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ECC Refrigerator: Investigate Potential Energy Savings and Likelihood of Success if an ECC is Used Instead of a Typical Vapor Compressor

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Investigate Potential Energy Savings and Likelihood of Success if an ECC is Used Instead of a Typical Vapor Compressor

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Investigate Potential Energy Savings and Likelihood of Success if an ECC is Used Instead of a Typical Vapor Compressor (Go/No Go)

Executive Summary

This report estimates energy saving potential of a refrigerator using an electrochemical compressor (ECC) and metal hydride heat exchangers, versus a baseline refrigerator using a single-speed reciprocating compressor. The ECC technology has is more efficient at high pressure ratio and has better part-load performance. In addition, metal hydrides are solid refrigerants suitable for extensive applications, having larger formation heat. It has the potential to achieve energy saving over 20% than the baseline refrigerator, after we break the technical barriers on the path. Based on evaluation of the project against the must meet criteria, it meets the requirements for a "go" decision.

Baseline System

Vapor compression systems have drastic performance degradation when increasing the pressure ratio, because of the losses caused by re-expansion of residue volume, reduced motor efficiency, etc. The selected baseline refrigerator uses a single-speed, reciprocating-piston compressor. We converted the measured compressor mass flow rate and power consumption to isentropic and volumetric efficiencies, as a function of the evaporating temperature, Te, and condensing temperature, Tc, as shown in Figures 1 and 2. These two figures represent typical isentropic and volumetric efficiency reductions with increasing the pressure ratio, i.e. Pressure at Tc/Pressure at Te. Large pressure ratios of refrigerator/freezer applications cause low system cooling efficiency and reduced refrigerating capacity. In addition, the single-speed refrigerator has cyclic loss due to turning the compressor on/off to meet the temperature setting point. The average COP of the baseline refrigerator was given as ***1.33.***

