



Thermodynamic analysis of a thermally operated cascade sorption heat pump for continuous cold generation

P. Muthukumar, D.V.N. Lakshmi

Department of Mechanical Engineering, Indian Institute of Technology, Guwahati – 781039, India.

Abstract

In this paper, the thermodynamic analysis of a cascade sorption system consists of a two-stage metal hydride heat pump as topping cycle and a single-stage lithium bromide water system as bottom cycle is presented. The effects of various operating temperatures such as driving heat, heat release and refrigeration temperatures, and design parameters such as ratio of metal hydride mass to reactor mass and sensible heat exchange factor on the combined coefficient of performance (COP) of the cascade cycle, and specific cooling power (SCP) and total cold output of the metal hydride heat pump cycle are presented. It is observed that the combined COP is found to increase with heat release and refrigeration temperatures and however, decreases with driving heat temperature. Increase of sensible heat exchange factor improves the system performances significantly. Reduction in mass ratio from 0.5 to 0.1 improves the combined COP of the cascade system by about 10 %. The maximum predicted combined COP of the system is about 1.66 at the driving heat, heat release and refrigeration temperatures of 270 °C, 125 °C and 12°C, respectively.

Copyright © 2013 International Energy and Environment Foundation - All rights reserved.

Keywords: Cascade system; Metal hydride heat pump; Lithium bromide-water; Thermodynamic analysis.

1. Introduction

In the recent years, there has been numerous research works reported on the development of thermally operated sorption cooling systems. These systems are environmental friendly; utilize low grade thermal energy; and offer flexible operating temperature. Though many heat driven vapor sorption systems have been developed in the past three decades, but a very few systems are competitive to the vapor compression systems. Among them, metal hydride based sorption systems are probably the most promising one, due to their extreme compactness, noise free and vibration less operation and high specific cooling power [1]. Further, these systems do not have any solution circuit and hence, it can be operated at any orientation. The currently available sorption cooling systems have the coefficient of performance (COP) of about 0.7 for single- stage single-effect, about 1.4 for double-effect and about 1.6 for triple-stage triple-effect [1, 2]. Therefore, it is possible to improve the COP of the sorption system by combining two different sorption systems such as metal hydride cooling system (MHCS) and lithium bromide - water system, called cascading and to operate them with different working pairs and temperature limits [2].

Many investigators have studied the performances of the MHCS conducting experiments [3-12] and using a thermodynamic model [13-20] and lithium bromide - water systems [21-24], separately. A bus air

- conditioning system with approximately 1 kW cooling capacity was developed by Ron [3] using $\text{LaNi}_{4.7}\text{Al}_{0.3} / \text{MmNi}_{4.15}\text{Fe}_{0.85}$. For a cooling time of 3 min, the specific cooling power (SCP) between 565 and 700 W/kg of desorbing hydride was reported. Nagel and his co-workers [4] developed a MHCS of 1.75 kW capacity using $\text{LaNi}_{4.65}\text{Al}_{0.3} / \text{MmNi}_{4.5}\text{Fe}$ hydride pair. The maximum reported COP at 140 °C was about 0.4. Lee et al. [5] investigated the performance of a MHCS using $\text{Zr}_{0.9}\text{Ti}_{0.1}\text{Cr}_{0.9}\text{Fe}_{1.1} / \text{Zr}_{0.9}\text{Ti}_{0.1}\text{Cr}_{0.6}\text{Fe}_{1.4}$. The maximum SCP obtained under the optimum operating conditions of 200 °C /30 °C/18 °C was about 272 W/kg of desorbing hydride. Imoto et al. [6] built a MHCS to generate cold below -20 °C using $\text{LaNi}_{4.6}\text{Mn}_{0.3}\text{Al}_{0.1} / \text{La}_{0.6}\text{Y}_{0.4}\text{Ni}_{4.8}\text{Mn}_{0.2}$. The maximum values of COP and cooling power of the system were 0.45 and 1.86 kW. Kang et al. [7] developed a MHCS using $\text{LaNi}_{4.7}\text{Al}_{0.3} / \text{MmNi}_{4.15}\text{Fe}_{0.85}$ hydride pair. The measured COP was about 0.2. Ram Gopal and Srinivasa Murthy [8] developed a prototype of MHCS with the working pair $\text{ZrMnFe} / \text{MmNi}_{4.5}\text{Al}_{0.5}$. The measured SCP was varied between 30 and 45 W/kg of desorbing alloy for the whole cycle, and the COP varied between 0.2 and 0.35. Willers et al. [9] built a multi-hydride thermal wave device for simultaneous heating and cooling using seven metal hydrides on the high temperature side ($T_d \cong 235$ °C) and two metal hydrides on the low temperature side ($T_c \cong 18$ °C). The cooling power of the device was about 500 W at 10 °C. The COP was 0.60 at the cooling temperatures between 0 °C and 10 °C. Chernikov et al. [10] demonstrated a MHCS using $\text{LaNi}_{4.6}\text{Al}_{0.4} / \text{MmNi}_{4.15}\text{Fe}_{0.85}$. The reported average cold generation rate was about 100 W/kg of desorbing alloy for the whole cycle at operating conditions of 130/25/1.5 °C with a COP of 0.33. Qin et al. [11] developed a MHCS working with $\text{LaNi}_{4.61}\text{Mn}_{0.26}\text{Al}_{0.13} / \text{La}_{0.6}\text{Y}_{0.4}\text{Ni}_{4.8}\text{Mn}_{0.2}$ using exhaust gas from an automobile as a heat source. The average cooling power of the cycle was 85 W, and the system COP was calculated system COP was about 0.26. Ni and Liu [12] tested a prototype of MHCS working with $\text{LaNi}_{4.61}\text{Mn}_{0.26}\text{Al}_{0.13} / \text{La}_{0.6}\text{Y}_{0.4}\text{Ni}_{4.8}\text{Mn}_{0.2}$. For the given operating temperatures of 150 °C/30 °C/20 °C, a maximum COP and cooling rate of 0.3 and 240 W, respectively were obtained.

