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Design and performance characterization of aqueous sodium hydroxide based thermochemical storage systems: Experimental and thermodynamic comparative analysis among various heat exchanger designs and working pairs#

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ABSTRACT

Absorption thermal storage technology has emerged as a viable option for both long and short term energy storage applications. Aqueous sodium hydroxide (NaOH) water pair has shown potential for high storage density and long-term storage. The present study experimentally investigates the impact of various design and operating conditions on the absorption performance of an aqueous sodium hydroxide storage system. The heat and mass transfer characteristics are further analysed and compared for two finned heat exchangers with various aspect ratios along with their energy and exergy performance characteristics. It has been observed that the solution depth is more critical to the system performance over the heat exchanger surface area, with a storage density reduction of up to 41.2% for the heat exchanger with higher fin height. Higher exergy efficiency is also observed for the heat exchanger with lower fin height owing to its better absorption characteristics. The performance of $NaOH-H_2O$ based heat exchangers is finally compared with that of the $LiBr-H_2O$ pair over a microchannel membrane heat exchanger design from the literature. It is seen that the $LiBr-H_2O$ pair offers a lower storage density by around 55% compared to the $NaOH-H_2O$ pair. The findings of the present study suggest significant potential for the $NaOH-H_2O$ pair and can assist in identifying better heat exchanger designs for thermal storage applications.

Keywords: absorption storage, thermal storage technologies, NaOH, LiBr, exergy, microchannel

NONMENCLATURE

Abbreviations	
Re	
Sc	Reynold's number
Sh	Schmidt number
	Sherwood number
Symbols	
m	Mass flow (kg/s)
h	Enthalpy (kJ/kg)
s	Entropy (kJ/kg.K)
T	Temperature (K)
D	Diffusivity (m^2/s)
d_h	Hydraulic diameter (m)
μ	Viscosity (Pa.s)
Subscripts	
avg	average of the inlet and outlet
in	inlet
out	outlet
ref	reference value of property at 25°C
v	vapor

1. INTRODUCTION

Thermal energy storage is seen to facilitate the integration of various renewable energy sources and waste heat recovery for various domestic and industrial thermal needs [1]. Absorption thermal storage technology is seen to offer the highest energy storage density along with enabling compact heat exchanger designs owing to the better heat and mass transfer characteristics [2]. Among the various widely studied absorption working pairs such as lithium chloride-water ($LiCl-H_2O$), lithium bromide-water ($LiBr-H_2O$), etc., aqueous sodium hydroxide ($NaOH-H_2O$) pair has emerged as a cheaper alternative [3] for long term storage applications.

The potential assessment of the $NaOH-H_2O$ pair for domestic heating applications has been explored in our previous study [4]. The effectiveness of a finned heat exchanger design for the $NaOH-H_2O$ pair was studied by various researchers in the literature [5,6]. The present

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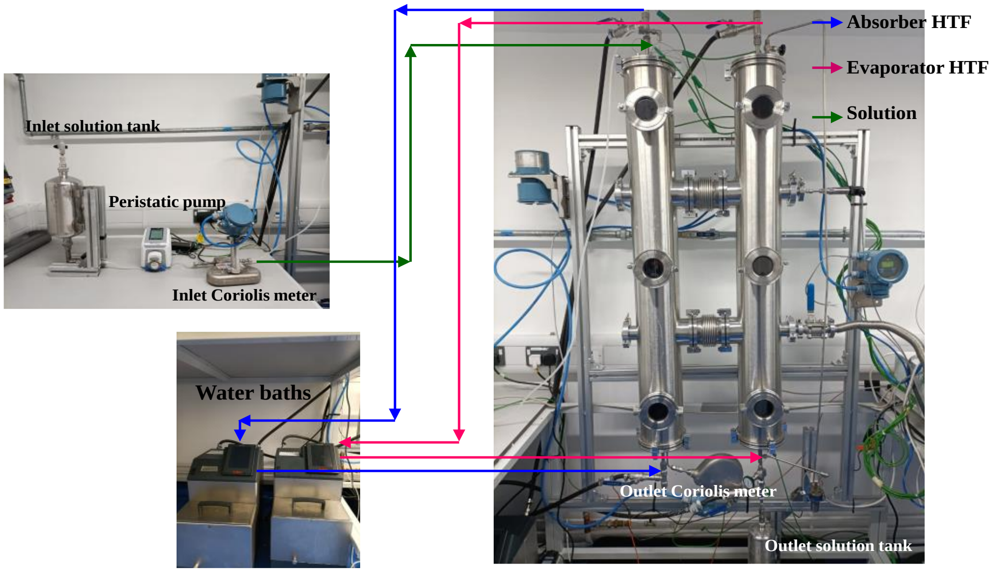