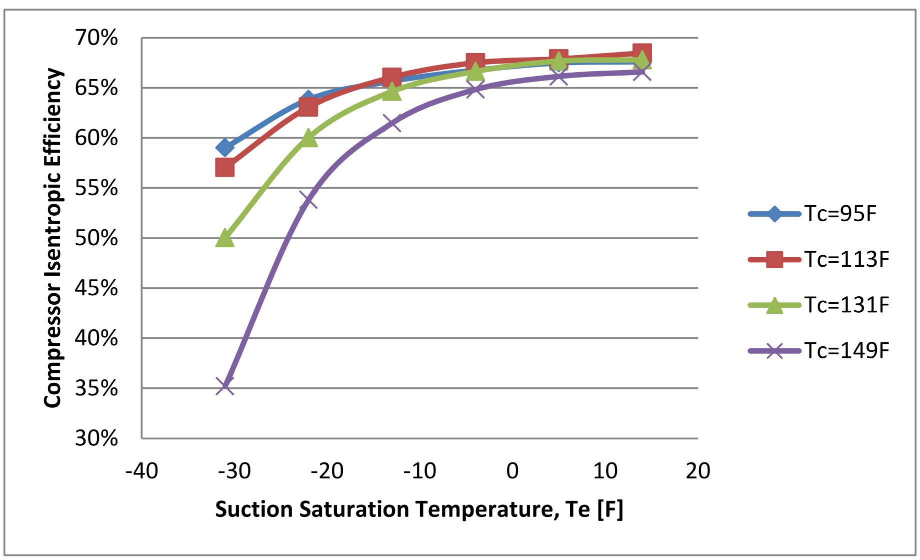

Figure 1: Compressor Isentropic Efficiency Plot

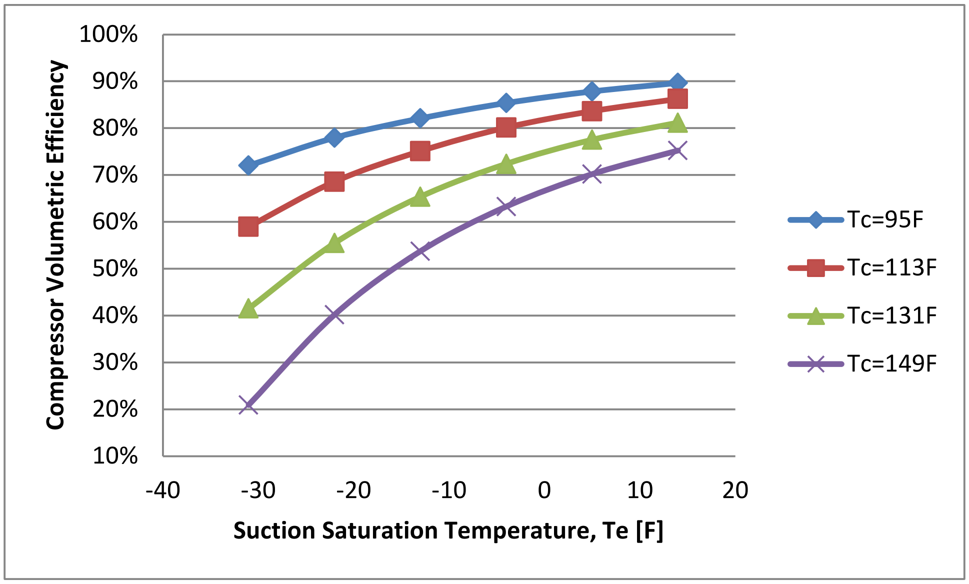

Figure 2: Compressor Volumetric Efficiency Plot

Energy Saving Potentials of Electrochemical Compression using Metal Hydride Heat Exchangers

1. **An electrochemical compressor is more efficient at high pressure ratio**

Electrochemical compressors (ECC) use membrane. The electrical voltage across a membrane consists of three parts,

$$U = U_{Nernst} + U_{ohm} + U_{ac} \qquad (1)$$

Where U_{Nernst} is Nernst potential, i.e. the actual force driving the hydrogen flow. U_{ac} is caused by the anode and cathode polarization, which is usually negligible for an ECC compressor using membranes. U_{ohm} is caused by the electrical resistance in the membrane, which is a loss factor and converts electrical energy to heat.

$$U_{ohm} = I \times \; R_i \qquad (2)$$

Where R_i is the internal electrical resistance of the membrane.

$$U_{Nernst} = \frac{R \times T_{EC}}{2F} \ln \left(P_{dis}/P_{suc}\right) \qquad (3)$$

Where R is the gas constant, T_{EC} is the ECC compressor's process temperature [K]. P_{dis} [pa] is the compressor's discharge temperature and P_{suc} [pa] is the suction pressure.

Thus, the electrochemical efficiency of the compressor is defined as Equation (4).

$$\eta_{EC} = U_{Nernst}/(U_{Nernst} + U_{ohm}) \qquad (4)$$