During the past two decades, numerous works on the thermodynamic analyses and thermal modeling of MHCS have been reported. Some of the important works are highlighted here. Dantzer and Orgaz [13] presented a thermodynamic model for selecting pair of alloys used in MHCS. Nishizkiet al. [14] developed a model for calculating the COP of MHCS and discussed the dependence of COP on various design parameters. Murthy and Sastri [15] presented a basic thermodynamic analysis of two-stage MHCS with five hydride pairs. Gopal and Murthy [16] predicted the performance of a MHCS working with $\text{ZrMnFe} / \text{MmNi}_{4.5}\text{Al}_{0.5}$ for various operating conditions employing a one-dimensional mathematical model in cylindrical co-ordinates. They observed that there exists an optimum value of bed thickness, effective bed thermal conductivity, and overall heat transfer coefficient for any given operating temperatures. Sun [17] presented a thermodynamic model for studying the performances of double-stage MHCS working with six different operating cycles. Dehouche et al. [18] developed a mathematical model of a MHCS employing a multi-hydride thermal wave concept. The modeling was applied to two different reactor geometries, viz., a capillary tube bundle reactor (CTBR) and a metal foam tube reactor (MFTR). The average COP for the MFTR was about 0.4-0.5, whereas the CTBR reactor had a more uniform COP of about 0.6. Satheesh et al. [19] presented a thermal model for investigating the performances of a MHCS working with $\text{MmNi}_{4.6}\text{Al}_{0.4} / \text{MmNi}_{4.6}\text{Fe}_{0.4}$, $\text{LaNi}_{4.61}\text{Mn}_{0.26}\text{Al}_{0.13} / \text{La}_{0.6}\text{Y}_{0.4}\text{Ni}_{4.8}\text{Mn}_{0.2}$, $\text{LmNi}_{4.91}\text{Sn}_{0.15} / \text{Ti}_{0.99}\text{Zr}_{0.01}\text{V}_{0.43}\text{Fe}_{0.09}\text{Cr}_{0.05}\text{Mn}_{1.5}$, $\text{LaNi}_{4.6}\text{Al}_{0.4} / \text{MmNi}_{4.15}\text{Fe}_{0.85}$ and $\text{Zr}_{0.9}\text{Ti}_{0.1}\text{Cr}_{0.9}\text{Fe}_{1.1} / \text{Zr}_{0.9}\text{Ti}_{0.1}\text{Cr}_{0.6}\text{Fe}_{1.4}$ hydride pairs. Their computational results were in good agreement with the experimental data reported by Ni and Liu [12]. The effects of various operating parameters, such as driving heat source and heat sink, and the refrigeration temperatures on the COP and SCP of the system were investigated. For the selected operating temperatures, a maximum COP of 0.66 was predicted for $\text{Zr}_{0.9}\text{Ti}_{0.1}\text{Cr}_{0.9}\text{Fe}_{1.1} / \text{Zr}_{0.9}\text{Ti}_{0.1}\text{Cr}_{0.6}\text{Fe}_{1.4}$ hydride pair, while $\text{LmNi}_{4.91}\text{Sn}_{0.15} / \text{Ti}_{0.99}\text{Zr}_{0.01}\text{V}_{0.43}\text{Fe}_{0.09}\text{Cr}_{0.05}\text{Mn}_{1.5}$ hydride pair produced the highest SCP of about 53.25 W/kg of total mass of the system. The same research group [20] presented the operational characteristics of a double-stage double-effect metal hydride heat pump (DSDE-MHHP) working with $\text{LaNi}_{4.1}\text{Al}_{0.52}\text{Mn}_{0.38} / \text{LmNi}_{4.91}\text{Sn}_{0.15} / \text{Ti}_{0.99}\text{Zr}_{0.01}\text{V}_{0.43}\text{Fe}_{0.09}\text{Cr}_{0.05}\text{Mn}_{1.5}$. For given operating temperatures of 568 / 361 / 296 / 289 K, the average COP and the average SCP of the system were found to be 0.471 and 28.4 W/kg of total hydride mass, respectively.

Klein and Groll introduced the concept of cascading between metal hydride based heat pump (MHHP) and lithium bromide- water cycle [2, 25]. They have built a cascade sorption system consisting of a two-stage MHHP as topping cycle and a single effect lithium bromide-water system as a bottom cycle for continuous cold production. The reported COP of a cascade system was about 1.4 at the driving heat,

heat release and refrigeration temperatures of 310°C, 125°C and 2°C, respectively. But the effects of various operating temperatures on the combined COP and total cold generation of the cascade system are yet to be studied. In this present paper, the authors present a thermodynamic analysis on the cascade sorption cooling system for predicting the effects of various operating temperatures such as driving heat, heat rejection/generator, and refrigeration temperatures, and design parameters such as sensible heat exchange factor, and mass ratio between metal hydride alloy and reactor on the combined COP and the total cold generation of the system.

2. Operating principle of the cascade system

The operating principle of a cascade sorption system is shown in Figure 1. The system consists of a two-stage metal hydride heat pump (MHHP) as topping cycle and a single-effect lithium bromide- water as bottom cycle. The MHHP comprises of three different metal hydrides (MH) namely, high temperature MH $\text{LaNi}_{4.1}\text{Al}_{0.52}\text{Mn}_{0.38}$ (A), intermediate temperature MH $\text{MmNi}_{4.91}\text{Sn}_{0.15}$ (B) and low temperature MH $\text{Ti}_{0.99}\text{Zr}_{0.01}\text{V}_{0.41}\text{Fe}_{0.99}\text{Cr}_{0.05}\text{Mn}_{1.5}$ (C) filled in 6 reactors (two in each). System operates in two half cycles and produces a continuous cold output. As illustrated in Figure 1, during the first half cycle, hydride A_1 desorbs hydrogen by utilizing the driving heat ($Q_{d,A1}$) at T_d , which is absorbed by hydride C_1 releasing the absorption heat ($Q_{m,C1}$) to the ambient at T_m . Simultaneously, hydride B_2 desorbs hydrogen by utilizing heat ($Q_{c,B1}$) at T_e . Since, B_2 is coupled with hydride A_2 ; hydride A_2 absorbs hydrogen from B_2 by releasing heat ($Q_{h,A2}$) at temperature T_h . This heat is used to drive the single-effect lithium bromide-water system bottom cycle. At the same time hydride C_2 desorbs hydrogen by utilizing heat input ($Q_{c,C2}$) at temperature T_e , which is absorbed by hydride B_1 releasing the absorption heat ($Q_{m,B1}$) at temperature T_m . This completes the first half cycle of operation. After the first half cycle, an internal heat recovery between A_1 and A_2 , between B_1 and B_2 and between C_1 and C_2 take place. After the internal heat recovery, the reactors positions are interchanged. The second half cycle consists of the following processes;

(i) A_2 desorbs H_2 by utilizing $Q_{d,A2}$ at T_d and C_2 absorbs H_2 by releasing $Q_{m,B1}$ to T_m .

(ii) B_1 desorbs H_2 by utilizing $Q_{c,B1}$ at T_e and A_1 absorbs H_2 by releasing $Q_{h,A1}$ at T_h .

(iii) C_1 desorbs H_2 by utilizing $Q_{c,C1}$ at T_e and B_2 absorbs H_2 by releasing $Q_{m,B1}$ at T_m .

Heat rejected from hydride A_2 at T_h is utilized to operate the lithium bromide-water cycle. During the operation, two cold outputs from MHHP (from hydrides B and C at T_e) and a continuous cold output from lithium bromide-water system are obtained.

3. Selection of metal hydride alloy pairs for MHHP

The performance of the MHHP depends on the proper selection of the MH alloy pairs. The desirable properties of the MH alloys used for the heat pump applications are:

- High hydrogen storage capacity.
- Enthalpy of formation of the refrigeration alloy (ΔH_C) should be reasonably high or closer to high temperature alloy.
- Reaction kinetics of the alloy pairs should be fast and preferably equal at their respective operating temperatures.
- Minimum desorption pressure of the high temperature alloy at driving temperature (T_d) should be greater than the maximum absorption pressure of the low temperature alloy at heat rejection temperature (T_m).
- The minimum desorption pressure of the low temperature alloy at refrigeration temperature (T_e) should be greater than the maximum absorption pressure of the high temperature alloy at heat rejection temperature (T_h).

Based on the above requirements $\text{LaNi}_{4.1}\text{Al}_{0.52}\text{Mn}_{0.38}$ (A), $\text{MmNi}_{4.91}\text{Sn}_{0.15}$ (B) and $\text{Ti}_{0.99}\text{Zr}_{0.01}\text{V}_{0.41}\text{Fe}_{0.99}\text{Cr}_{0.05}\text{Mn}_{1.5}$ (C) are selected as the suitable MH alloys for the present thermodynamic analysis.