Figure 1. Absorption storage test rig layout

study attempts to further the performance characterization of the $NaOH-H_2O$ pair over 2 finned heat exchanger tubes through a non-dimensional analysis. This characterization could facilitate the selection of the appropriate heat exchanger design as well as various operating parameters for the desired application. Second law analysis of the $NaOH-H_2O$ pair, which can help to identify and reduce the irreversibility of the system hasn't been carried out in the literature as far as the knowledge of the authors is concerned. To address this gap, the present study carries out an exergy evaluation of the system with the two absorption heat exchangers. Finally, the efficacy of the $NaOH-H_2O$ pair is evaluated on a compact microchannel membrane based heat exchanger from the literature and compared with that of the widely studied $LiBr-H_2O$ pair. Thus, the thermodynamic characterization presented in this study can assist researchers to assess the potential of $NaOH-H_2O$ pair over other widely used pairs for absorption storage in the literature, along with facilitating the heat exchanger design and operating parameter selection.

2. SYSTEM DESCRIPTION

2.1 Experimental test rig

The experimental test setup layout of the NaOH absorption rig developed at the University of Warwick is shown in Figure 1. It can be seen that there are two cylindrical vessels for absorption and evaporation, connected to solution tanks and water baths to regulate the heat transfer fluid temperature as described in our previous work [5]. The vessels are fitted with a spiral finned heat exchanger each. The solution heat exchanger has a preheating section on the first 15cms to enhance the heat transfer. The absorption heat exchanger has two thermocouples positioned at the end of the preheating section and the end of the heat exchanger respectively, to measure the solution inlet and outlet temperatures. A similar thermocouple arrangement is provided for the evaporator vessel as well. The specifications of the finned heat exchangers are provided in Table 1.

Table 1. Finned heat exchanger dimensions

Heat exchanger	Length (m)	Outer diameter (mm)	Pitch (mm)	Fin height (mm)
HEX 1	1.04	12.7	1.9	3
HEX 2	1.04	15.8	1.9	6.35

2.2 Membrane based microchannel heat exchanger

The membrane based microchannel heat exchanger design adopted by Isfahani and Moghaddam (2013)[7] is considered in the present study. A channel depth of 0.16mm and a channel width of 1mm are considered for the heat exchanger with the total water mass flow rate fixed at 13kg/hr. The mass flow rates of the solution along with the other heat exchanger dimensions are varied to maintain identical discharge heat and water temperature conditions as that of the experimental test rig.

3. MATHEMATICAL MODELING

3.1 Heat and mass transfer parameter evaluation

The key non dimensional parameters of the heat and mass transfer of the experimental test rig are evaluated as follows:

$$Re = \frac{\rho_{avg} v d_h}{\mu_{avg}} \quad (1)$$

$$Sc = \frac{\mu_{avg}}{\rho_{avg} D_{avg}} \quad (2)$$

$$Sh = \frac{\dot{m_v}}{A(\rho_{in} - \rho_{out}) D_{avg}} \quad (3)$$

Further, storage density is a key performance index evaluated using equation (4).

$$Storage\ density = \frac{Q_{disch}}{\dot{m_{s,in}}} \quad (4)$$

$$Q_{disch} = \dot{m_w} \times 4.18 \times (T_{w,out} - T_{w,in})$$

3.2 Exergy evaluation

The exergy input and outputs in the absorption process is evaluated as shown in equations (5-7). The exergy efficiency is evaluated based on these equations as shown in equation (8).

$$\mathrm{Ex_{in}} = \mathrm{Ex_{sol\,in}} + \mathrm{Ex_v} - \mathrm{Ex_{sol\,out}} \quad (5)$$

$$\mathrm{Ex_{out}} = \mathrm{Ex_{htf\,out}} - \mathrm{Ex_{htf\,in}} \quad (6)$$

Where $\mathrm{Ex_k} = \dot{\mathrm{m}}_\mathrm{k}(\mathrm{h_k} - \mathrm{h_{ref}}) - \mathrm{T_o}(\mathrm{s_k} - \mathrm{s_{ref}})$ (7)

$$\mathrm{Ex_{eff}} = \frac{\mathrm{Ex_{out}}}{\mathrm{Ex_{in}}} \quad (8)$$

3.3 Microchannel membrane heat exchanger heat and mass transfer

The heat and mass transfer resistances of the microchannel heat exchanger are evaluated using the correlations described by Venegas et al. (2016) [8]. The vapor flux at a given length is evaluated as shown in equation (9).

$$\dot{m_v''} = \frac{P_{eva} - P_{eq}(T_{sol}, X_{sol})}{R_{tot}} \quad (9)$$

$$\dot{m_w} C_p \frac{dT_w}{dx} = \frac{d\dot{m_s} h_s}{dx} + \dot{m_v''} h_v W \quad (10)$$

4. Results and discussion

4.1. Parametric analysis of the NaOH-H_2O absorption

The performance comparison of the two heat exchanger designs at various evaporation temperatures is shown in Table 2. It can be seen that the discharge power and storage density are higher for HEX 1 with lower fin height. The higher mass transfer resistance with increasing solution depth is observed to be the critical parameter affecting the system performance.

