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Integrated Cabin and Fuel Cell System Thermal Management with a Metal Hydride Heat Pump

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INTEGRATED CABIN AND FUEL CELL SYSTEM THERMAL MANAGEMENT WITH A METAL HYDRIDE HEAT PUMP

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Abstract
Integrated approaches for the heating and cooling requirements of both the fuel cell (FC) stack and cabin environment are critical to fuel cell vehicle performance in terms of stack efficiency, fuel economy, and cost. An integrated FC system and cabin thermal management system would address the cabin cooling and heating requirements, control the temperature of the stack by mitigating the waste heat, and ideally capture the waste heat and use it for useful purposes. Current work at the National Renewable Energy Laboratory (NREL) details a conceptual design of a metal hydride heat pump (MHHP) for the fuel cell system and cabin thermal management. This paper details the design of a metal hydride heat pump to capture heat at 80°C, thereby capturing waste heat and cooling the FC stack partially, and cool the vehicle cabin (0°C). The waste heat available from a typical sedan is near 7 kW over a variety of drive cycles, and for an SUV the average waste heat is near 15 kW. This amount of waste heat can be successfully turned into the required 3-7 kW of cooling required to cool the vehicle cabin environment with a MHHP. Additionally, using waste heat to generate cabin cooling eliminates this load from the fuel cell, saving a significant amount of energy.
Keywords: Hydrogen storage materials (A); Thermal analysis (D); Metal hydride heat pump; Fuel cell; Waste heat

1. Introduction

Why study heat-generated cooling in vehicles? The air-conditioning load in a vehicle is the largest ancillary load in the vehicle. That means that each year, 7.1 billion gallons (27 billion liters, Figure 1) are used in the United States for air conditioning, which is equivalent to 10% of foreign crude oil imports [1]. The problem is similar across the globe. Therefore, by eliminating the air-conditioning load in vehicles, waste-heat generated cooling has the potential to save significant energy world-wide.

Figure 1: Millions of Gallons Used for Light-Duty Vehicle Air Conditioning

Why address thermal management in fuel cells? It makes sense to focus research at the largest energy consumers in a vehicle, which in the case of fuel cells are the air-conditioning and air compressors (Figure 2). As many companies are focused on advancing air compressor technology, this work focuses on air-conditioning. A 5 kW air-conditioning load in a fuel cell vehicle affects the vehicle operation, sizing and cost significantly. Assuming fuel cells reach the Department of Energy's cost target of $45/kW by 2010, an extra load of 5 kW would drop fuel economy 10-50%, affect vehicle performance, or increase the fuel cell stack cost by $225, all of which are deterrents to fuel cell vehicle implementation and acceptance into the marketplace. Hydrides materials have a unique advantage in fuel cell vehicles. Capturing the waste heat is difficult in fuel cells due to their low operating temperatures (80°C). Other technologies, for example absorption heat pumps, require higher waste temperatures. A metal hydride heat pump has other advantages that make it suitable for fuel cell vehicles. Metal hydride systems have fewer total parts and fewer moving parts than a conventional vapor compression air-conditioning system, as the system doesn't use a compressor or evaporator. Also, a metal hydride system does not require chloroflourocarbons (CFC) for cooling. CFC's, such as freon, have been linked to the destruction of stratospheric ozone. Therefore, in a fuel cell energy-efficient and environmentally friendly vehicle of the future, a metal hydride heat pump has its place.

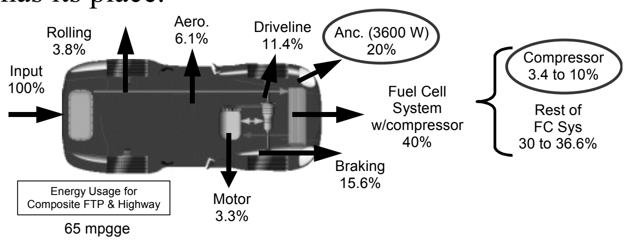

Figure 2: Energy Usage in a Fuel Cell Vehicle

2. Metal Hydride Heat Pump Operation

2.1 System Operation

Hydride heat pumps utilize the fact that when hydrogen is adsorbed by the metal, heat is released because it is an exothermic reaction. Desorbing or releasing the hydrogen is endothermic, which needs heat as an input. In the equation below, *M* represents the metal, and MH_x the metal hydride:

$$M + \frac{x}{2} H_2 \leftrightarrow MH_x + Heat$$

Figure 3 shows the basic operation of a hydride heat pump, for a dual-bed system. This system uses two metal hydride beds (a low temperature and high temperature metal), three heat exchanger sections (high, ambient, and low temperatures), and cycles the beds through these heat exchangers through time to achieve cooling.