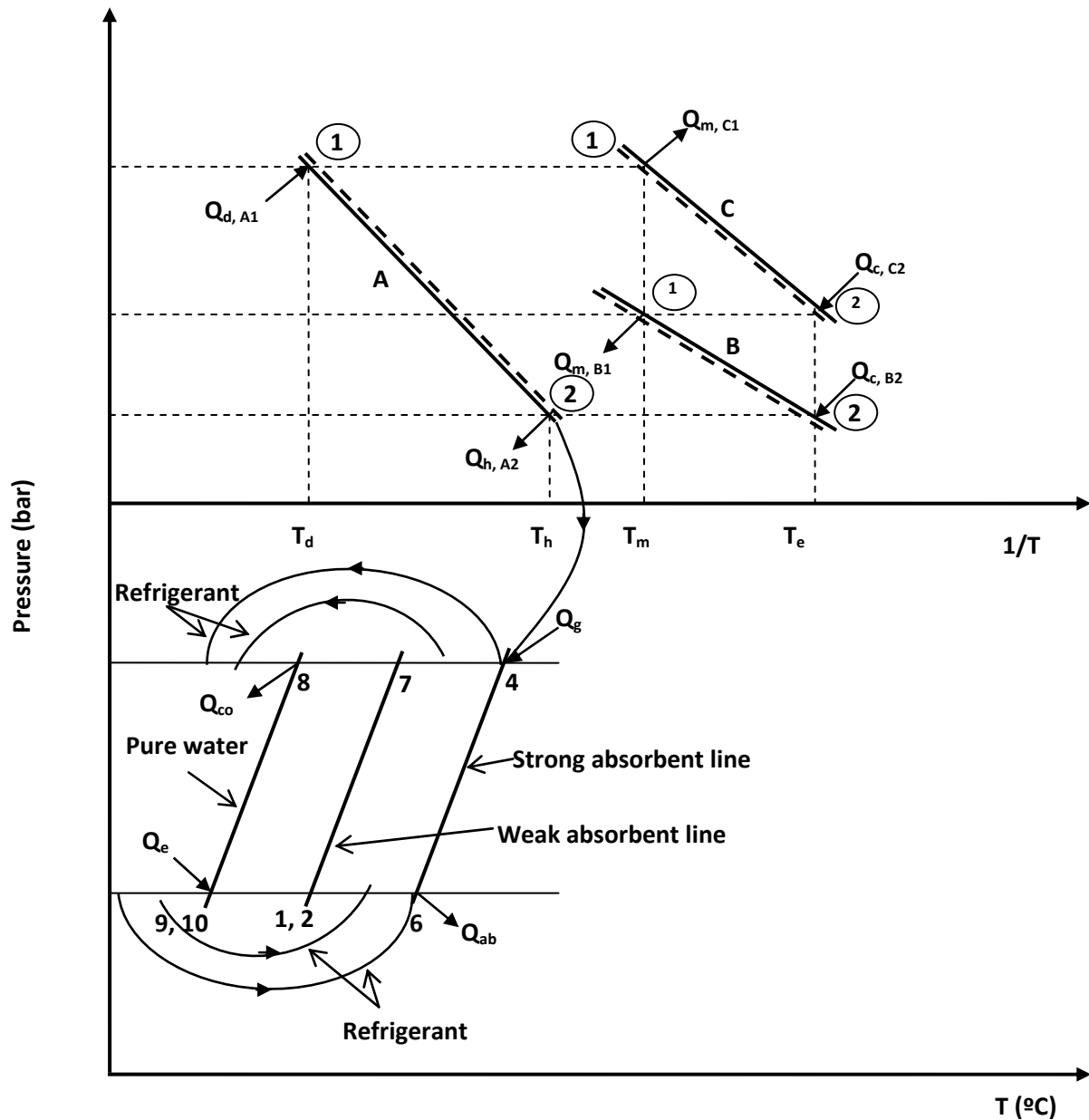


Figure 1. Operating principle of cascade sorption cooling system

4. Thermodynamic analyses

The various assumptions used in the present thermodynamic analysis are listed below.

- The half cycle time (t) is taken as 10 min.
- Thermo-physical properties of the MHs are assumed to be independent of temperature.
- For a given set of operating temperatures, absorption and desorption kinetics of the MH pairs are assumed to be equal.
- The cooling capacities (Q_c) of alloy B and lithium bromide cycle are taken as 3.5 kW. Cooling capacity of alloy C will be calculated based on the operating conditions.
- 75% heat exchange is assumed between MHHP and LiBr₂-H₂O system.
- The system is well insulated.

The PCT characteristics of the selected alloys are generated using the van't Hoff equation.

$$P_{eq} = \exp \left[\frac{\Delta S}{R_u} - \frac{\Delta H}{R_u T} + (\varphi_s \pm \varphi_o) \tan \left(\pi \left(\frac{x}{x_f} - \frac{1}{2} \right) \right) \pm \frac{\varphi}{2} \right] 10^5 \text{ N/m}^2 \quad (1)$$

where, ΔH and ΔS are enthalpy and entropy of reaction [J/mole H_2]. R_u is ideal gas constant [J/mole H_2 - K]. The van't Hoff equation correlates the equilibrium pressure with the hydride temperature, enthalpy of formation and entropy formation. "+" denotes absorption process and "-" denotes desorption process. Metal hydrides used for heat pump applications require high enthalpy formation and moderate operating pressure and temperatures. The hysteresis factor is given by;

$$\text{Hysteresis factor } (\varphi) = \ln \left[\frac{P_{abs}}{P_{des}} \right] \quad (2)$$

where P_{des} and P_{abs} are the equilibrium desorption and absorption pressures at constant temperature T and concentration x . The slope factor is given by;

$$\text{Slope factor } (\varphi_s) = \frac{\ln \left[\frac{P_{x1}}{P_{x2}} \right]}{x_1 - x_2} (x - x_m) \quad (3)$$

The PCT characteristics are generated by considering the effects of hysteresis and slope factors. The amount of hydrogen required (n_{H_2} , moles) for meeting the required cooling load is given by;

$$n_{H_2} = Q_c t / \Delta H_c \quad (4)$$

Required mass of the alloy (m_A , kg) for reactor A is calculated from the total mass of the hydrogen required and the reversible hydrogen storage capacity (wt_A) of the alloy using the following expression.

$$m_A = n_{H_2} / wt_A \quad (5)$$

where

$$wt_A = \frac{1000(x_{max} - x_{min})N_{alloyA}}{2M_A} \quad (6)$$

where x_{max} and x_{min} are the maximum and minimum concentration limits of the alloy, N_{alloyA} is number of metal atoms per mole of alloy and M is the molecular weight of the alloy. The same procedure is repeated for estimating the masses of alloys B and C.

The amount of driving heat (Q_d) is calculated from the enthalpy of formation of the high temperature alloy (A) and the amount of sensible heat requirement to raise the temperature of the metal hydride alloy and the reactor materials from T_h to T_d .

$$Q_d = n_{H_2} \Delta H_{A,DES} + (1 - \phi)(m_{rA} C_{pr} + m_A C_{pA})(T_d - T_h) \quad (7)$$

where ϕ = sensible heat exchange factor. The second term in right hand side of Eq. (7) represents the amount of sensible heating requirement. At any given time, two cooling outputs are obtained from MHHP and hence, the net amount of useful cooling effect obtained from MHHP cycle is given by;

$$Q_c = n_{H_2} \Delta H_{B,DES} - (1 - \phi)(m_{rB} C_{pr} + m_B C_{pB})(T_m - T_e) \\ + n_{H_2} \Delta H_{C,DES} - (1 - \phi)(m_{rC} C_{pr} + m_C C_{pC})(T_m - T_e) \quad (8)$$

where, m_r is the mass of the reactor.