It can be seen that the electrochemical compression has advantages for the refrigerator application with high pressure ratios. High pressure ratios lead to larger U_{Nernst}/U_{ohm} at the same electric current (hydrogen flow rate). As reported by [1] and illustrated in the table below, a state-of-art electrochemical compressor reached an isentropic efficiency of 75% having a pressure ratio of 293.

TABLE 1. Progress Made Towards Meeting Technical Targets for Small Compressors for Fueling Sites [1]

Characteristic	Units	DOE 2015 Target	FCE Status
Reliability	-	Improved	20,000 h§&
Compressor Efficiency (Isentropic)	%	73%	75%§#
Losses (% of H_2 throughput)	%	0.5	1§#
Uninstalled Capital Cost	$	400,000	300,000 Projected for EHC Stack
Outlet Pressure Capability	bar	860	Up to 880*^
Contamination	-	Varies by Design	None

§For compression from 3 to 208 bar; ^3 bar inlet pressure; &0.1 kg H_2/d; #0.3 kg H_2/d; *<0.01 kg H_2/d

2. Electrochemical compressors have better part-load performance.

Hydrogen flow rate of an electrochemical compressor can be varied by adjusting the DC power input, i.e. electric current. And it doesn't have on/off cyclic loss like a mechanical compressor. Therefore, it has the advantage of a variable-speed compressor, and will lead to superior part load performance in a refrigerator system.

