Hybrid Membrane-based Ionic Liquid Absorption Cycle for Water Heating, Dehumidification, and Cooling

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Abstract

To meet the growing energy consumption and mitigate climate concerns, novel energy efficient technologies need to be developed. Water heating, dehumidification and space cooling form a significant percentage (~24%) of a typical U.S. household energy consumption and a total of 2.6 quad of primary energy consumption. In this paper, we present a novel system for combined water heating, dehumidification, and space cooling. The three processes can be achieved by one device using a novel semi-open absorption based system combined with evaporative cooling. The absorption based system absorbs water vapor from its ambient. The latent heat of absorption, released into the absorbent, is transferred into the process water that cools the absorbent. The water absorbed is later released in the desorber through heating, and the water vapor generated in the desorber is condensed and its heat of phase change is transferred to the process water in the condenser. The condensed water vapor can either be drained if dehumidification is desired or be used in an evaporative cooling process for space cooling. The major innovations that enable such an absorption-based device are demonstrated in this study through an experimental test setup. First, a membrane based absorption system in a compact and scalable platform is used to alleviate the liquid entrainment issue encountered in the conventional packed bed absorbers. Second, architecture reconfigurations, like novel fluid circuits and semi-open absorption system are deployed to enhance performance and lower system cost. Finally, an ionic liquid is implemented to minimize corrosion and eliminate crystallization risks, a major concern with conventional salts. The water heating and dehumidification component of the device are experimentally evaluated and the device is characterized for various system parameters. A water heating COP of 1.4 is achieved in this first generation prototype. These innovations pave the way for a compact, efficient, and low cost absorption based system for residential scale applications.

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1. Introduction

Absorption systems have been around for more than 150 years [1]. The inherent advantage of an absorption-based heat pump over other cooling/heating systems that currently dominate the market is that it can provide high efficiency with the ability to utilize low-grade heat. The advent of cheap electricity in mid-20th century increased the sales and market capture of residential cooling systems by vapor compression technology. However, in industrial applications, absorption technology continued to be deployed for large capacity systems, in the form of combined cooling, heating, and power systems [2]. In the last decade, an aim to decarbonize world energy ecosystem has driven the energy efficiency standards to higher levels and also led to new regulations to

minimize and eliminate the use of high global warming potential (GWP) refrigerants used in vapor compression systems [3]. This has renewed interest in research and development for alternate residential cooling and heating systems such as absorption systems.

In a typical US home, two sources of significant primary energy consumption are water heating (approximately 14-18% of the total utility bill) and dehumidification. Overall, the annual water heating expenditure for US is around $32.6 billion as indicated in the building energy end user data for 2011 [4]. In recent years, new water heating technologies claiming high site energy factors have been introduced to the market [5], however, the high product and installation cost has hampered market penetration of these technologies. On the other hand, the dehumidification process in the conventional vapor compression cooling systems consumes significant amount of primary energy as excess water vapor is removed by cooling the air to water saturation conditions. An alternative approach to controlling the humidity is through use of solid desiccant wheels or liquid desiccant systems. Solid desiccant systems have relatively poor energy efficiency and may also lead to additional sensible heating load in the conditioned space. Liquid dehumidification [6] systems are currently available only for large-scale applications.

A hybrid absorption based system can reduce the primary energy consumption for both water heating and dehumidification. However, four major issues with the existing absorption systems make it infeasible for residential scale applications. First, thermodynamics constrains operational limits to sub-atmospheric conditions within the system to enable refrigerant (i.e. water) evaporation at below ambient temperatures necessary for sensible heat exchange with the environment. Maintaining such low pressures requires hermetic all metal designs and additionally may require auxiliary vacuum pumps to purge non-condensable gas from the system to ensure continuous operation. Second, the shell and tube heat exchanger architecture used in the existing large systems does not lend itself to small scales [7]. Third, the conventional absorbents, lithium bromide, lithium chloride, calcium chloride and similar brines have limited operating range mainly due to crystallization risk [8]. To avoid costly shut downs triggered by crystallization, sophisticated control strategies are implemented using sensors and processors to monitor and rapidly adjust the system working conditions. The cost of such a control system prohibits its implementation in economically viable residential-scale absorption systems. Finally, the current absorbents, like lithium bromide and chloride are highly corrosive due to the presence of the halide ions particularly in an open system with oxygen presence, with pronounced corrosion rates in the desorber that operates at relatively high temperatures [9].