The amount of cooling load required to cool the reactors from T_m to T_e is deduced from the total cooling load. The amount of useful heating output obtained at T_h is estimated as follows

$$Q_h = n_{H_2} \Delta H_{A, ABS} + (1 - \phi)(m_{rA} C_{pr} + m_A C_{pA})(T_d - T_h) \tag{9}$$

The second term in right hand side of Eq. (9) represents the amount of heat recovery from the high temperature reactor. The coefficient of the performance of the topping cycle (COP^{TC}) is defined as the ratio of net cooling effect to the total amount of heat supplied. The coefficient of amplification (COA^{TC}) is defined as the ratio of the amount of useful heat output to amount of driving heat input.

$$COP^{TC} = \frac{Q_c}{Q_d} \tag{10}$$

$$COA^{TC} = \frac{Q_h}{Q_d} \tag{11}$$

The COP's of the bottoming cycle (COP^{BC}) and the combined system (COP^{CS}) are defined as follows [2]

$$COP^{BC} = \frac{Q_{cb}}{Q_h} \tag{12}$$

$$COP^{CS} = COP^{TC} + COP^{BC} COA^{TC} \tag{13}$$

where Q_{cb} is the net cooling output obtained from the bottom cycle.

5. Results and discussion

The thermodynamic analysis of the cascading system is carried out by varying the operating temperatures, and the design parameters such as sensible heat exchange factor and ratio of hydride alloy mass to reactor mass. Thermo-physical properties of the selected MHs are listed in Table 1. List of operating temperatures and their range for both MHHP and lithium bromide-water systems, and range of other design parameters of the MHHP are listed in Table 2.

Table 1. Thermo physical properties of the selected metal hydrides [2]

Metal hydride		Enthalpy (kJ/mol)		Entropy (J/mol.K)		Slope factor f _s		Hystersis factor f	
No	Name	Abs	Des	Abs	Des	Abs	Des	Abs	Des
A	LaNi _{4.1} Al _{0.52} Mn _{0.38}	46.1	48.6	114.6	118.1	0.2	0.22	0.075	0.075
B	MmNi _{4.91} Sn _{0.15}	28.0	30.1	105.4	110.6	0.24	0.28	0.075	0.075
C	Ti _{0.99} Zr _{0.01} V _{0.43} Fe _{0.09} Cr _{0.05} Mn _{1.5}	20.1	25.9	107.4	112.6	0.24	0.23	0.1	0.1

Table 2. List of operating temperatures and their ranges

Sl.No	Parameter	Levels			
1	Heat rejection temperature T _h (°C)	100	115	125	
2	Refrigerant temperature T _c (°C)	2	7	12	
3	Generator Temperature T _g (°C)	100	115	125	
4	Absorber temperature T _{ab} (°C)	-	40	-	
5	Condenser Temperature T _{co} (°C)	-	-	55	
6	Mass ratios (m _r)	0.1	0.25	0.5	
7	Sensible heat exchange factor (ϕ)	0	0.25	0.45	

Note: Italic bold values represent the constant parameter while analyzing the effect of variation of other parameters

In the following section, the effects of various operating and design parameters on the performances of the system are discussed.

5.1 PCT characteristics

Pressure-concentration-temperature (PCT) characteristics of the selected metal hydrides play a major role in fixing the total mass of hydride alloys used in the MHHP system. PCT characteristics of the selected alloys are generated using Eq.(1). The effects of plateau slope and hysteresis factors are considered while generating the PCT. The PCT characteristics of alloys A, B and C at different operating temperatures are illustrated in Figures 2, 3 and 4, respectively. Figure 2 illustrates desorption PCTs of hydride C at 2, 7 and 12°C, and absorption PCTs of hydride B at 30, 35 and 40°C, respectively. The maximum and minimum operating concentration limits between the hydride pair B and C are fixed based on the condition that the minimum desorption pressure of hydride C at 2°C should be greater than the maximum absorption pressure of hydride B at 30 °C, and the corresponding concentration limits are fixed at $x_{\max} = 0.78$ and $x_{\min} = 0.18$, respectively. Similarly, Figures 3 and 4 illustrate the desorption PCT s of hydride A at 300, 310 and 320°C and the absorption PCTs of hydride C at 30, 35 and 40°C, and the desorption PCTs of hydride B at 2, 7 and 12°C and the absorption PCTs of hydride A at 105, 115 and 125°C, respectively. Based on the concentration limits the amounts of reversible hydrogen storage capacities of the three alloys are estimated using Eq. (6). The operating limits between A and C are 0.1 to 0.78, while the operating limits between B and A is 0.2 to 0.8.

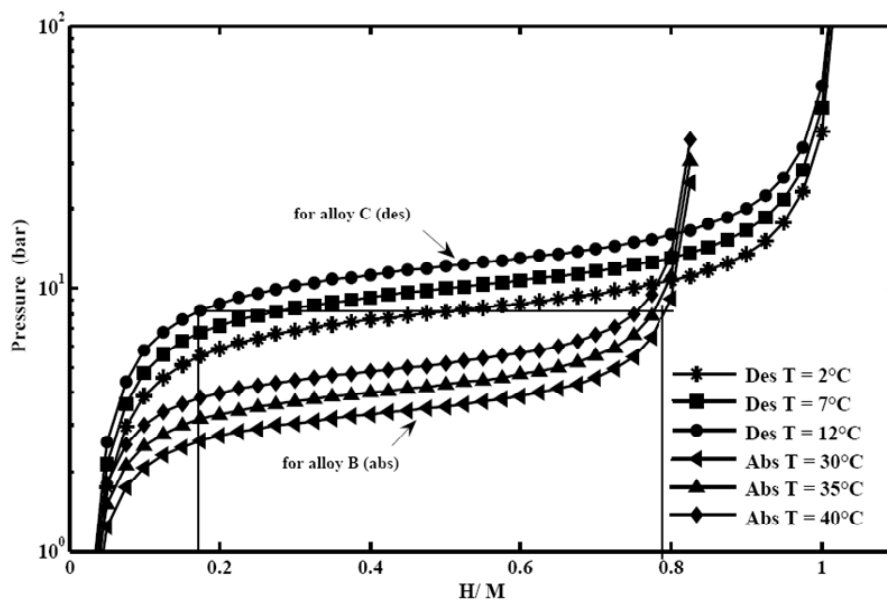


Figure 2. PCT characteristics of C (desorption) and B (absorption) at different operating temperatures

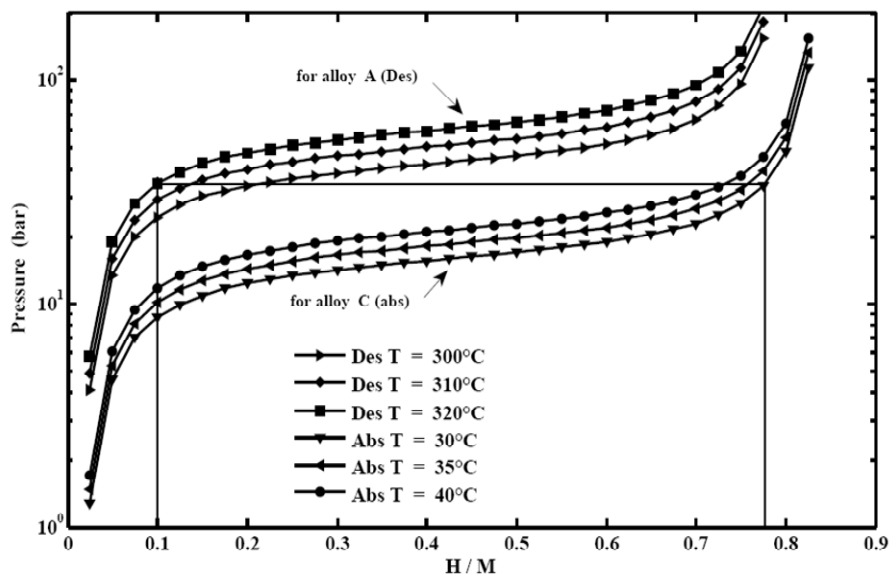


Figure 3. PCT characteristics of A (desorption) and C (absorption) at different operating temperatures

