- \rightarrow CO_3^{2-}$	MCFC	600–700	45–55	100–2000[c]	Stationary
O^{2-} conductive ceramics	H_2 CO CH_4	Air	$H_2+O^{2-} \rightarrow H_2O + 2e^-$ $CO + O^{2-} \rightarrow CO_2+2e^-$ $CH_4+4O^{2-} \rightarrow 2H_2O + CO_2+8e^-$	$\frac{1}{2}O_2+2e^- \rightarrow O^{2-}$ $2O_2+8e^- \rightarrow 4O^{2-}$	SOFC	600–1000	45–60	2.5–250[c]	Stationary

[a] Presence of CO_2 is not allowed.
[b] MW sized plants.
[c] Plants up to 100 MW.