In order to alleviate these issues, we have proposed a semi-open absorption [10], [11] architecture made of membrane-based plate-and-frame heat exchangers in which an ionic liquid (IL) is used as the desiccant. The proposed architecture eliminates the need for hermeticity hence greatly reduces the system cost. The membrane-based plate-and-frame heat exchangers reduce the components size and cost. In these heat exchangers, 3D surface structures are utilized [12] to control the desiccant film thickness and induce mixing to enhance mass transfer [13]–[16]. Implementation of ILs alleviates the crystallization issue. ILs are composed of large asymmetric organic cations and inorganic or organic anions. With numerous anion-cation combinations possible, properties such as vapor pressure can be tuned for specific applications. Other important properties of ILs are their low volatility [17] and environmental friendliness [18]. Additionally, ILs have a significantly lower corrosion rate compared to conventional absorbents [9]. Numerous theoretical studies have been reported in the literature, discussing the potential use of ILs in absorption based systems [19]–[25]. However, to the best of our knowledge, experimental data on an operating IL system has not been presented.

In this paper, first, the concept of semi-open absorption system is briefly described. Then, the architecture of the membrane based plate-and-frame absorber heat and mass exchanger is presented. An experimental setup used to study the system performance is described. Finally, the experimental results are presented and discussed.

2. Concept:

The semi-open system has been discussed in detail by Chugh et al. [11] and Gluesenkamp et al. [10]. Figure 1 provides a process diagram of the system. The system absorbs water vapor from the air stream into the absorbent, which interfaces with ambient air through the membrane. The latent heat of absorption, released into the absorbent, is transferred into the process water that cools the absorbent. The solution is regenerated in the desorber, where it is heated by a heating fluid. The water vapor generated in the desorber is condensed and its heat of phase change is also transferred to the process water. The condensed water is then used in an evaporative cooling process to cool the dehumidified air exiting the absorber. Essentially, this open-absorption cycle collects space sensible heat and transfers it to hot water. Another novel feature of the cycle is recovery of the heat energy from the solution exiting the desorber by heat exchange with process water rather than with the solution exiting

the absorber. Thus, the semi-open system can be used for heating applications such as water and can provide dehumidification to a process air stream (similar to an open system).
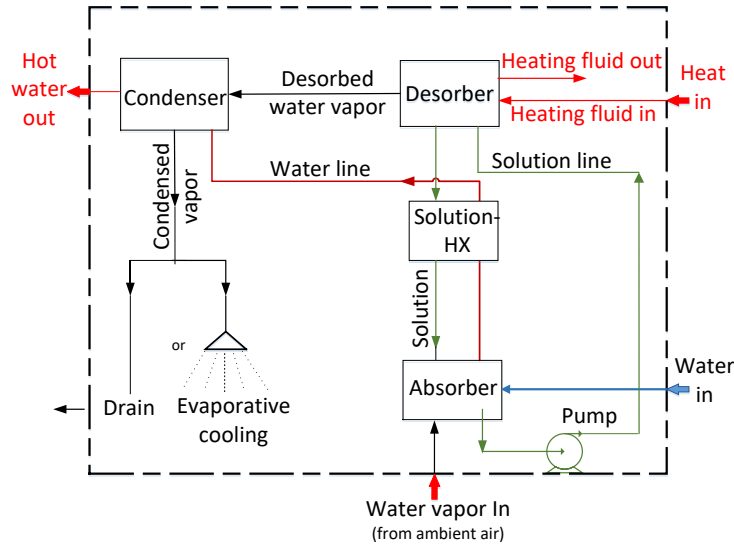

Figure 1. System concept for combined water heating, dehumidification and space cooling [11].