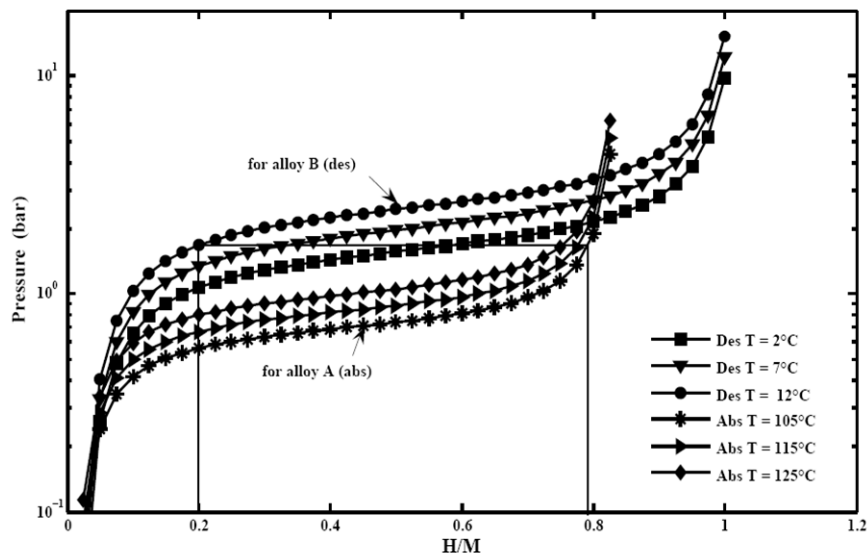


Figure 4. PCT characteristics of B (desorption) and A (absorption) at different operating temperatures

5.2 Effects of driving heat and refrigeration temperatures on the system performance

Effects of driving heat and refrigeration temperatures on the performance of the MHHP in terms of total cold output and SCP are illustrated in Figures 5 and 6. It is observed from Figure 5 that the total cold output from the MHHP cycle is found to increase with driving heat and refrigeration temperatures. For a given refrigeration temperature, the increase in total cold output with driving heat temperature is mainly due to exchange of more amount of hydrogen between the pair of reactors. This is more clearly illustrated in Figures 2 to 4. Similarly at higher refrigeration temperatures, the driving potential (pressure difference between the paired reactors) is more resulting in larger amount of hydrogen exchange. This results in increasing the cooling output. Due to the increase in cooling outputs of both the hydrides (B and C) of the MHHP system, the specific cooling power is also found to increase with driving and refrigeration temperatures, which is illustrated in Figure 6. However, the increase in SCP at higher refrigeration temperature is found to be very marginal. This is due to the fixed the cooling time. At a refrigeration temperature of 12°C, the expected increase in cold out and specific cooling power of the MHHP are about 17% and 18% when the driving heat temperature is increased from 270 °C to 320 °C. Figures 7 and 8 illustrate the effects of operating temperatures on the COPs of the topping cycle and the combined cycle. In general, the COP of the thermally operated sorption system increases with heat source temperature till it reaches a maximum value and then becomes stable. But in the case of two-stage MHHP increasing the heat source temperature beyond a certain value will not improve the COP of the system, as there will not be any hydrogen left out in the hydride. Therefore, increasing the heat source temperature beyond a certain value increases only the sensible heating of the hydride alloy and reactor materials. The increase in COP due to more hydrogen exchange at higher heat source temperature is lesser than the decrease in COP due to increase in sensible heating requirements for both the reactor material and alloy. Further, after the first half cycle, the reactor positions are interchanged. Therefore, hydride mass (m_A) is fixed considering the requirements at T_d and T_h . Even though the system requires low mass of hydride A at higher T_d , due to constraints at T_h , larger among these two positions will be taken for the analysis. Hence, the COP of the MHHP is found to decrease at higher T_d . The combined COP of the system is found to be more at higher refrigeration temperatures (shown in Figure 8). The improvement in the combined COP at higher refrigeration temperatures is mainly from the lithium bromide-water side. At higher refrigeration temperatures, the weak concentration of lithium bromide-water system is found to be lower. As a result, the operating width increases resulting in lower mass flow rate of the solution. Hence, the COP is found to increase due to the reduction in heat requirement. At a given driving heat temperature of 270 °C, increasing the refrigeration temperature from 2 to 12° C, improves the COP of the combined cycle by about 14 %. Based on the above observation one can conclude that the cascade system should be operated just above the threshold limit of the driving heat temperature and higher refrigeration temperatures. However, higher driving heat temperatures improve the capacity of the system significantly (18% improvement in the cooling capacity for a rise of 50°C) at the cost of slight decrease in the overall system COP.

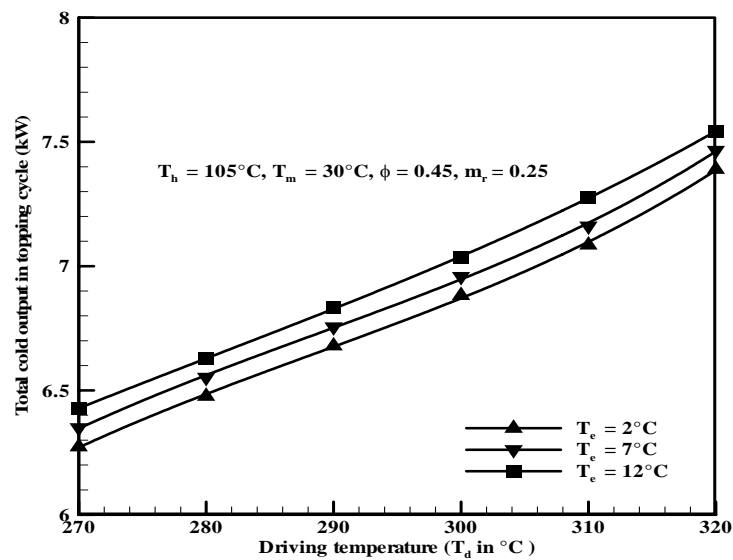


Figure 5. Effects of driving heat and refrigeration temperatures on total cold output of the MHHP cycle

