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Experimental Study of an Energy-efficient Sorption-based Clothes Dryer

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ABSTRACT

In most advanced thermal drying processes, a strong coupling between the sensible and latent heat loads results in a significant reduction in drying energy efficiency. The hot and humid air leaving the drum section carries both sensible and latent heat loads which are either exhausted to ambient or wasted during the low-temperature condensation process. This study proposes an energy-efficient sorption-based clothes dryer capable of recuperating both sensible and latent heat loads of the hot/humid air leaving the drum. The approach employs a hygroscopic desiccant cycle directly dehumidifying the outlet drum hot/humid air at high temperatures. This functionality allows converting the latent heat (i.e., humidity) to sensible heat load (i.e., temperature), thereby significantly improving the drying energy efficiency. Here, a well-equipped sorption-based system is developed and integrated into a commercial clothes dryer. The dehumidifier module of the system includes a textured dehumidifier surface offering a uniform liquid desiccant distribution on a polymeric surface. It also employs a desorber-condenser module to transfer the latent heat of the condensation process to the air entering the drum. The energy efficiency and drying time of the proposed sorption-based clothes drying system are analyzed at different sorption cycle working conditions under the DOE standard testing procedure. The experimental results showed a decrease in the drying time and an increase in the combined energy factor (CEF) with an increase in the desorption temperature. This study confirms the promise of the sorption-based heat pump drying concept for next-generation clothes dryer systems.

1. INTRODUCTION

Clothes dryers are widely used in both residential and commercial buildings. In the U.S., for example, nearly 80% of households are equipped with a clothes dryer (Denkenberger *et al*., 2012; EIA, 2018). The U.S. Department of Energy reports that the fabric drying process consumes 195.9 tBTU electricity (i.e., 7% of household electricity consumption) with an annual cost of 7.3 billion dollars (*Table CE5 . 1a Detailed household site electricity end - use consumption , part 1 — totals , 2015*, 2018; *Table CE5 . 5a Detailed household electricity end - use expenditures , part 1 — totals , 2015*, 2018). Despite the high energy usage of the clothes dryer systems, over the past few decades, there has been limited progress in improving their energy efficiency (Denkenberger *et al*., 2011; Horowitz *et al*., 2014).

In conventional clothes dryers, the ambient air is heated and then sent to the drum unit where the water is extracted from the textile. The air is typically heated by either an electric resistance or a gas combustor. The warm and humid air leaving the drum is then vented into the ambient. Although this method offers a simple and reliable fabric drying process, it suffers from a low drying energy efficiency. This is because nearly 60% of the input energy is wasted to ambient (Wei *et al*.,2018). Particularly, it is found that the exhaust air could carry as much as 33% of the input energy (Lambert *et al*., 1991). Therefore, the maximum theoretical coefficient of performance (COP) of conventional clothes dryers is restricted to less than one (Gluesenkamp *et al*., 2021).

The condensing clothes dryers recover the latent heat of the exhaust air, thereby reducing the drying energy consumption. In a condensing clothes dryer, a heat pump vapor compression cycle (VCC) is integrated into the drum unit to dehumidify the humid air, thereby allowing air recirculation (Ahmadi *et al*., 2021; Bengtsson *et al*., 2014; Braun, Bansal, & Groll, 2002; Gatarić *et al*., 2019; Goh *et al*., 2011b; Lee *et al*., 2019; Mancini *et al*., 2011; Minea, 2013; Patel *et al*., 2018; Peng *et al*., 2019). Heat pump dryers (HPDs) have been shown to boost energy efficiency while offering a higher control on the drying temperature and air humidity (Goh *et al*., 2011a). Bengtsson et al. (Bengtsson et al., 2014) examined the effect of operating parameters of a HPD on drying time. Their transient simulations showed a 14% decrease in the drying time at the same energy consumption level when a compressor with a larger cylinder volume was employed. However, a major concern with VCC-based HPDs is the usage of high global warming potential (GWP) refrigerants.

A heat pump dryer integrated with an absorption refrigeration cycle (ARC) (Currie & Pritchard, 1994; Le Lostec *et al*., 2008) could eliminate the usage of high-GWP refrigerants. The overall functionality of an ARC-based HPD is similar to that of a VCC-based HPD. The main difference is that a VCC-based HPD utilizes a high-grade electrical energy source while an ARC-based HPD is driven by a low-grade thermal energy source. One of the early works on ARC-based HPD (Currie & Pritchard, 1994) utilized the heat of absorption process to indirectly heat the air. In their work, a two-stage absorption heat transformer was integrated into the exhaust air stream of a spray drying unit. They reported a 63°C increase in the air temperature by leveraging the heat of absorption, thereby improving the fuel economy of the dryer. However, two factors negatively affecting the energy efficiency of VCC or ARC-based HPDs are the low-temperature condensation-based dehumidification process and the need for subsequent heating of the return air.