3. Experimental set up

3.1. Test loop schematic:

A fully instrumented test loop was designed and fabricated to test the experimental test set up at desired climate conditions. To achieve high humidity conditions for testing, an air loop with separate control of humidity and temperature was incorporated. Figure 2 shows the schematic of the experimental set up.
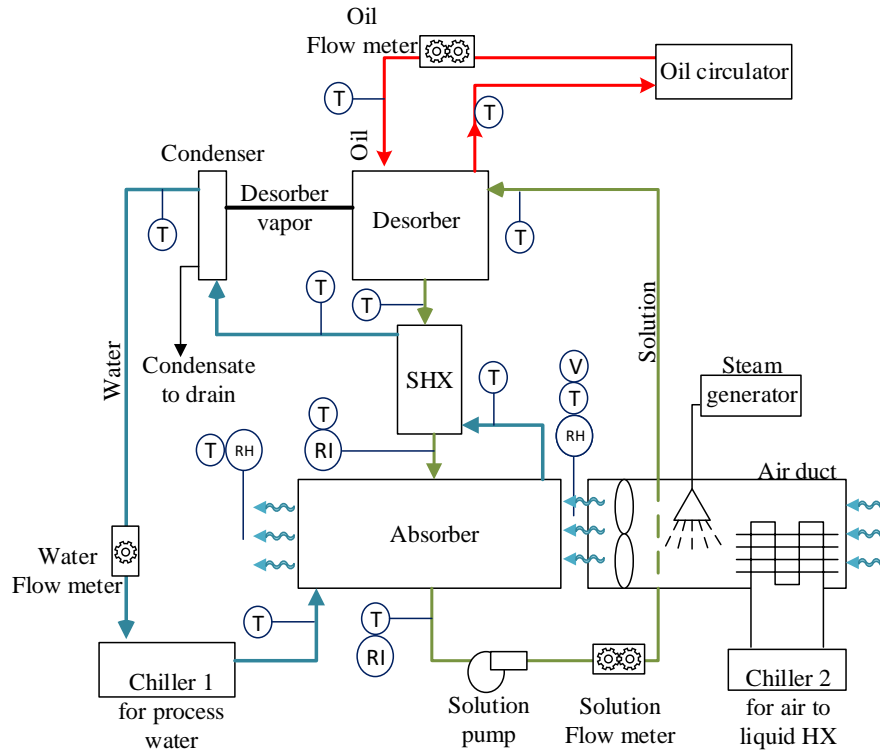

Figure 2. Schematic for the experimental test setup.

3.2. New Architecture and Semi-Open design:

Absorber: A schematic of the absorber is shown in Figure 3**Fout! Verwijzingsbron niet gevonden.**A. Currently, it is made from metal and polymer. The water side is made with stainless steel (SS) sheets that sandwich copper fins through which water passes. The solution side fins are fabricated using an additive manufacturing technique and bonded onto the stainless sheet. A frame was bonded on the edge of the SS sheet for membrane support. Commercially available superhydrophobic membranes facilitate air-solution interface as it allows water vapor to pass through but does not allow the liquid to pass through. Four such panels were fabricated and assembled as shown in Figure 3**Fout! Verwijzingsbron niet gevonden.**B with a gap in between each panel. Such a gap was necessary for airflow pathway and to incorporate the solution distribution manifold for each side of the panel. Air flows across the panels through the gap between the panels. This open absorption cycle architecture utilizes the ambient water vapor as refrigerant, thereby eliminating the need for an evaporator.