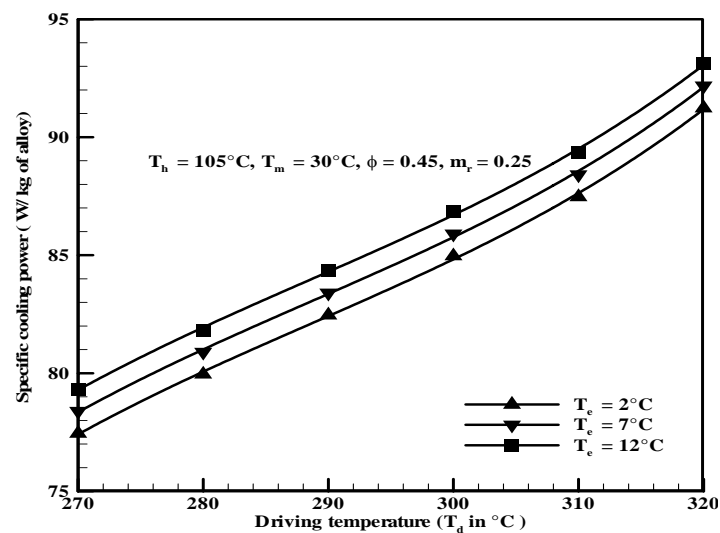


Figure 6. Effects of driving heat and refrigeration temperatures on SCP of the MHHP cycle

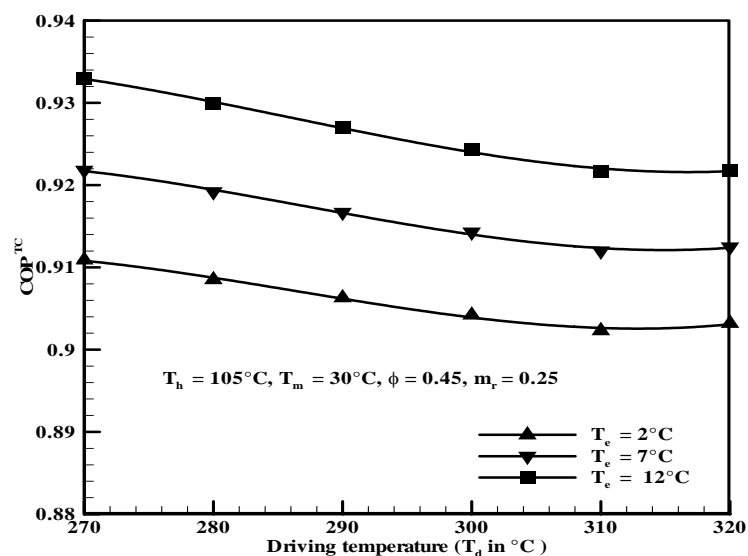


Figure 7. Effects of driving heat and refrigeration temperatures on COP of the MHHP cycle

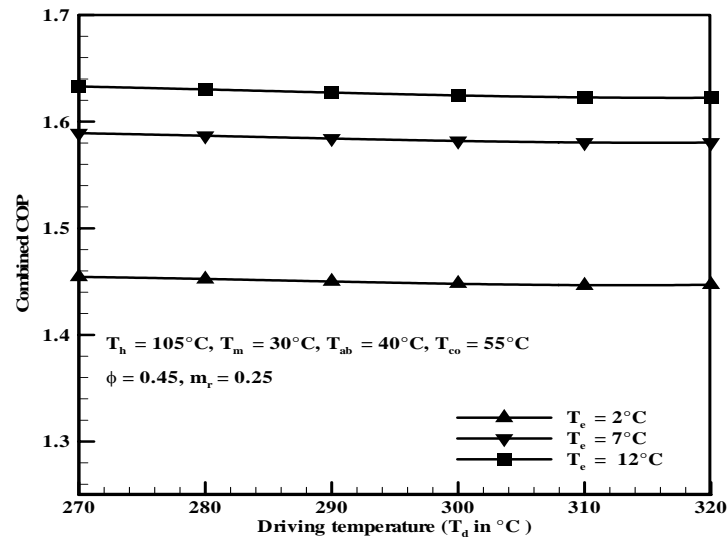


Figure 8. Effects of driving heat and refrigeration temperatures on combined COP

5.3 Effect of heat release temperature on system performances

Figures 9 to 11 illustrate the effect of heat release temperature (T_h) on system performance in terms of specific heating power of MHHP and COPs of both topping and combined cycles. Similar to SCP, specific heating power (SHP) is also a strong function of the driving heat source temperatures. As illustrated in Figure 9 that the improvement in the SHP of the system is very marginal when the heat release temperature is increased from 105°C to 125°C. It is observed from Figure 10 that for a given driving heat temperature, increase in heat release temperature from 105°C to 125 °C increases the COP of the MHHP by about 2 %. This marginal improvement is mainly due to the accumulation of more amount of heat in the hydride alloy and reactor mass in the form of sensible heat at higher T_h and this reduces the sensible heating load from T_h to T_d . Figure 11 reveals that the influence of heat release temperature on the combined COP is also not significant. The COP of the combined cascade system at the operating temperatures of driving heat temperature, $T_d = 320^\circ\text{C}$, heat release temperature, $T_h = 125^\circ\text{C}$ and refrigeration temperature, $T_e = 2^\circ\text{C}$ is 1.45, which closely matches with the experimental value of 1.4 at the same operating temperatures [2]. Since, higher heat release temperature does not have any significant effect on the COPs of the combined or MHHP systems, considering the favorable condition for hydrogen transfer at low pressure side of the MHHP system, heat release temperature of 105 °C could be fixed. The maximum predicted COP of the cascade system is about 1.66 at the operating temperature of $T_d = 270^\circ\text{C}$, $T_h = 125^\circ\text{C}$ and $T_e = 12^\circ\text{C}$.

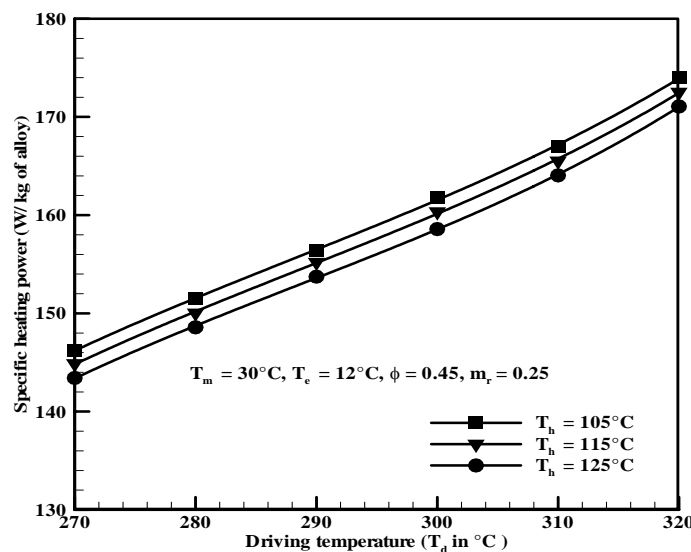


Figure 9. Effects of heat release temperature on specific heating power of the MHHP cycle