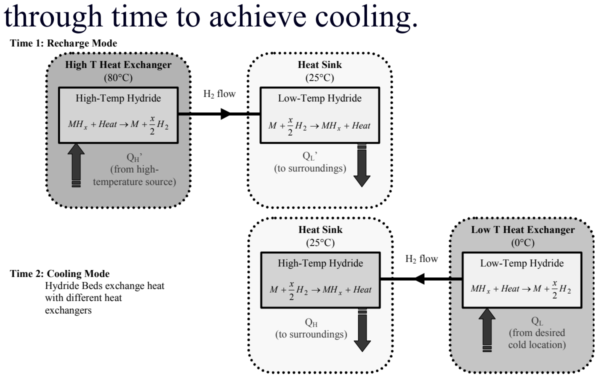

Figure 3: Basic Operation of Metal Hydride Heat Pump

2.2 Material Selection

The list of potential high-temperature and low-temperature hydride materials was made by compiling materials used in past heat pumps with similar operating temperatures [3] and searching compatible materials through the Hydride Material Listing available on the web [4]. The material performances are shown in Figure 4 and Figure 5, with the two top hot and cold materials in bold. Criteria for material selection included: compatible temperatures (80°C and 0°C), reasonable pressures (less than 5 atm), a high temperature (>30°C) for the ambient rejection temperature, and high weight percent hydrogen.

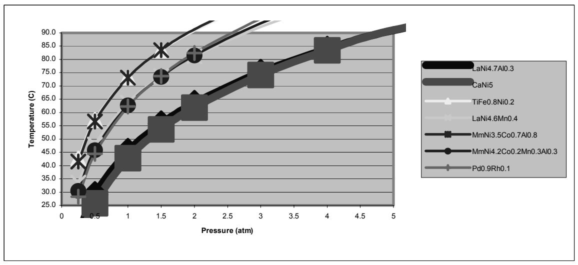

Figure 4: Hot-side Potential Hydride Materials, Pressure-Temperature Plot

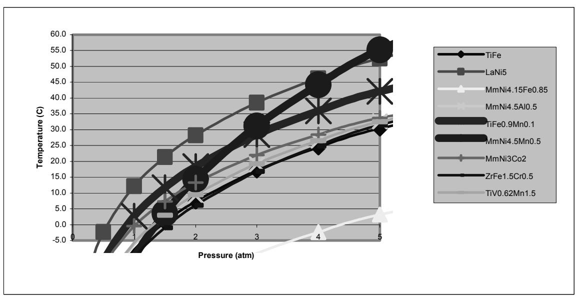

Figure 5: Cold-side Potential Hydride Materials, Pressure-Temperature Plot

Table 1 details the material parameters for candidate materials. The top two materials for hot and cold materials are highlighted. The final material pair selected was $CaNi_5$-$TiFe_{0.9}Mn_{0.1}$. The system operated near 3.5 atm, 80°C, and 32°C in the recharge mode and 1 atm, 40°C, and 0°C in cooling mode for the system pressure, hot-side temperature, and low-side temperature, respectively.

Table 1: Detailed Hydride Material Data Used for Selection

	Material	ΔH	ΔS	Wt%	Plateau Slope	Hysteresis
		kJ/mol	kJ/mol*K		dlnP/d(H/M)	ln(Pa/Pd)
Cold Matls	TiFe	-28.1	-0.106	1.86	0	0.64
	LaNi5	-30.8	-0.108	1.49	0.13	0.13
	MmNi4.15Fe0.85	-25.3	-0.105	1.14	0.36	0.17
	MmNi4.5Al0.5	-28	-0.105	1.2	0.36	0.11
	**TiFe0.9Mn0.1	-29.5	-0.107	1.9	0.92	0.62
	*MmNi4.5Mn0.5	-17.6	-0.067	1.3	1.2	0.75
	MmNi3Co2	-32.7	-0.12	1.4	0.28	n/a
	ZrFe1.5Cr0.5	-25.61	-0.0975	1.5	1.26	0.34
	TiV0.62Mn1.5	-28.6	-0.107	2.15	1.4	n/a
Hot Matls	*LaNi4.7Al0.3	-34	-0.1068	1.44	0.48	0.05
	**CaNi5	-31.9	-0.101	1.87	0.19	0.16
	TiFe0.8Ni0.2	-41.2	-0.119	1.3	0.36	0.05
	LaNi4.6Mn0.4	-39.4	-0.117	1.49	0.76	0.1
	MmNi3.5Co0.7Al0.8	-39.8	-0.115	1.24	1.2	n/a
	MmNi4.2Co0.2Mn0.3Al0.3	-36.5	-0.1087	1.38	1.3	0.18
	Pd0.9Rh0.1	-34.2	-0.102	0.69	0.29	0.71

2.3 Design Parameters

The system was designed for 5 kW cooling, including four hydride beds for continuous cooling. The mass of the hydride per bed was 1.25 kg, with a 1.9 weight percent H/M. The cycle time was 2 minutes, a somewhat aggressive target. An example past cycle time (e.g. of the HYCSOS heat pump) was 4 minutes [5]. This 2-minute cycle time was chosen to design the system to 1 kW/kg based on hydride weight, as from [7], a heat pump having greater than 1kW/kg hydride is competitive in weight (and cost) with a conventional air conditioner.