Desorber-condenser module: The required hot water outlet temperature (52°C as per DOE standard) determines the condenser temperature which in turn dictates the desorber vapor pressure and temperature. To achieve the required temperatures, the desorber was an all-metal design. To enhance the desorption rates, similar structures as used in the absorber were used and the whole assembly was brazed. The heat input was provided to the solution in the desorber using an external temperature controlled silicone oil loop. The condenser used was a commercially available plate heat exchanger and is connected to the desorber using a half inch stainless steel tube.
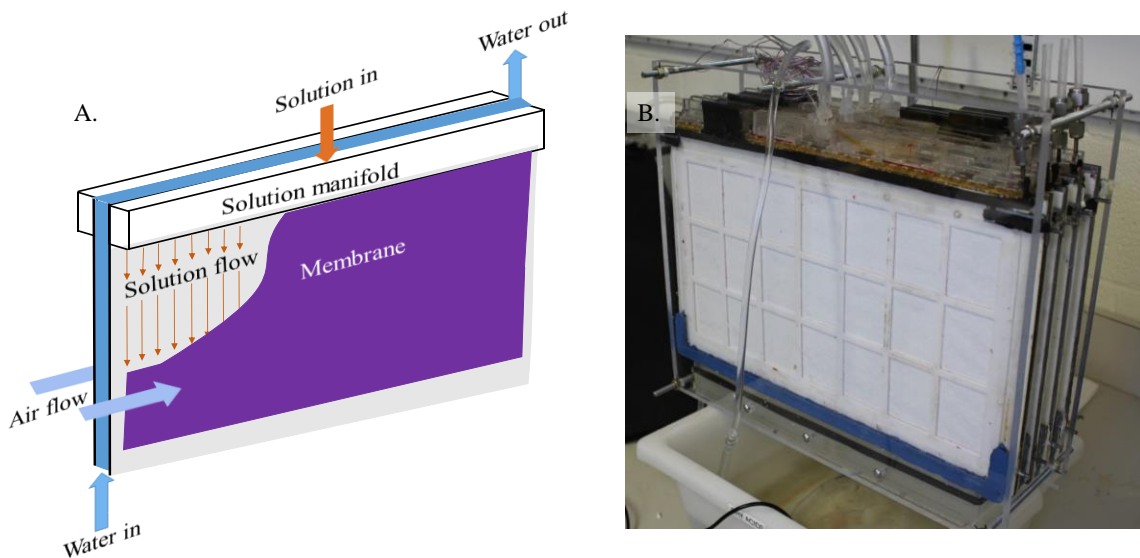

Figure 3. A) Schematic for absorber of one panel. B) Four panels assembled.

Modified solution flow loop: The solution flow loop is modified as described in [11] and depicted in Figure 1, wherein the hot solution flowing out of the desorber exchanges heat with water flowing out of the absorber. The solution heat exchanger was procured as a standard liquid-liquid heat exchanger available in market.

Concentration measurement: The concentration of the solution is measured at inlet and outlet of the absorber using inline refractometer index (RI) sensors (Maselli Inc.). RI was used instead of density (as conventionally done in LiBr systems) because the variation in density for ILs is very small over a wide concentration range, making estimation of the concentration infeasible using density measurement. The RI curves at different temperature and concentration were generated for the IL under testing. The concentration was then back-calculated using the measured temperature and RI at inlet and outlet of the absorber.

Experimental test set up: The complete assembled experimental test set up, with the labeled sub components, is shown in Figure 4.

3.3. Data reduction and Uncertainty

Thermocouples were installed at inlet and outlet of each component and the respective heat capacities were calculated.

3.3.1. Absorption rate:
To calculate the absorption rate, the mass flow rate of the vapor is to be estimated. This can be by performing mass and species balance on the absorber as shown in equations 1-6.