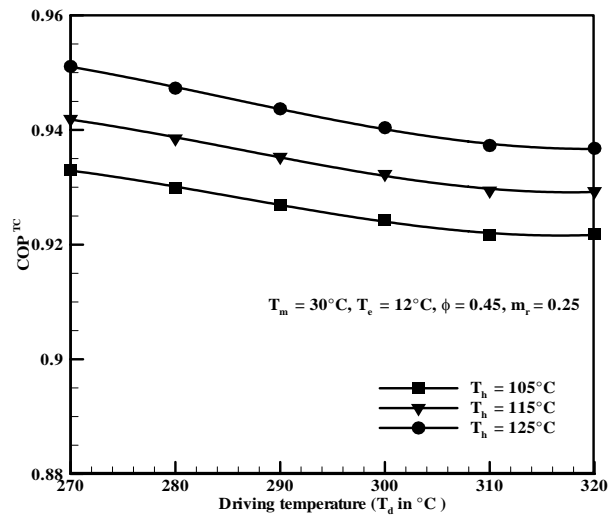


Figure 10. Effect of heat release temperature on COP of the MHHP cycle

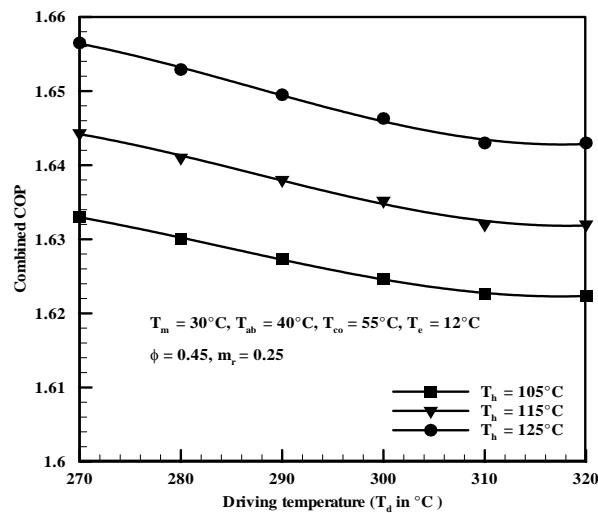


Figure 11. Effect of heat release temperature on combined COP

5.4 Effect of sensible heat exchange factor on the system performance

Effect of sensible heat exchange factor on the performance of the MHHP system is illustrated in Figures 12 and 13. For a given driving heat temperature, the specific cooling power is found to be more at the higher values of sensible heat exchange factor. This is mainly due to the effective utilization of sensible heat available at T_d for heating the reactor A from T_h to T_d after the first half cycle. This will significantly reduce the total heat supplied to the reactor A₂ during the sensible heating process. Because of the internal heat recover, the net cooling capacity and specific cooling power are found to increase due to significant reduction in cooling requirement for cooling the reactors from T_m to T_e . It is observed from Figure 13 that the increase in sensible heat exchange factor from 0 to 0.45 improves the COP of the MHHP by about 20 %. The maximum achievable sensible heat exchange factor for a normal heat exchanger is about 0.5 and in the case of a counter flow heat exchanger or reactor with thermal wave concept, sensible heat exchange factor could be achieved as close as 1.0 [9]. In such cases, the COP of the system is expected to increase further by 25 %. Hence, the introduction of internal heat exchange within the MHHP is a good option for improving the COP at the cost of additional accessories.

5.5 Effect of mass ratio on system performance

Figures 14 and 15 show the effect of mass ratio between the hydride alloy mass and the reactor mass on the performance of the cascade cooling system. The effect of mass ratio on specific cooling power and total cold output is found to be negligible when compared to its effects on the COP. This is mainly to the lesser sensible heat saving corresponding to the temperature difference between T_m and T_e . However, the

effect of m_r on the COP of MHHP and combined COP is significant. Reduction in mass ratio from 0.5 to 0.1 improves the COP of the MHHP system by about 10 %, as a large amount of sensible heat required to rise temperature of the excessive material from T_h to T_d is saved. It should be noted that sensible heating requirement of the reactor material should be kept as minimum as possible. This can be done by choosing lower specific heat material for reactor fabrication or choosing a larger reactor with embedded cooling tubes for effective heat transfer [18].

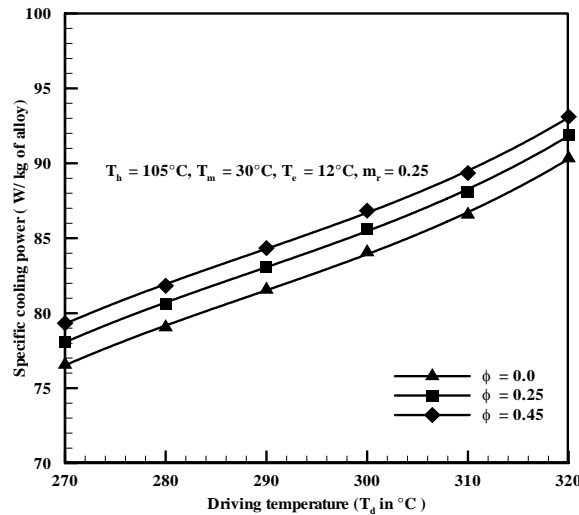


Figure 12. Effect of sensible heat exchange factor on specific heating power of the MHHP

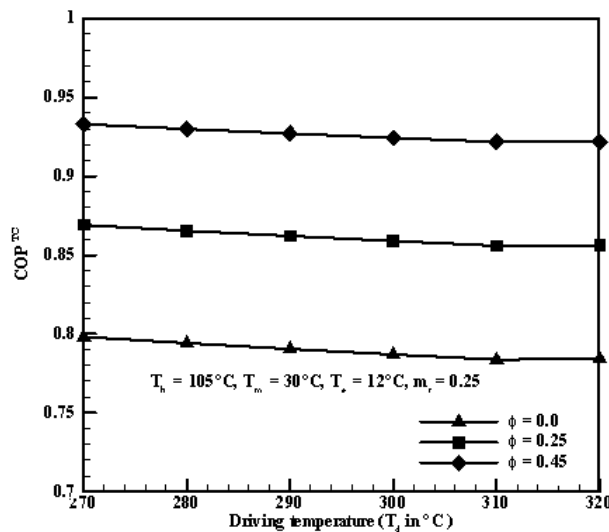


Figure 13. Effect of sensible heat exchange factor on COP of the MHHP

6. Conclusions

A thermodynamic analysis of a cascade sorption system consisting of a two-stage MHHP and a single-stage lithium bromide-water is presented. The effects of various operating temperatures and design parameters on the performances of the cascade system are investigated. Driving heat source temperature has an adverse effect on the system COP. However, 50°C increase in heat source temperature improves the total cooling capacity of the system by about 18%. Higher refrigeration and heat release temperatures improve the COPs of the MHHP cycle and the cascade cycle. Increase in sensible heat exchange factor from 0 to 0.45 improves the COP of the MHHP by about 20%. Within the range of parameters studied a maximum COP of the cascade cycle of about 1.66 is obtained for the driving heat, heat release, heat sink and refrigeration temperatures of 270°C, 125°C, 30°C and 12°C, respectively. Reduction in mass ratio from 0.5 to 0.1 improves the COP of the MHHP system by about 10 %. At the refrigeration temperature of 12°C, the cold out and specific cooling power of the MHHP are found to increase about 17% and

18%, when the driving heat temperature is increased from 270 °C to 320 °C. In general MHHP - lithium bromide water cascade system should be operated just above the threshold limit of the driving heat and heat release temperatures for better overall system performance. Incorporation of suitable internal heat recovery is necessary for the effective heat utilization and also for enhancing the overall COP of cascade system.