More recently, hygroscopic materials (i.e., desiccants) are proposed to improve drying performance. Notably, a novel liquid-desiccant-based heat pump clothes dryer was proposed to decouple sensible and latent heat loads of the drying process (M. Ahmadi et al., 2021). This allowed dehumidifying of the hot and humid air at high temperatures, thereby recuperating both sensible and latent heat loads simultaneously. Thermodynamic modeling showed a 112% improvement in the combined energy factor (CEF) of the proposed sorption-based system compared with state-of-the-art gas clothes dryers. El Fil et al. (El Fil & Garimella, 2022) proposed an adsorption-based thermal energy storage system integrated into a gas-fired dryer. Their system employs a silica gel adsorbent bed to capture waste heat from the exhaust stream, store it, and reuse it in the current and subsequent drying cycles. Their results indicated a 19% reduction in drying cycle time and a 22% decrease in specific moisture extraction ratio (SMER) over a conventional gas-based clothes dryer.

As indicated in the above literature review, the liquid-desiccant-based heat pump clothes dryer has recently shown great promise in improving the overall performance of the clothes drying process. In this study, a well-equipped clothes dryer test setup is developed to experimentally evaluate the performance of the sorption-based clothes dryer system. Particularly, the effects of the desorption temperature and sorbent flow rate on energy efficiency and drying time are investigated.

2. CONCEPT

The fabric drying process is a thermally-driven phenomenon governed by the water vapor partial pressure difference between the clothes and the air stream. The drying process involving both sensible and latent heat loads increase air humidity and decreases its temperature. The proposed sorption-based drying system recuperates the waste latent heat of the warm and humid air leaving the drum unit and reuses it to improve the system's energy efficiency. As shown in Fig. 1, the warm and humid air leaving the drum enters a liquid-desiccant-based dehumidifier module. Desiccant materials are best known for their hygroscopic properties effectively capturing water vapor molecules (Bigham, Yu, Chugh, & Moghaddam, 2014; Mortazavi, Nasr Isfahani, Bigham, & Moghaddam, 2015; Puttur, Ahmadi,

Ahmadi, & Bigham, 2022). In this module, the air humidity is adiabatically absorbed by the lithium bromide (LiBr) solution distributed on polymeric textured surfaces. The heat generated during the exothermic absorption process is partially transferred to the air stream increasing its temperature. In other words, the liquid-desiccant-based dehumidification process both dehumidify the air and increases the air temperature (B. Ahmadi, Ahmadi, Nawaz, Momen, & Bigham, 2021). The water vapor molecules absorbed in the LiBr solution is thermally rejected in a membrane-based desorber module. A hot oil heater delivers the thermal energy required for the regeneration process. A solution heat exchanger placed between the dehumidifier and desorber modules preheats the LiBr solution entering the desorber module and cools the solution entering the dehumidifier module. The water vapor generated during the desorption process is condensed in an air-cooled condenser module. The condensation of vapor enables the usage of the latent heat for the second time. The latent heat of the condensation process is then transferred to the air stream, thereby further increasing its temperature before entering the drum.

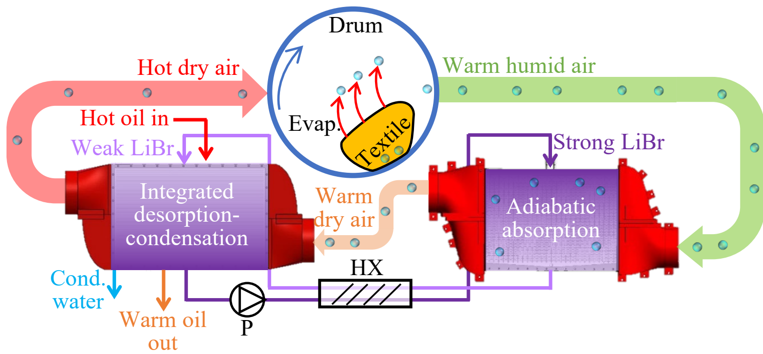

Figure 1: A schematic of the sorption-based dryer system.

3. DRYING EXPERIMENTAL STUDIES

3.1 Clothes dryer test facility

An experimental test facility was developed to evaluate the drying performance of the proposed sorption-based drying concept. The system has two interacting loops: air and sorption streams. The test facility was well equipped to monitor and control important thermo-hydraulic properties of air and liquid desiccant flow streams. The weight of the wet fabrics during the transient drying process was recorded by a high-accuracy weight scale (SAEROM Go-440) with a resolution of 0.04 kg. Each loop is discussed in detail in the following sections.