Table 2. Absorption performance comparison among the two heat exchangers for NaOH-H_2O pair

Evaporator temp. (℃)	Water inlet temp. (℃)	Discharge power (W)		Storage density × 10^3(MJ/m³)	
		HEX 1	HEX 2	HEX 1	HEX 2
10	20	150.7	100.8	2.18	1.28
15	25	151.8	122.8	2.03	1.69
20	28	141.4	126.3	2.08	1.76

To further understand the reduction in the discharge power of HEX 2, the Sherwood numbers of both the heat exchanger designs are evaluated as shown in Figure 2. The mass transfer parameter Sh is plotted against the product of Re and Sc to take into account both the inertial and diffusive components of the solution flow. It can be seen that Sh increases linearly with the increase of the product Re.Sc for both the heat exchangers. A higher value of the product Re.Sc is observed for higher mass flow rates or lower evaporator temperatures, which result in higher flow velocity and lower vapor diffusivity respectively. To maximize Sh, an operating condition with lower evaporator temperature could be preferred over that of a higher mass flow rate. Such a measure would yield higher storage density for the system. Another key observation from the Figure 2 is that the HEX 1 outperforms HEX 2 for all the similar operating conditions and mass flow rates. The relatively lower Re number of the flow in HEX 2 under similar operating conditions is the primary reason for the lower Sh values of HEX 2 compared to HEX 1.

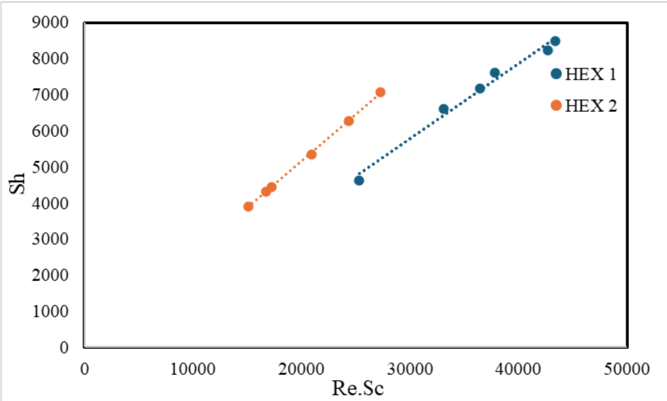

Figure 2. Mass transfer comparison among the two heat exchanger designs

4.2. Exergy efficiency evaluation

The exergy efficiency evaluation has been carried out for both the heat exchanger designs and is shown in Figure 3. It can be said that the general trend for exergy efficiency is that it increases with evaporator temperature for a given solution mass flow rate. Further, HEX 1 is seen to have a higher exergy efficiency over HEX 2 at all the considered operating conditions. Both of these trends could be attributed to the increasing exergy inlet and outlet values with increasing vapor intake. The higher heat and mass transfer resistances of the solution in HEX 2 due to its deeper fins, result in higher solution temperatures and lower vapor absorption rates. Along with the reduction in discharge power, the heat transfer at higher temperature difference reduces the exergy efficiency in HEX 2.

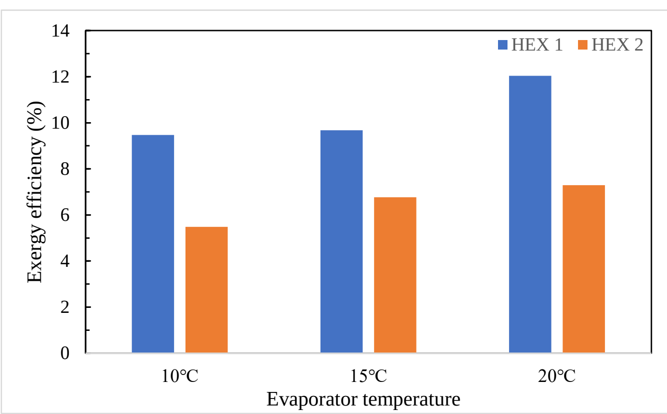

Figure 3. Exergy efficiency comparison among the two heat exchanger designs of NaOH-H_2O pair

4.3. Microchannel heat exchanger based performance comparison

The first and second law based thermodynamic analysis on aqueous sodium hydroxide based heat exchangers indicate that solution depth is the most critical parameter affecting system performance. Based on this observation, a microchannel heat exchanger is considered for a simulation based performance analysis in this study. The based on the correlations (9-10) in Matlab® 2023 platform and has been validated with the experimental results of Isfahani and Moghaddam (2013) [7] as shown in Figure 4. It can be seen that the simulated results are in close agreement with the experimental results at various design and operating conditions for the LiBr-H_2O pair studied in [7].