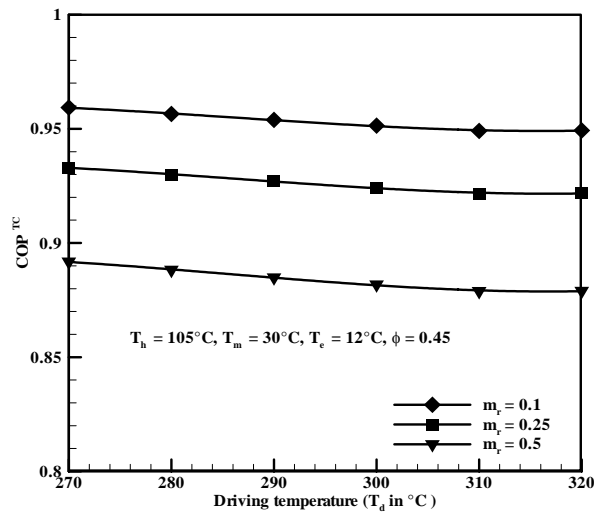


Figure 14. Effect of mass ratio on COP of the MHHP cycle

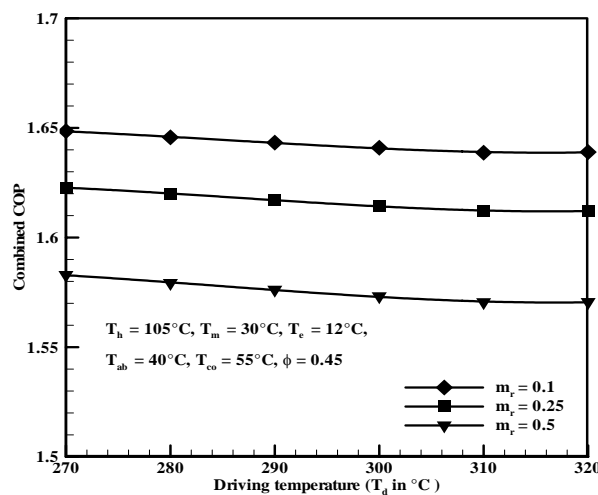


Figure 15. Effect of mass ratio on combined COP

References

- [1] Muthukumar P, Groll M. Erratum to “Metal hydride based heating and cooling systems: A review” [Int J Hydrogen Energy (2010) 35: 3817–3831]. Int J Hydrogen Energy 2010;35:8816-8829.
- [2] Klein HP, Groll M. Development of a two stage metal hydride system as topping cycle in cascading sorption systems for cold generation. Applied Thermal Engineering, 2002, 22:631-39.
- [3] Ron M. A hydrogen heat pump as a bus air conditioner. J Less Common Metals, 1984, 104:259-78.
- [4] Nagel M, Komazaki Y, Uchida M, Suda S. Operating characteristics of a metal hydride heat pump for generating cooled air. J Less Common Metals, 1984, 104:307-18.
- [5] Lee SG, Kim YK, Lee JY. Operating characteristics of metal hydride heat pump using Zr-based laves phases. Int J Hydrogen Energy, 1995, 20:77-85.
- [6] Imoto T, Yonesaki T, Fujitani S, Yonezu I, Hiro N, Nasako K, Saito T. Development of an F-class refrigeration system using hydrogen-absorbing alloys. Int J Hydrogen Energy, 1996, 21:451-5.
- [7] Kang BH, Park CW, Lee CS. Dynamic behaviour of heat and hydrogen transfer in a metal hydride cooling system. Int J Hydrogen Energy, 1996, 21:769-74.

- [8] Gopal MR, Murthy SS.. Experiments on a metal hydride cooling system working with ZrMnFe/MmNi_{4.5}Al_{0.5} pair. *Int J Refrigeration*, 1999, 22:137-49.
- [9] Willers E, Wanner M, Groll M. Multi-hydride thermal wave device for simultaneous heating and cooling. *J Alloys and Compd.*, 1999, (293–295): 915-918.
- [10] Chernikov AS, Izhvanov LA, Solovey AI, Frolov VP, ShaninYuI. An installation for water cooling based on a metal hydride heat pump. *J Alloys Compd.*, 2002, 330-332: 907-10.
- [11] Qin F, Chen J, Lu M, Chen Z, Zhou Y, Yang K. Development of a metal hydride refrigeration system as an exhaust gas-driven automobile air conditioner. *Int. J Hydrogen Energy*, 2007, 32:2034-52.
- [12] Ni J, Liu H. Experimental research on refrigeration characteristics of a metal hydride heat pump in auto air-conditioning. *Int J Hydrogen Energy*, 2007, 32:2567-72.
- [13] Orgaz E, Dantzer P. Thermo dynamics of the HCHP-II: Considerations for multi stage operation. *J Less Common Metals*, 1987, 131:385-98.
- [14] Nishizki T, Miyamoto K, Yoshida K. Coefficient of performance of hydride heat pumps. *J Less Common Metals*, 1983, 89:559-66.
- [15] Murthy SS, Sastri MVC. Thermodynamic analysis of two stage metal hydride heat pumps. *Int J Hydrogen Energy*, 1993, 17:31-7.
- [16] Gopal MR, Murthy SS. Prediction of metal-hydride refrigerator performance based on reactor heat and mass transfer. *Int J Hydrogen Energy*, 1995, 20: 607-14.
- [17] Sun DW. Thermodynamic analysis of the operation of two stage metal hydride heat pumps. *Applied Energy*, 1996, 54:29-47.
- [18] Dehouche Z, Jong WD, Willers E, Isselhorst A, Groll M. Modeling and simulation of heating/air-conditioning systems using the multi-hydride thermal-wave concept. *Applied Thermal Engineering*, 1998, 18:457-80.
- [19] Satheesh A, Muthukumar P. Performance investigations of a single-stage metal hydride heat pump. *Int J Hydrogen Energy*, 2010, 35: 6950-6958.
- [20] Satheesh A, Muthukumar P. Performance Investigation of a Double-Stage Double-effect Metal Hydride Heat Pump. *Applied Thermal Engineering*, 2010, 30 (17-18): 2698-2707.
- [21] Aphornratana S, Eames IW. Thermodynamic analysis of absorption refrigeration cycles using the second law of thermodynamics method. *Int J Refrigeration*, 1995, 18:244-52.
- [22] Sun DW. Thermo dynamic design data and optimum design maps for absorption refrigeration systems. *Applied Thermal Engineering*, 1997, 17:211-21.
- [23] Florides GA, Tassou SA, Wrobel LC. Design and construction of LiBr–water absorption machine. *Energy Conversion and Management*, 2003, 44:2483-2508.
- [24] Kaynakli O, Kilic M. Theoretical study on the effect of operating conditions on performance of absorption refrigeration system. *Energy Conversion and Management*, 2007, 48:599-607.
- [25] Klein HP, Groll M. Development of a two stage metal hydride system as topping cycle in cascading sorption system for cold generation. 2nd Int.Heat powered Cycle Conference. Paris 2001.



P. Muthukumar received PhD degree in Mechanical Engineering from IIT Madras during 2005. He joined at IIT Guwahati as Assistant Professor in January 2006 and he became Associate Professor in January 2010. He received DAAD research fellowships during September – December 2000, June-July 2008, and June - July 2010. He is the recipient of IEI Young Engineer Award - 2010 in Mechanical Engineering from Institute of Engineers (India). He is the reviewer of many international journals in the area of hydrogen energy, energy storage, refrigeration, and heat transfer. He has published over 80 research articles in various international journals and conference proceedings. His area of interests are hydrogen energy storage, metal hydride based thermal machines, coupled heat and mass transfer in porous medium, porous medium combustion, sorption heating and cooling systems, etc.
E-mail address: pmkumar@iitg.ernet.in; pmuthukumar@yahoo.com



D.V.N. Lakshmi received M. Tech degree in Mechanical Engineering from IIT Guwahati in 2008 in the specialization of Fluid and Thermal Science. She has carried out her M. Tech thesis work under the supervision of Dr. P. Muthukumar. At present she is working as Assistant Professor in C. V. Raman College of Engineering, Bhubaneswar, Odisha, India. Her area of interests are hydrogen energy storage, metal hydride based thermal machines and computational fluid dynamics.
E-mail address: lakshmiratan2311@gmail.com