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Thermodynamic investigation of a novel metal hydride based solar thermal energy storage reactor for solar bakery unit: Energy and Exergy analysis

Iqra Ayub[1], Muhammad Salman Nasir[2], Yang Liu[1], Anjum Munir[3], Zaoxiao Zhang[1*]

[1]State key Laboratory of Multiphase Flow in Power Engineering, School of Chemical Engineering and Technology, Xi'an Jiaotong University, No.28 Xianning West Road, Xi'an 710049, P. R. China. (*) email: zhangzx@mail.xjtu.edu.cn

[2]Shcool of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China.

[3]Department of Energy Systems Engineering, University of Agriculture, Faisalabad 38000, Pakistan.

ABSTRACT

Metal hydride based concentrated solar thermal energy storage system is an effective way to overcome the problem of incompatibility between solar system and its users. This research article presents thermodynamic analysis of a novel metal hydride (MgH_2 + V_2O_5) based solar thermal energy storage reactor for bakery unit operated by Scheffler reflector. The three key parameters for performance assessment, exergy efficiency, improvement potential rate (IP) and exergetic factor (f) were determined. It was found that the Scheffler receiver and the HTMH reactor deals with considerable quantity of solar energy and exposed energy losses. These components possessed high IP rate (6.574 kW, 0.534 kW), high f value (85.68%, 6.73%) and low exergy efficiency (15%, 13.8%) as compare to bakery unit. Thermodynamic investigation of high temperature metal hydride reactor presented variations in rate of energy stored (Q_{stored}), efficiency of charging process (η_{ch}), exergy losses and exergy efficiency in the range of 229–2066 kW, 50–90%, 0.109–1.017 kW and 9.63–49.82%, respectively. Research findings provide a comprehensive approach to perform the thermodynamic analysis of metal hydride based solar thermal energy storage reactor for solar bakery unit and pointed out the tendency of system optimization for efficient energy storage.

Keywords: Solar thermal energy storage, metal hydride reactor, bakery unit, energy and exergy analysis

Nomenclature

Abbreviations

MHTES	Metal Hydride thermal energy storage
HTMH	High temperature metal hydride
LTMH	Low temperature metal hydride
HTF	Heat transfer fluid

Symbols

Q	Energy (kW)
η	Efficiency (%)
Ex	Exergy (kW)

Subscripts

l	loss
ch	Charging process
r, in	Inlet of reactor
r, out	Outlet of reactor

1. INTRODUCTION

Solar thermal energy is the best opportunity for cooking and baking applications. Storage of thermal energy for the continues working at a temperature of around 400°C is the major issue. There is an urgent need to develop efficient system and materials for high temperature thermal energy storage (TES), which enables the solar based technologies for continues working. Mg-based metal hydrides are considered as an auspicious choice for high temperature TES materials [1]. Kumar S et al. [2] used vanadium doping to improve the reaction kinetics of Mg bed. It was found that there is noteworthy rise in temperature (up to 192.5°C) in just 40s during absorption. Meng et al. [3] presented the thermodynamic analysis of metal hydride based Combined Cooling, Heating and Power system operated by solar thermal energy. Ayub et al. [4] presented the comprehensive theoretical analysis of novel solar bakery unit. The overall exergy efficiency of bakery system was calculated as 59.26%. Ayub et al. [5] conducted the research on design, development and CFD simulation of solar bakery unit. It was concluded that only small portion 0.201 kW of energy was utilized by the cake out of the total energy of 3.29 kW and as a result the value of energy utilization ratio (EUR) in baking chamber was estimated as 45%. It was found that there is a loss of considerable amount of energy and we must design an appropriate solar energy storage system for solar bakery unit.