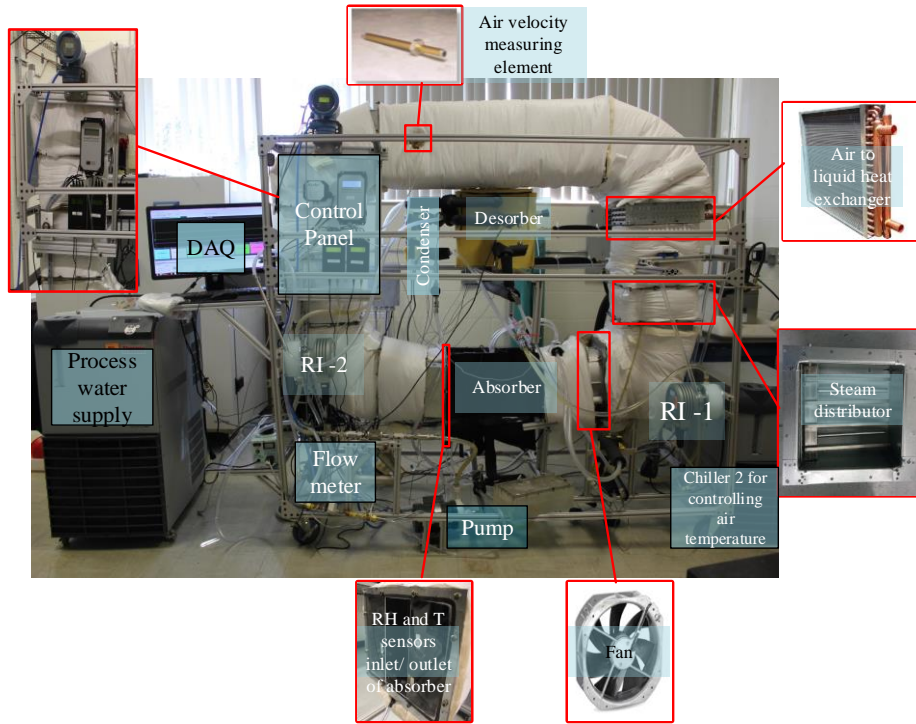$$\dot{J} = \frac{Mass\ flow\ rate\ of\ vapor(absorbed)}{Area} = \frac{\dot{m}_v}{A} \tag{1}$$

Figure 4. Photograph of experimental test loop with all the auxiliary components. (RI-Inline refractometer, DAQ-Data acquisition system)

Using species balance in the absorber:

$$\dot{m}_{soln_{in}} * X_{soln_{in}} = \dot{m}_{soln_{out}} * X_{soln_{out}} \tag{2}$$

Mass balance in the absorber:

$$\dot{m}_{soln_{in}} + \dot{m}_v = \dot{m}_{soln_{out}} \tag{3}$$

Substituting in (2),

$$\dot{m}_{soln_{in}} * X_{soln_{in}} = (\dot{m}_{soln_{in}} + \dot{m}_v) * X_{soln_{out}} \tag{4}$$

$$\Rightarrow \dot{m}_v = \dot{m}_{soln_{in}} * \frac{X_{soln_{in}} - X_{soln_{out}}}{X_{soln_{out}}} \tag{5}$$

Flow ratio is calculated as the ratio of the flow rate of the solution to ratio of the mass flow rate of the vapor

$$FR = \frac{\dot{m}_{soln_{out}}}{\dot{m}_v} \tag{6}$$

3.3.2. Uncertainty:
The uncertainty was calculated using EES subroutine for propagation of uncertainty. Table 1 below lists all the relevant uncertainties in this experimental study.

Table 1. Measurement error and uncertainty propagation

Variable	Uncertainty
Temperatures -All T-type TC	1°C
Solution volumetric flow rate	0.5%
Solution RI	0.5%
Water volumetric flow rate	1%
Oil volumetric flow rate	0.5%
Air Relative humidity	3%
Water heat	±5%
Oil heat	±7.5%
Solution heat	±2%
Concentration (X)	±0.06% w/w
Absorption rate	±10%
COP	±8.9%

4. Results and discussion

The performance of the system was studied experimentally in response to variation of various parameters. One major indicator of performance in any absorption based device is the absorption rate, which was strongly dependent upon the design parameters like air-solution interface, solution fin design, and various membrane parameters (thickness, porosity etc.). The results reported in this study are for the first generation of IL based device, based on the analysis designs parameters can be optimized to yield higher absorption rates and efficiency in future generations. The ambient conditions selected was a typical humid condition of 30°C, 70%RH. Other parameters like flow rates of solution, water and oil were based on the results of the thermodynamic cycle analysis performed using MATLAB.

