INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–13

Available online at www.sciencedirect.com

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Open and closed metal hydride system for high thermal power applications: Preheating vehicle components

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ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form
10 February 2017
Accepted 5 March 2017
Available online xxx

Keywords:
Thermochemical energy storage
Metal hydrides
High power
Cold start
Coupled chemical reaction

ABSTRACT

Many vehicle components operate at temperatures above ambient conditions. At cold start, most of the pollutants are produced and lifespan is reduced. Thermochemical energy storage with high power density could prevent these disadvantages. In order to investigate achievable power densities of a thermochemical energy storage at technically relevant boundary conditions, a laboratory scale device using metal hydrides ($LaNi_{4.85}Al_{0.15}$ and C5®) is designed and preheating operation modes (open and closed) are analyzed. The impact of the ambient temperature (from −20 to +20 °C), a s well as other influencing factors on the thermal power output such as heat transfer flow rate, regeneration temperature and pressure conditions are investigated. The experiments proved the suitability of the reactor design and material selection for the considered application boundary conditions. For the coupled reaction (closed system), the ambient temperature has the greatest influence on the thermal power with decreasing values for lower temperatures. Here, values between 0.6 kW/kg_{MH} at ambient temperature of −20 °C and 1.6 kW/kg_{MH} at 20 °C, at otherwise same conditions, were reached. If hydrogen can be supplied from a pressure tank (open system), the supply pressure in relation to equilibrium pressure at the considered ambient temperature has to be large enough for high thermal power. At −20 °C, 1.4 kW/kg_{MH} at a supply pressure of 1.5 bar and 5.4 kW/kg_{MH} at a hydrogen pressure of 10 bar were reached.

Introduction

Many vehicle components operate at temperatures above ambient conditions. At cold start, especially at winter temperatures of −20 °C and below, most of the pollutants are produced and lifespan is reduced. This is described here in more detail for combustion drives and fuel cells.

Conventional engines are designed for temperatures around 100 °C. Starting at ambient temperatures neither the combustion process nor the exhaust gas treatment work sufficiently until operation temperature is reached. In these first couple of minutes, 60–80% of all pollutants of the whole driving cycle are produced [1,2]. As combustion engines become more and more efficient, waste heat is reduced and this leads to a prolonged cold start phase and more pollutants.

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http://dx.doi.org/10.1016/j.ijhydene.2017.03.024
0360-3199/

Nomenclature

c_p	heat capacity
$\dot{m}$	mass flow
P	thermal power
p	pressure
Q	overall heat
R	universal gas constant
T	temperature
x	hydrogen conversion
ΔH	reaction enthalpy
ΔS	reaction entropy

Subscripts

300 sec	after 300 s
600 sec	after 600 s
amb	at ambient level
eq	equilibrium state
f_c	fuel cell
H_2	hydrogen
heat	produced heat level
HTF	heat transfer fluid
in	at inlet of reactor
MH	metal hydride
out	at outlet of reactor
reg	regeneration level
storage	hydrogen storage material
tank	at tank level
waste	waste heat source

If the components are preheated, a large amount of the pollutants can be prevented.

Even in fuel cell driven vehicles, water produced in fuel cells would freeze below zero degrees. The ice layer prevents gas flow and the expansion in volume can cause mechanical destruction of the fuel cell [3–6]. Therefore, fuel cells are dried before shut down. When restarting, the membrane has to be wetted which requires temperatures above freezing point. So the fuel cell needs to be preheated to temperatures above 0 °C in order to avoid degradation and prolonging life time significantly.

Therefore, both combustion engines as well as fuel cells require preheating for long service life and reduced exhaust emissions. Since in both cases thermal energy is available later during the driving cycle, thermal energy storages are a suitable option to overcome the described problem. A high energy density of the application, including both storage material and containment, is of importance, because the thermal storage adds weight to the vehicle. A promising option is a thermochemical energy storage system, due to the high energy density at limited temperature conditions and its long-term storage possibility. Here, a gas reacts with a solid and absorption heat is released. If heat is supplied to the storage material, the gas is released while heat is absorbed. This relation between solid temperature and gas pressure is described in the Van't Hoff equation [7]:

$$\ln\left(p_{eq}\right) = -\frac{\Delta H}{RT} + \frac{\Delta S}{R} \quad (1)$$

Where p_{eq} is the equilibrium pressure of the gas, ΔH is the reaction enthalpy, R is the universal gas constant, T is the absolute temperature of the solid and ΔS is the reaction entropy. By controlling the chemical reaction, generating heat on demand and controlling the temperature and power of the released thermal energy is possible.

This study focuses on the investigation of metal hydrides for high power thermal energy storage systems. In this case, a metal alloy forms a hydride phase by chemisorption of hydrogen. Originally metal hydrides were investigated as hydrogen storage materials [8–10]. But because they release and absorb heat during reaction, more and more investigations deal with thermal applications such as e.g. thermally driven heat pumps [11–20]. Consequently, the available data in literature deals mainly with temperatures above freezing point. However, the intended application in this paper – the pre-heating of components – addresses also automotive applications with respective temperature conditions for both metal hydrides down to −20 °C. Since according to Arrhenius the reaction rate decreases at lower temperatures, the most important but so far hardly investigated aspect is related to the technically achievable power densities of metal hydrides at these boundary conditions. The systems developed in this work are designed for the following two generic applications:

a) **Combustion engines – coupled reaction as a closed system.** At nominal operation the combustion engine releases around 2/3 of the energy as heat [21] and consequently cooling is needed. This thermal energy can be stored in a thermochemical energy storage consisting of two reactors with different metal hydrides. The thermal energy leads to a desorption of hydrogen in one of the reactors. The released hydrogen is stored in the second reactor. This closed system doesn't require any exchange of hydrogen with the surrounding, but works only by absorbing and releasing heat. If the back reaction is prevented, e.g. by a separating valve, the chemically stored thermal energy can be released at the next cold start by opening the valve to preheat the respective component.
b) **Fuel cells – hydrogen supply from tank as an open system.** The potential energy stored in the hydrogen pressure tank, e.g. around 15% of the overall energy stored at 900 bar [22], is currently throttled on board and therefore lost. By conducting hydrogen at higher pressure onto a metal hydride, heat can be produced, e.g. to preheat the fuel cell. For regeneration, the waste heat of the fuel cell can be used to regenerate the thermochemical storage. In this open system, a combination of thermal energy from the fuel cell and the potential energy of the hydrogen tank is used to run the system. The hydrogen itself is not consumed since it is desorbed during regeneration and can be converted to electricity in the fuel cell.

Both applications (open and closed system) have in common that the chemical potential of the thermochemical energy storage is used to generate thermal energy when it is needed. Depending on the type of propulsion, the regeneration of the storages differs. However, the underlying challenge can be summarized to the requirement of high thermal power

Please cite this article in press as: Dieterich M, et al., Open and closed metal hydride system for high thermal power applications: Preheating vehicle components, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.03.024