3. Metal hydride alloys are solid refrigerants

Metal hydride (MH) alloys have great potential to replace refrigerants in vapor compression systems. Metal hydrides are widely used to store hydrogen in automobile and power industries. As shown in the figure below, some metals can be bonded with hydrogen and form metal hydrides. With increasing the hydrogen concentration, the material bond goes through the α phase, similar to the subcooled state of a refrigerant; in the α+β phase, the absorption/desorption temperature at a given plateau pressure doesn't change, similar to the two-phase state of a pure refrigerant; in the β phase, the hydride's temperature increases with the concentration, like the superheat state of a refrigerant. The whole process is reversible from absorption to desorption. Major energy transfer of hydrogen absorption/desorption occurs in the α+β phase. The energy change is defined as formation heat absorbed per mole of hydrogen, [kJ/mole H_2].

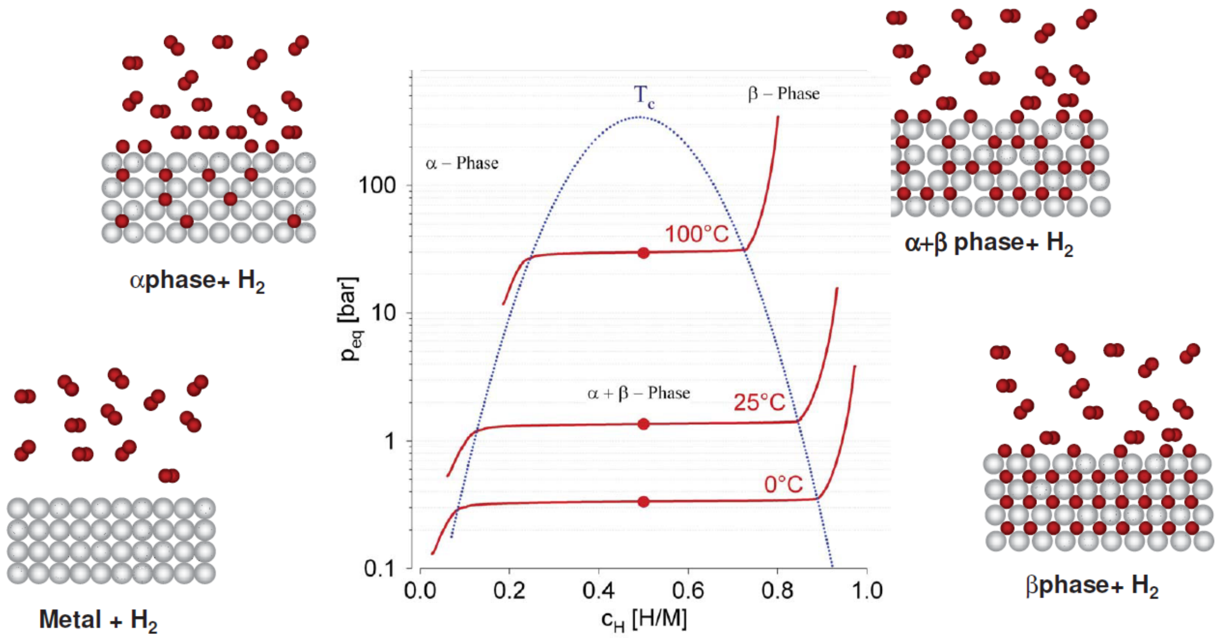

Figure 3: Mechanism of Metal Hydride Absorbing (Desorbing) Hydrogen

Various MH alloys are suitable for hydrogen compression system, as Table 2 summarized by [2]. It shall be noted that formation heat (-ΔH0) ranges from 20 to 50 kJ/mole H_2. Formation heat is equivalent to latent evaporation heat of a refrigerant. R-134a, a typical refrigerant used for refrigerators, has the latent evaporation heat of 22.7 kJ/mole at -30°F. It can be seen, most of the MH alloys have higher formation heat than R-134a.