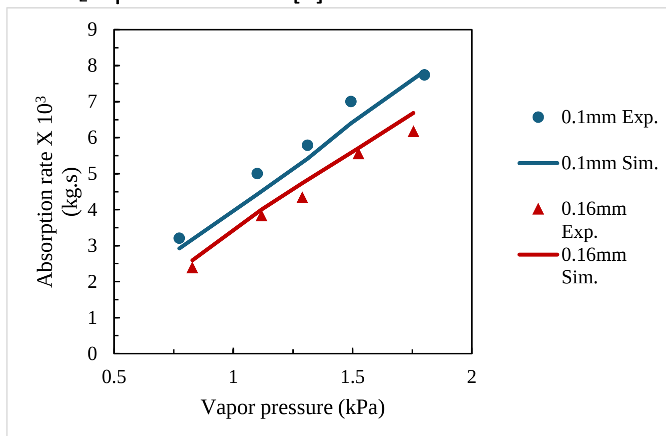

Figure 4. Performance validation of the simulation on membrane based microchannel heat exchanger with the results of [7]

A comparison has been made between the two pairs *viz.*, NaOH-H_2O and LiBr-H_2O on the based membrane based microchannel heat exchanger. The heat exchanger design and solution flow rate conditions shown in Table 3 are considered for the two working pairs, so as to yield similar discharge power as that of HEX 1 for the evaporator and water inlet temperature conditions of 15℃ and 25℃ respectively. It can be seen from Table 3 that the NaOH-H_2O pair requires a significantly lower solution flow rate for a comparable heat exchanger surface area than that of the LiBr-H_2O pair. Figure 5 compares the thermal storage densities of the 2 pairs for the given conditions. It can be seen that the thermal storage densities of both the pairs increase with increasing evaporator temperatures. It is also evident that the NaOH-H_2O pair outperforms the LiBr-H_2O pair, offering significantly higher storge densities. The absorption equilibrium concentration is observed to be lower for the NaOH-H_2O pair compared to that of the LiBr-H_2O pair, resulting in lower saturation pressures and higher vapor flux for the former pair.

Table 3. Microchannel heat exchanger and solution flow characteristics of the two pairs

Working pair	Heat exchanger surface area (mm^2)	Solution flow rate (kg/hr)
LiBr-H_2O	12512	1.2
NaOH-H_2O	15600	0.48

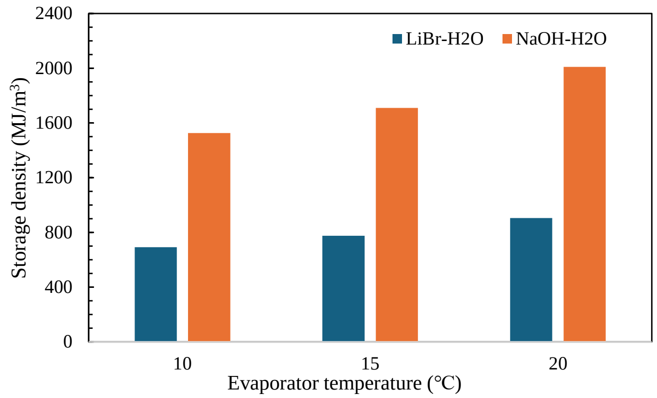

Figure 5. Performance comparison among LiBr-H_2O and NaOH-H_2O based working pairs

5. CONCLUSIONS

The present work investigates the absorption performance characteristics of NaOH-H_2O pair on finned heat exchanger design through experimental and thermodynamic analyses. The favorable operating conditions for yielding higher storage densities are identified through a non-dimensional mass transfer analysis for the two heat exchangers. Further, a second law analysis is carried out on both the heat exchanger designs. It is identified that solution thickness is the critical parameter affecting both the mass transfer and second law efficiency parameters. A membrane based microchannel heat exchanger design from the literature is proposed for the NaOH-H_2O pair based on these observations. The simulated results using the widely used LiBr-H_2O pair are validated with the experimental results of the literature and are further compared against the NaOH-H_2O pair. It is observed that the NaOH-H_2O pair offers significantly higher thermal storage densities over the widely used LiBr-H_2O pair under all the operating conditions and its potential can be explored for various other applications utilizing sorption pairs. Further, it can be concluded that the microchannel heat exchanger designs offer a significant promise for the NaOH-H_2O pair through offering lower surface areas and higher storage densities over the conventional finned heat exchanger designs and can help to realize compact and cost-effective thermal storage systems with this pair.

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