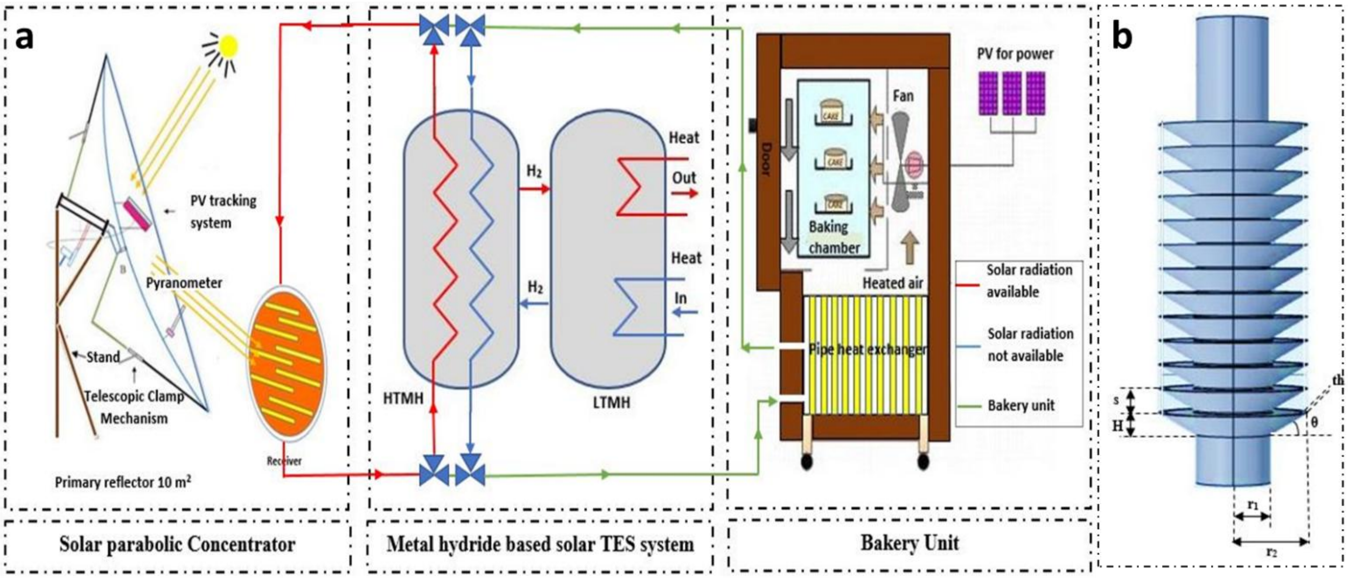


Fig. 1. a) Schematic diagram of the novel solar bakery unit using MH-TES system b) Design of annular fins type heat exchanger

The proposed system in this investigation comprised of 3 major parts: 1. metal hydride pair ((MgH_2 + V_2O_5)/ $LaNi_5$) based reactors 2. Scheffler reflector and 3. bakery unit. The first and second laws of thermodynamic were used for performance evaluation of the system. This paper presents the influence of system design configurations on systems efficiency and assistance in optimization of system.

2. MATERIAL AND METHODS

2.1 Working principle and system configuration

The schematic diagram of the proposed integration of metal hydrides system with the solar bakery unit is shown in Fig 1(a). During the sunshine hours, the bakery unit is driven directly by the solar Scheffler reflector. The accessible excess thermal energy is stored in the MH-TES system. During the charging process, the high-temperature metal hydride (HTMH) material absorb the solar thermal energy from high temperature HTF and release the hydrogen by dehydrogenation of metal hydride. The hydrogen liberated from HTMH is then absorbed by low-temperature metal hydride (LTMH) material through an exothermic process.

In contrast, during the night time or during cloudy weather condition, the discharging process occurs. The hydrogen is transferred back to HTMH from LTMH and thermal energy is released by the hydrogenation of HTMH. The exothermic hydrogen absorption of HTMH delivers the required heat to the bakery unit for baking operation while direct solar thermal heat is inaccessible. For dehydrogenation of LTMH, heat is provided to the LTMH by using hot water. The water gets hot by absorbing the heat released during hydrogen absorption process and stored in the water tank provided with LTMH reactor. However, the temperature may not be enough to support the dehydrogenation of LTMH, so an electric heater operated by battery charged from PV panel and a temperature controller are also required.