Table 2: Equilibrium characteristics of MH Alloys, cited from [2]

Equilibrium characteristics of the interaction of hydride-forming alloys suitable for H_2 compression with H_2 gas in plateau region. The data are sorted in the ascending order for desorption plateau pressure at T = 25 °C (P_0). The plateau pressures are calculated using Equation (2); the lower (P_L) and higher (P_H) values correspond to the lower (T_L) and higher (T_H) temperatures, respectively, as reported in the original works.

#[a]	Alloy	$-\Delta S^0$ [J/(mol H_2 K)]	$-\Delta H^0$ [kJ/mol H_2]	Temperature range [°C]		Pressure [atm]			Ref.
				T_L	T_H	P_0	P_L	P_H	
1 (A)	$V_{75}Ti_{17.5}Zr_{7.5}$	145.1	52.98	30	120	0.02	0.03	3.47	[15]
2 (B)	$MmNi_{4.8}Al_{0.2}$	111.3	37.20	50	150	0.02	0.63	16.66	[16],[b]
3 (B)	$LaNi_{4.7}Sn_{0.3}$	112.6	36.51	25	80	0.31	0.31	3.03	[17]
4 (A)	$V_{75}Ti_{10}Zr_{7.5}Cr_{7.5}$	132.3	42.23	30	120	0.32	0.43	19.90	[15]
5 (B)	$LaNi_{4.8}Sn_{0.2}$	104.3	32.83	20	90	0.50	0.40	5.32	[18],[b]
		105.0	32.80	0	240	0.55	0.16	139.9	[19]
6 (B)	$Mm_{0.5}La_{0.5}Ni_{4.7}Sn_{0.3}$	111.2	33.80	25	80	0.77	0.77	6.44	[17]
7 (B)	$LaNi_{4.8}Al_{0.2}$	101.6	30.40	50	150	0.96	2.47	35.84	[16],[b]
8 (B)	$LaNi_5$	110.0	31.80	25	200	1.49	1.49	171.9	[20,21],[b]
9 (B)	$MmNi_{4.7}Fe_{0.3}$	87.4	25.00	20	102	1.53	1.29	12.14	[22],[b]
10 (A)	$V_{0.85}Ti_{0.1}Fe_{0.05}$	148.0	42.90	−20	100	1.64	0.08	53.14	[20,23],[b]
11 (C)	$TiFe_{0.9}Mn_{0.1}$	107.7	29.70	0	100	2.64	0.88	29.39	[20,24],[b]
12 (B)	$La_{0.85}Ce_{0.15}Ni_5$	91.28	24.30	10	110	3.24	1.93	28.50	[b,c]
13 (B)	$MmNi_{4.7}Al_{0.3}$	107.8	28.88	20	90	3.73	3.05	29.98	[18]
14 (A)	$V_{92.5}Zr_{7.5}$	147.0	40.32	30	60	4.11	5.38	22.71	[15]
15 (B)	$La_{0.2}Y_{0.8}Ni_{4.6}Mn_{0.4}$	105.3	27.10	20	90	5.62	4.67	39.78	[25]
16 (D)	$Zr_{0.7}Ti_{0.3}Mn_2$[d]	85.0	21.00	30	150	5.77	6.63	70.41	[26],[b]
17 (D)	$Ti_{0.9}Zr_{0.1}Mn_{1.4}Cr_{0.35}V_{0.2}Fe_{0.05}$[e]	106.9	25.89	25	100	11.17	11.17	91.14	[27]
18 (B)	$MmNi_{4.15}Fe_{0.85}$	105.4	25.00	25	200	11.36	11.36	502.8	[20,24],[b]
19 (B)	$La_{0.4}Ce_{0.4}Ca_{0.2}Ni_5$	115.3	28.20	15	100	12.08	8.14	118.9	[28]
20 (D)	$Ti_{0.8}Zr_{0.2}CrMn$	108.6	24.60	−20	50	23.06	3.95	49.69	[20],[b]
21 (B)	$Mm_{1-x}Ca_xNi_{5-y}Al_y$[e]	103.0	22.85	5	90	23.82	12.28	124.0	[29]
22 (B)	$Ca_{0.2}Mm_{0.8}Ni_5$	109.5	24.50	0	100	26.75	10.83	195.0	[20,24],[b]
23 (D)	$Zr_{0.8}Ti_{0.2}FeNi_{0.8}V_{0.2}$	118.3	26.80	20	90	30.49	25.35	211.1	[30],[b]
24 (D)	$Ti_{0.77}Zr_{0.3}Cr_{0.85}Fe_{0.7}Mn_{0.25}Ni_{0.2}Cu_{0.03}$	93.66	19.26	20	110	32.98	28.88	184.8	[c]
25 (D)	$TiCr_{1.9}Mo_{0.01}$	113.0	24.80	−50	90	36.11	1.25	216.4	[30]
26 (D)	$TiCr_{1.9}$	122.0	26.19	−100	30	60.77	0.03	72.34	[31],[b]
27 (D)	$ZrFe_{1.8}Cr_{0.2}$	109.0	22.30	20	90	61.19	52.49	306.2	[30]
28 (D)	$(Ti_{0.97}Zr_{0.03})_{1.1}Cr_{1.6}Mn_{0.4}$	115.0	23.40	10	99	80.80	49.00	527.9	[32]
29 (D)	$TiCr_{1.5}Mn_{0.25}Fe_{0.25}$[e]	101.6	19.32	−10	165	83.61	29.65	1009	[27]
30 (D)	$TiCr_{1.5}Mn_{0.2}Fe_{0.3}$[e]	101.0	18.32	−10	148	116.4	43.57	1008	[27]
31 (D)	TiCrMn	106.0	19.60	−60	100	126.8	5.42	621.2	[34],[b]
32 (D)	$ZrFe_{1.8}Ni_{0.2}$	119.7	21.50	20	90	306.0	264.0	1445	[30]
33 (D)	$Ti_{0.86}Mo_{0.14}Cr_{1.9}$	117.0	17.20	−50	90	1253	121.7	4340	[30]