4.1. Absorption rate vs solution inlet concentration:

The absorption rate was first studied as a function of the solution concentration. A higher solution concentration would yield higher absorption rates but higher concentration also requires higher desorption temperature. In the water heating application, the condenser temperature predominantly determines the desorber heating temperature. The experimentally measured absorption rate for two different solution concentrations can be seen in Figure 5. It is shown that 90% (w/w) IL has higher absorption rate than at 80%. Temperature also plays an important part as a lower water inlet temperature would lower the vapor pressure to enhance the absorption rate, as can be seen that absorption rate for 21.5°C is slightly higher than for 25°C.
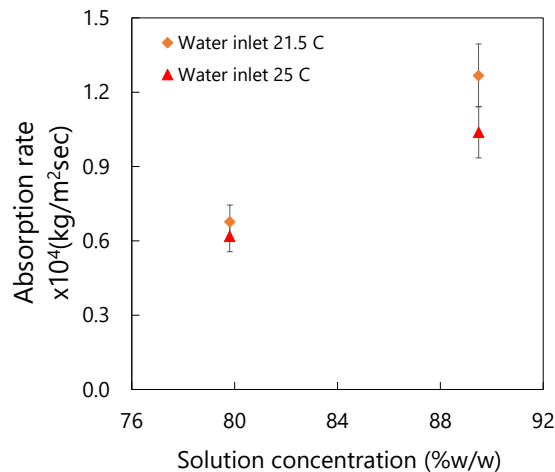

Figure 5. Absorption rate as a function of solution concentration (Ambient T and RH: 30±1°C, 70 ±5%, Solution flow rate: 2±0.1 g/sec).

4.2. Absorption rate vs water inlet temperature:

The effect of inlet water temperature on absorption rate was studied. The US DOE water heating standard dictates the water inlet temperature to the tank at 14.4°C – this is not necessarily the temperature entering the absorber. The water inlet temperature to the heat pump is dependent upon the hot water storage tank temperature

conditions, draw rates from the tank and water flow rate between the hot water storage tank and heat pump. Therefore, it is important to study the absorption rate as a function of the water inlet temperature. Lower inlet water temperatures enhance the absorption rates due to lowering of the absorbent vapor pressure as shown in the experimental measurements of Figure 6. A stratified tank might supply a temperature in the range of 15-35°C depending upon above mentioned factors like water heating load and inlet water temperatures.
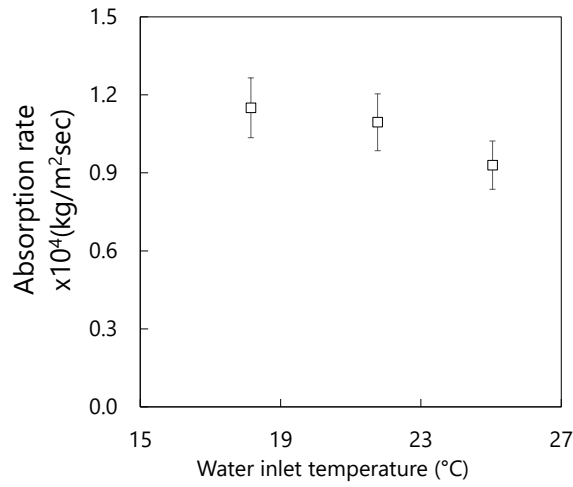

Figure 6. Absorption rate as a function of water inlet temperature. (Ambient T and RH: 30±1°C, 70 ±5%, Solution flow rate: 2.1±0.05 g/sec, Solution inlet X: 89.7±0.1 g/sec)