Referring to the work of Mellouli S et al. [6] the MH-TES system presented in this research work is shown in Fig. 2 and the geometrical parameters of this innovative system are listed in Table 1. The proposed MH-TES system consists of a two stainless steel metal hydride tanks coupled by a pipe for the movement of H_2: 1) HTMH tank filled with Nano-engineered (MgH_2 + V_2O_5) composite as energy storage medium that could be dehydrogenated even below 200^oC [4]. 2) LTMH tank for $LaNi_5$ that is carefully chosen as LTMH (operating at less than 100^oC) as hydrogen storage medium. An annular inclined fins type heat exchanger (presented in Fig. 1(b)) is designed and installed inside both MH tanks for efficient heat transfer and reduction of stress creating by the enlargement and the shrinkage behavior of the MH bed which in turn avoids the cracking of the pipe and fins. The synthetic oil Dowtherm A is used as high temperature HTF and the water is selected as the low temperature HTF.

Table 1. The detailed Geometric parameters of MH-TES

Geometric parameters	HTMH	LTMH

Radius of reactor, R_{Tank} (m)	0.1	0.1
Radius of pipe, R_{Pipe} (m)	0.048	0.048
Length of metal hydride bed, L (m)	0.8	0.5
Total length of reactor, L_{Tank} (m)	1	0.7
Number of fins	40	24
Fin height, H (m)	0.02	0.02
Fin thickness, th (m)	0.004	0.004
Fins spacing, s (m)	0.02	0.02
Total volume, Vt (m^3)	0.023	0.0086

2.2 Thermodynamic analysis

In this article, first and second laws of thermodynamics are applied successively for comprehensive system analysis. The energy efficiency of charging process was calculated by using Eq. 1.

$$\eta_{ch} = 1- \frac{Q_{l,ch}}{Q_{ch,TES}} \quad (1)$$

Exergy loss and exergy efficiency during the charging mode of HTMH reactor are given as follows:

$$E_{x,l} = E_{x-r,in} - E_{x,-r,out} \quad (2)$$

$$\eta_{ex,ch} = \frac{E_{x-r,out}}{E_{x,-r,in}} = 1- \frac{E_{x,l}}{E_{x,-r,in}} \quad (3)$$

3. RESULTS AND DISCUSSION

Here we consider the climatic conditions of Faisalabad, Pakistan for discussion. The scheme of monthly average ambient temperature and the average