[a] Type of the alloy is specified in brackets as BCC-V solid solution (A); AB_5- (B), AB- (C) and AB_2-type (D) IMC's.
[b] The data are also available at the US DoE hydrogen storage materials database, http://hydrogenmaterialssearch.govtools.us; section "Hydride Information Center (Hydpark)".
[c] Previously unpublished experimental data by the authors of this review (ML, VY).
[d] Dynamic PCT experiments.
[e] ΔS^0 fitted by ML to agree with the reported T–P conditions.

For the prototype ECC compressor, provided by Xergy Inc., the figure below compares the isentropic efficiency curves with using a single ECC compressor and put two in parallel (reduced ohm loss). Using two ECC compressors in parallel can increase the isentropic efficiency to 67% at the 0.7 A current.

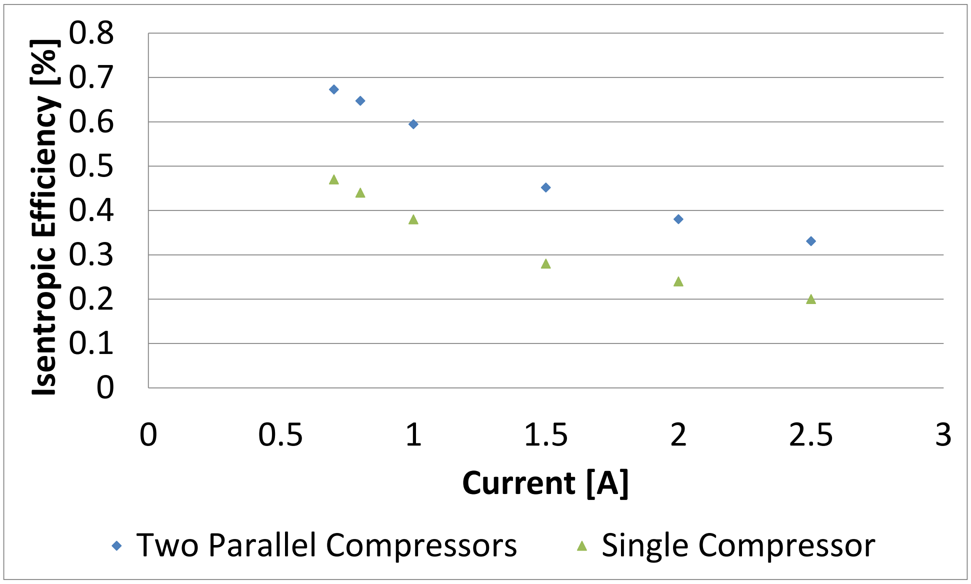

Figure 4: Isentropic Efficiency Curves with using a single and two parallel ECC compressors.

Figure 4 presents the max theoretical COPs using one or two parallel prototype ECC compressors (formation heat/ECC power consumption absorbing one mole H_2), assuming the formation heat of 20 kJ/mole (Low) H_2 and 40 kJ/mole H_2 (High), respectively. It can be seen, if use a species of MH alloy having the high formation heat and operate the ECC compressor(s) at small current densities, the ECC refrigerator can achieve COPs at least 20% higher than the baseline refrigerator having an average COP of 1.33.

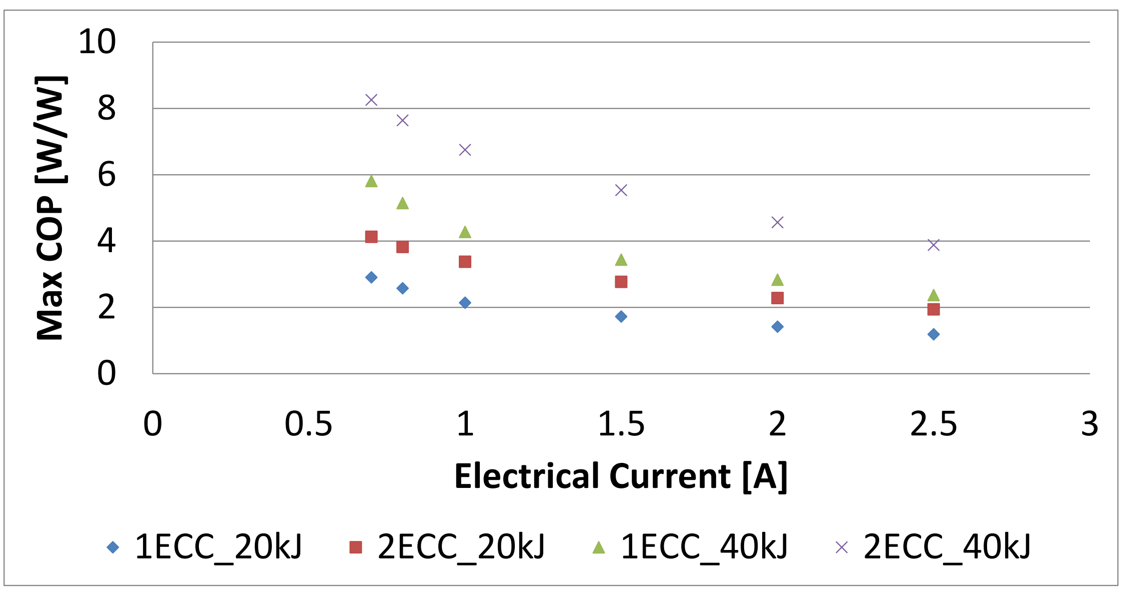

Figure 5: Max COPs of ECC refrigerator using one or two ECC compressors, with the formation heat of 20 kJ/mole H_2 and 40 kJ/mole H_2.

References

[1] DOE Hydrogen and Fuel Cells Program, 2015, FY 2015 Annual Progress Report, https://www.hydrogen.energy.gov/pdfs/progress15/iii_10_lipp_2015.pdf

[2] M.V. Lototskyy, V.A. Yartys, B.G. Pollet, R.C. Bowman, Metal hydride hydrogen compressors: A review, In International Journal of Hydrogen Energy, Volume 39, Issue 11, 2014, Pages 5818-5851, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2014.01.158.