4.3. Absorption rate vs vapor pressure differential:
The main driving force in an absorption system is the vapor pressure differential. A holistic plot can be created between the driving potential (i.e. net vapor pressure difference) and the absorption rate using the above discussed data and is shown in Figure 7. Considering the solution vapor pressure from the pressure-temperature-concentration (PTX) data and the partial water vapor pressure of the ambient conditions, the net driving force for absorption rate is estimated. The major tradeoff of using an open absorption architecture is the significant reduction in the absorption rate due to the presence of the non-condensable gases. This can be seen by comparing the absorption rates of the closed system as reported in Nasr Isfahani [6] and Mortazavi et al [8], wherein absorption rates of 0.004 kg/m^{2}sec were achieved with pressure differential of 0.8 kPa. Although the absorbent used in these studies is LiBr, in the same experimental set up Nasr Isfahani reported similar absorption rate for an IL [25].
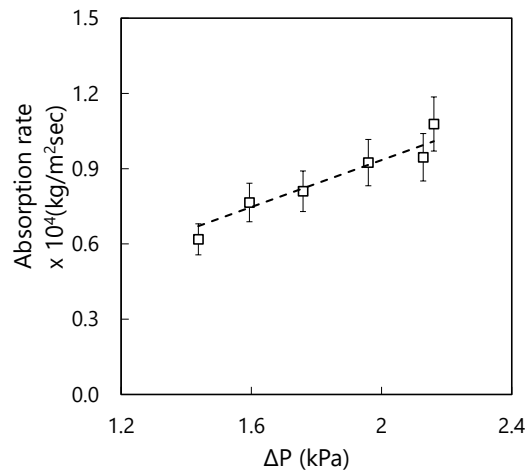

Figure 7. Absorption rate in an open system as a function of the differential vapor pressure.

4.4. Absorption rate vs air flow rate:
The absorption rate is also dependent upon the mass transfer resistance, which is strongly influenced by the presence of non-condensable gases like O_2, N_2 in an open absorption cycle. A higher air velocity suppresses the mass boundary layer, which can lead to higher absorption rates. However, after a threshold velocity, a limit is reached and this trend can be observed in Figure 8 below, wherein absorption rate is plotted as a function of the air flow velocity.
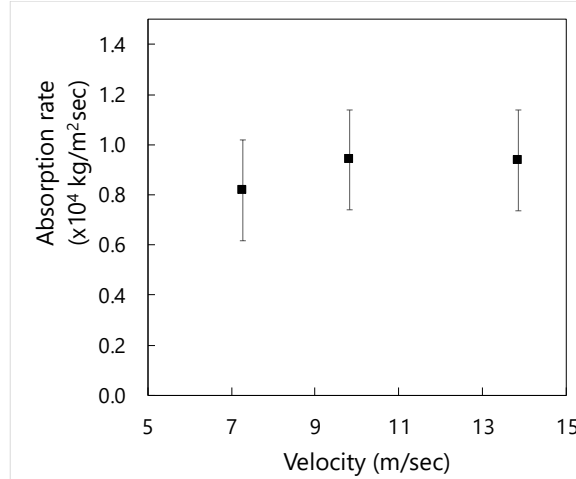
Figure 8. Absorption rate as a function of the air velocity. (Ambient T and RH: 30.0±1°C, 70 ±5%, Solution flow rate: 2.2±0.19 g/sec, Solution inlet X: 89.6±0.16 %, water inlet temperature 25.1±.03°C)