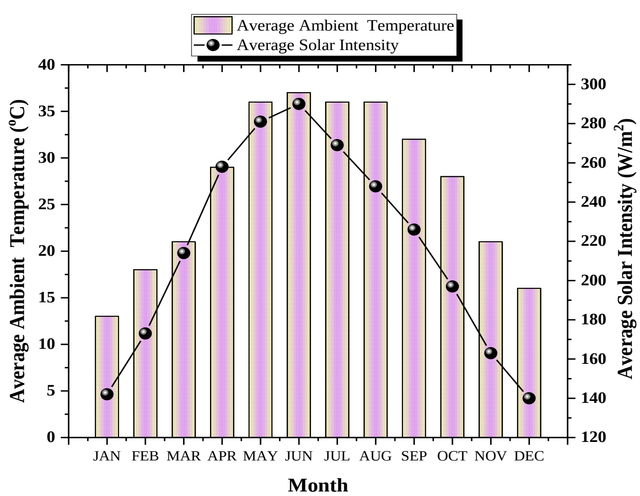


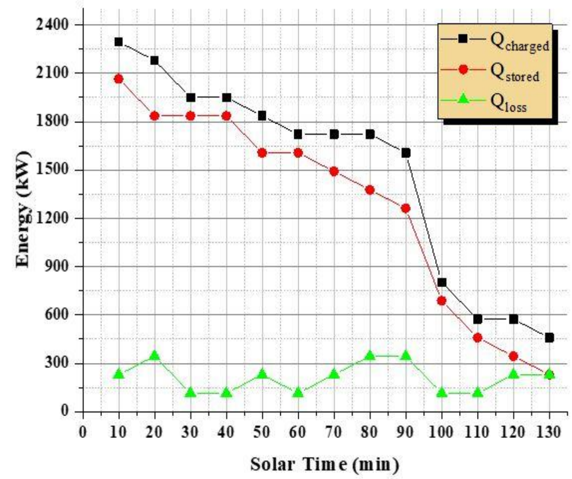
Fig 2 Average ambient temperature and solar intensity in 2015 at Faisalabad

solar intensity in 2015 at Faisalabad is shown in Fig. 2.

3.1 Energy Analysis

Fig. 3 shows the amount of energy charged, stored and lost as a function of solar time in HTMH reactor during dehydrogenation of MgH_2+V_2O_5 (HTMH). It can be observed that the initially energy storage increases due to a high temperature gradient between HTF and HTMH and then decreases gradually with solar time.

Correspondingly, Fig. 4 represents the comparative view between energy efficiency of reactor during charging process, energy efficiency of Scheffler receiver and energy utilization ratio (EUR) of bakery unit. It can be clearly observed that energy efficiency of Scheffler receiver rises from 35 to 63% by virtue of rise in temperature at receiver. During the entire energy storage process, the energy efficiency of charging



process decreased from 90 to 50%.

Fig. 3. Amount of energy charged, stored and lost in HTMH during charging process

The energy transfer efficiency increased for the first half of charging process and then begin to decrease as a result of little rate of heat transfer due to already heated recirculated oil.

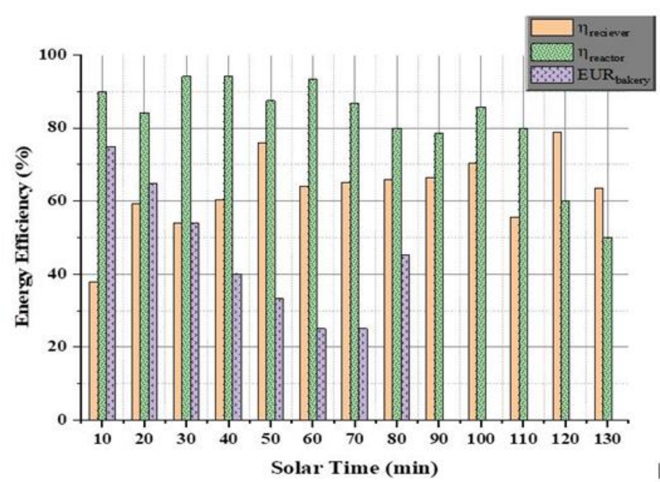


Fig. 4. Scheme of energy efficiency of MHTES system for bakery unit

From Fig. 4, it is found that the value of energy utilization ratio (EUR) of bakery unit was estimated high (75%) initially due to more heat transfer to the baking product and declined (25%) afterward.

3.2 Exergy Analysis

The comparative view between exergetic efficiency and exergy loss of Scheffler receiver, reactor and bakery unit are presented in Figs. 5 and 6. The results estimation shows that the solar intensity is the major factor affecting the system efficiency. The system's exergy efficiency can be enhanced by increasing the exergy efficiency of MH-TES system depends upon the solar intensity.