The Coefficient of Performance (COP) was calculated as follows [7]:

$$COP = \frac{m_H \Delta H_{low} - \left[(mc_p)^{low}_{hydride} - (mc_p)^{low}_{container/heatExchanger}\right]\Delta T_{low}}{m_H \Delta H_{high} + \left[(mc_p)^{high}_{hydride} + (mc_p)^{high}_{container/heatExchanger}\right]\Delta T_{high}}$$

The heat exchanger was assumed to be stainless steel for heat capacity and the mass was assumed to be 0.5 that of the hydride [6]. Assuming a ΔT_{low} of 30°C and a ΔT_{high} of 20°C, the COP was 0.5, which is similar to others reported in literature [6]. In order to increase the performance of the system, it is necessary to research improved heat exchanger efficiency, smaller component sizes, and system integration with the vehicle waste heat.

3. Fuel Cell Vehicle Modeling

To determine the amount of waste-heat potential in fuel cell vehicles, modeling was performed using the Advanced Vehicle Simulator (ADVISOR [2]) developed at NREL. Two typical vehicles were simulated: a small sedan (1043 kg, 50 kW fuel cell) and a Sport Utility Vehicle (SUV, 2285 kg, 150 kW fuel cell). The waste thermal heat available varies with time, vehicle type (sedan, SUV) and drive cycle (Figure 6).

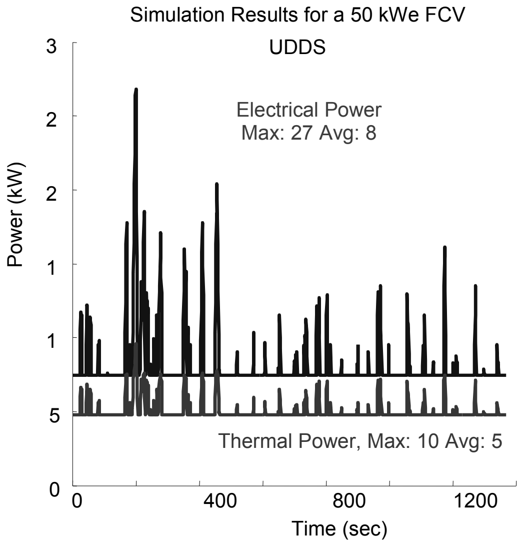

Figure 6: Sample Electrical and Thermal Power over the UDDS Drive Cycle

The thermal waste power averaged over the heat pump cycle time (2 minutes) for various cycles is shown in Table 2. Using the COP of 0.5, the metal hydride heat pump can deliver 2.5-3 kW of cooling to the sedan and 5-10 kW cooling to the SUV. This amount of cooling is similar to the required cabin cooling, though cooling load reduction techniques may be necessary before commercial implementation of metal hydride heat pumps.

Table 2: Two-minute Averages of Thermal Power vs. Cycle

	Thermal Power (kW)	
	Sedan (50 kW)	**SUV (150 kW)**
Cycle	**Avg 2 min**	**Avg 2 min**
UDDS	5	14
FTP	3.8	11
SC03	5	15
US06	6	20
HWFET	5.2	15
Japan 1015	5	14
NEDC	5	15
NREL to Vail	7.5	20

4.Summary and Future Work

Initial design of a metal hydride heat pump for a fuel cell vehicle was completed, showing the potential to have waste-heat generated cooling (3-7 kW) and saving a significant amount of fuel energy. Addressing the cooling requirements of the cabin environment is critical to fuel cell vehicle performance in terms of stack efficiency, fuel economy, and cost. The MHHP design shows a moderate COP, in line with those reported in the literature. The next steps are to evaluate more detailed models ([6] - [11]) and realize the design by creating a bench-top working prototype involving industry. By linking this work with other work at NREL (integrated modeling, passenger thermal comfort, cabin thermal load reduction, etc), advanced cooling systems could reduce the vehicle cooling load significantly, aiding implementation of a metal hydride heat pump.

Future design will include addressing well-known issues of metal hydride heat pumps, including hydrides with large hydrogen storage capability, increasing the thermal conductivity of the beds, and enhancing heat transfer in the heat exchangers [12].

By eliminating the air-conditioning load in vehicles, waste-heat generated cooling has the potential to save significant energy across the world.

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