4.5. COP and capacity:

Using the prototype, the system water heating capacity and the COP were also experimentally characterized, as shown in Figure 9. The maximum COP achieved by the prototype is 1.4 and the maximum capacity recorded is 1.05 kW. The design is a scalable design and can easily be scaled up by adding panels to the absorber and increasing the desorber and condenser surface areas, thereby increasing the absorber capacity and efficiency.
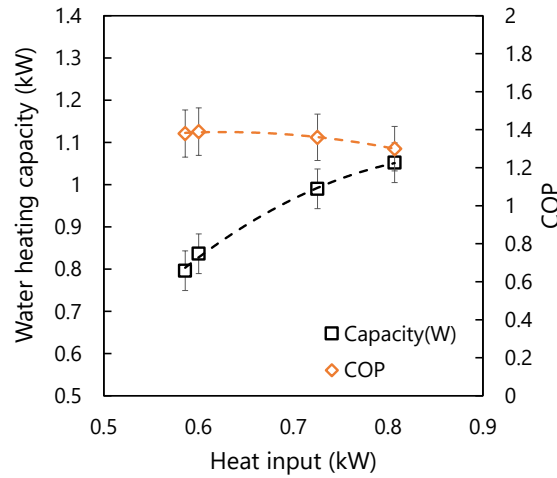

Figure 9. COP and capacity of the experimental prototype. (Ambient T and RH: 30±1°C, 70 ±5%, Solution inlet X: 89.5±0.2 g/sec

4.6. Comparison of COP with theoretical model:

The COP can be compared with a theoretical model described in Gluesenkamp et al. [10]. That model needs modification to accommodate the change in solution flow loop that was described in section 2.2. The modified equation obtained is:

$$COP = 1 + \frac{(L_{cond} + Q_{air}/m_v)}{FR * Cp * \Delta T_{D-A} * \varepsilon + L_{des}} \tag{7}$$

Where COP is the coefficient of performance, FR is the flow ratio (mass flow rate of solution/mass flow rate of vapor), Cp is the specific heat of solution (kJ/kg-K), $\Delta T_{(D-A)}$ is the temperature difference from desorber to absorber, L_{cond} is the heat of condensation of water in the condenser, L_{des} is the heat of desorption for the water vapor from solution in the desorber (taken equal to~L_{abs}- here), and Q_{air} is the heat of gain of water from the air through the solution and into the process fluid, m_v is the mass flow rate of the vapor. The experimentally measured COP and the predicted COP using equation 7 are plotted in Figure 10 and the two values agree well over a wide range of FR.
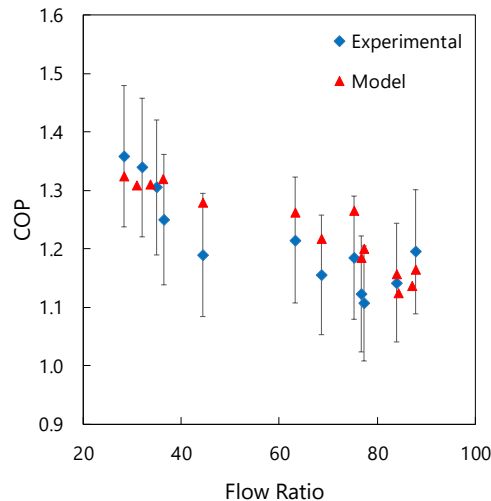
Figure 10. Theoretical and experimental values of the COP

5. Conclusion

Three major innovations that can help make a compact, low-cost, scalable absorption based device have been discussed. The innovations are membrane-based open-absorption cycle, novel absorbents, and modified architecture. The membrane-based open-absorption cycle eliminates the need of hermetic and expensive designs. Novel absorbents used are the ionic liquids, which do not crystallize and have minimal corrosion issues. The modified architecture offers a scalable platform to fabricate the device in a compact form factor. These innovations are demonstrated through a working prototype for water heating application which can also serve as dehumidifier and cooler. The prototype is characterized for various system parameters and a thermal COP of 1.4 is achieved for water heating. This demonstrates an economical absorption system based devices for small scale applications. Further improvement in absorption rates can result in higher COPs and capacities. The proposed changes for an absorption cycle based device which are demonstrated in this article pave the path for a cost-effective, compact, highly efficient open absorption system for residential scale application.

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