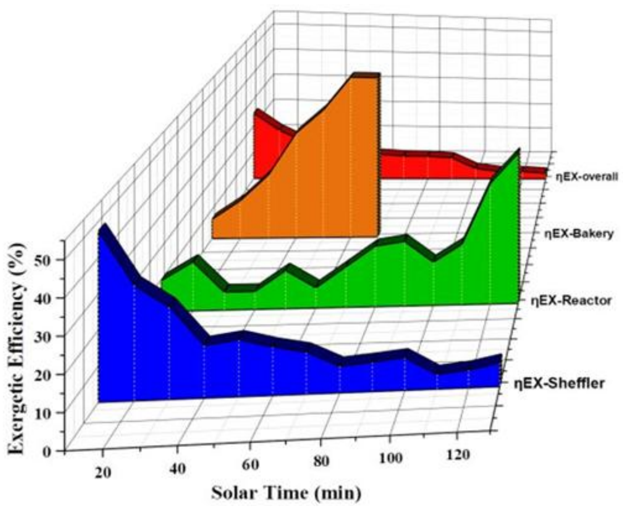


Fig. 5. Scheme of exergy efficiency of entire system (Scheffler receiver, reactor and bakery unit)

Fig. 6 presents that the Scheffler receiver has the highest values of exergy loss as compare to the other system components. Therefore, we can optimize the design of receiver to make it more efficient. Different strategies will be adopted for design improvement of receiver are: Firstly, efficient insulation of receiver and pipelines is required. Secondly, we can cover the receiver with the tempered glass and create a vacuum between the receiver surface and glass in order to avoid the conduction and convection losses. Thirdly we can change the design of receiver by providing the secondary reflector such as glass mirrors around the circumference of receiver in order to further concentrate the reflected radiations towards receiver. It was also observed that exergy loss decreases as the solar time proceeds. The maximum and minimum values of exergy loss were calculated as 1.1 and 0.1 kW respectively.

3.3 Performance Assessment of Overall System

The three important parameters; exergy efficiency, improvement potential rate (IP) and exergetic factor (f) were determined in order to investigate the relative inefficiencies of system. Higher value of exergetic factor of any component means that higher quantity of energy is utilized by this component. Correspondingly, higher value of IP for a component presumes the probable enhancement in that component to make the system efficient.

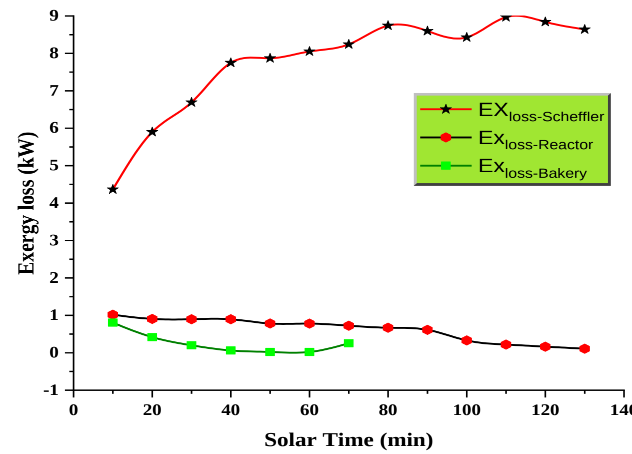


Fig. 6. Scheme of exergy loss of whole system

3.4 Experimental and Predicted Results

Polynomial cubic model was solved by using Sigmaplot-14 for the sake of relating the experimental results with the model outcomes. Following equation (4) is used for the basic polynomial cubic model:

$$Y = y_o + ax + bx^2 + cx^3 \quad (4)$$

Fig. 7 presents the comparative trend between the experimental and predicted parameters: a) energy utilized/stored by reactor, b) energy efficiency of reactor during charging process, c) reactor exergy loss and d) reactor exergetic efficiency. All the parameters were found to be best fitted. These calculated outcomes can be further applied for the design optimization of entire system.

4. CONCLUSIONS

This research article presents the thermodynamic investigation of novel metal hydride based solar thermal energy storage reactor for bakery unit powered

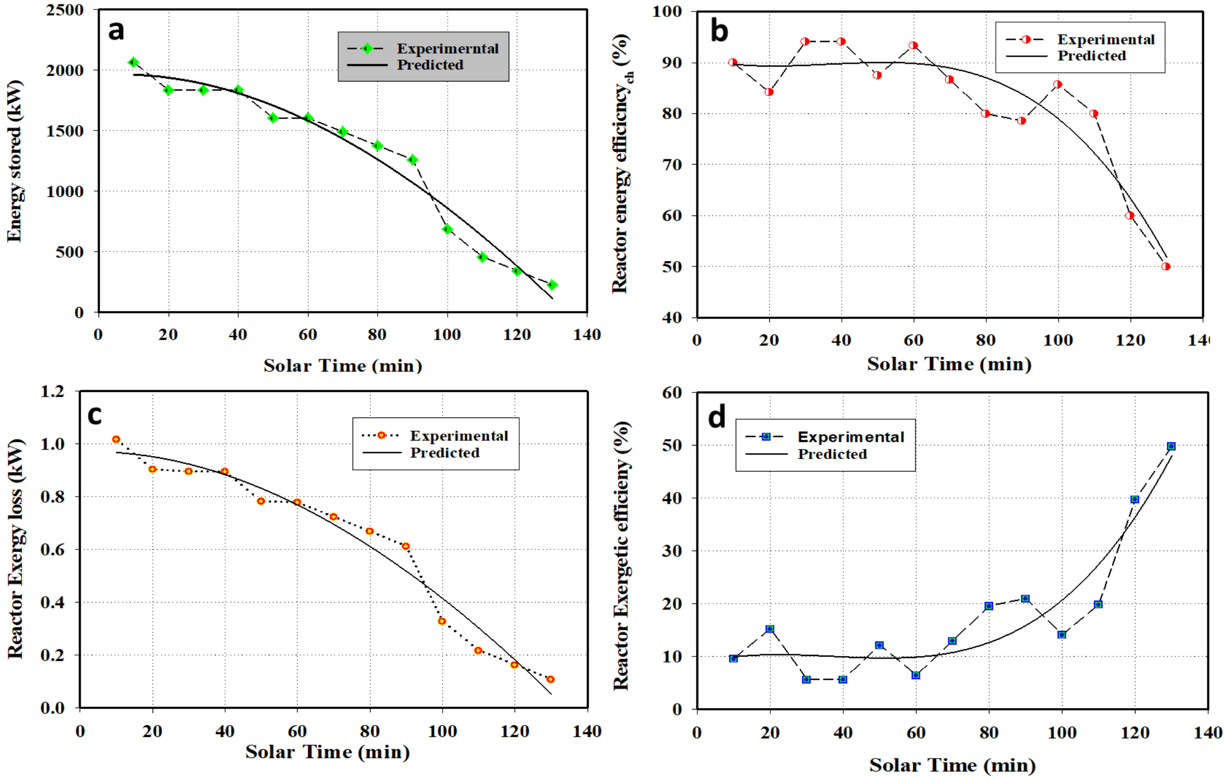


Fig. 7 Comparative trend between experimental and model predicted parameters: a) rate of energy stored, b) reactor energy efficiency during charging process, c) reactor exergy loss, d) reactor exergy efficiency

by Scheffler reflector. It was found that the Scheffler receiver and the HTMH reactor deals with considerable quantity of solar energy and exposed energy losses. These components possessed high IP rate (6.574 kW, 0.534 kW), high f value (85.68%, 6.73%) and low exergy efficiency (15%, 13.8%) as compare to bakery unit. The overall exergy efficiency of the whole system was estimated as 18.7%. It is summarized that intensity of solar radiation is the main parameter affecting the system performance. It was concluded that firstly, modification in the design of receiver and heat exchanger is required to improve the system efficiency. Secondly, the proposed novel system with MH-TES has a better performance as compare to system without energy storage system.

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