3.1.1 Sorption loop: The sorption loop consists of a textured dehumidifier module, a membrane-based desorber-condenser module, a solution heat exchanger, a solution-to-air heat exchanger, two solution pumps, and two Coriolis mass flow meters. The liquid desiccant solution is pumped between dehumidifier and desorber module with two solution pumps. The LiBr mass flow rate and density before and after the dehumidifier module were measured by two Coriolis flowmeters (Model: Emerson Electric Co., Micro Motion Elite Coriolis Flow/Density Meter, CMFS series). The LiBr temperature was monitored with several thermocouples (Model: ReoTemp F-M12T1SU4) at the inlet and outlet of the dehumidifier and desorber modules. Also, the oil flow rate was measured with a high-temperature variable area flow meter (Model: H3S-7HB05). Additionally, the oil temperature at the inlet and outlet of the desorber module was measured with two thermocouples (Model: ReoTemp F-M12T1SU4).

3.1.2 Air flow loop: In this loop, a clothes drum unit (Model: Samsung, DVG45M5500W, 0.21 m^3) was integrated with the sorption loop. The hot and humid air leaving the drum enters the dehumidifier module of the sorption cycle. The dehumidifier module was made of five double-sided polycarbonate textured plates (46×30×1 cm^3). The total desiccant-air interfacial area provided by the dehumidifier module is 1 m^2. The air then enters a honeycomb laminated air flow meter (Model: Air Monitor Inc., 4" LO-flo/P with an integral temperature probe) that accurately measures the air volumetric flow rate in the range of 0 to 680 m^3/hr. The dehumidified air is then heated in the condenser module before entering back to the drum unit.

3.2 Data reduction and uncertainty analysis

This study considers combined energy factor (CEF), specific moisture extraction rate (SMER), and drying time to assess the performance of the proposed sorption-based clothes drying process. The U.S. Department of Energy (DOE) Code of Federal Regulations "10 CFR Part 430" Subpart B, Appendix D1, "Uniform Test Method for Measuring the Energy Consumption of Clothes Dryers" was followed to conduct the clothes drying tests (*U.S. DOE federal standards, 10 CFR 430.32 (h), Energy and Water Conservation Standards and Compliance Dates.*, 2013). The DOE-D1 test procedure considers the energy consumed to dry 3.83 kg (8.45 lbm) of fabrics from an initial Remaining Moisture Content (RMC) of 57.5% to 3.5% (Shen *et al*., 2016).

The RMC is defined as the mass ratio of water to the bone-dry cloth as follows:

$$RMC = m_{water} \,/\, m_{bone\ dry\ cloth} \tag{1}$$

where m_{water} is the mass of water inside fabrics and $m_{bone\ dry\ cloth}$ is the mass of dry fabrics.

Table 1 lists nominal values, ranges, experimental errors, and uncertainties of main experimental parameters including solution flow rate, oil temperature, oil flow rate, air flow rate, fabrics weight, air relative humidity, and air temperature.

The net desorber heat input ($\dot{Q}_{des}$) excluding the heat loss is calculated as follows:

$$\dot{Q}_{des,net} = \dot{m}_{oil}\, c_{p,oil}\, (T_{oil,in} - T_{oil,out}) \tag{2}$$

where $\dot{m}_{oil}$ is the oil flow rate, $c_{p,oil}$ is the oil heat capacity, and $T_{oil,in}$ and $T_{oil,out}$ are the oil temperature at the inlet and outlet of the desorber module, respectively.

The uncertainty associated with the desorber heat input is calculated as follows:

$$\frac{\delta \dot{Q}_{des}}{\dot{Q}_{des}} = \sqrt{\left(\frac{\delta \dot{m}_{oil}}{\dot{m}_{oil}}\right)^2 + 2\left(\frac{\delta T_{oil}}{T_{oil}}\right)^2} \tag{3}$$

The combined energy factor (CEF), an important drying energy metric, is defined as follows:

$$CEF = \frac{m_{clothes}}{(\dot{Q}_{des,net} + \dot{W}_{blower})\ Drying\ time} \left[\frac{lbm}{kWh}\right] \tag{4}$$

where $m_{clothes}$ is the mass of fabrics, $\dot{Q}_{des,net}$ is the net desorber heat input, and $\dot{W}_{blower}$ is the work of the air blower.

The uncertainty associated with the CEF is calculated as follows:

$$\frac{\delta CEF}{CEF} = \sqrt{\left(\frac{\delta(m_{clothes})}{m_{clothes}}\right)^2 + \left(\frac{\delta(\dot{Q}_{des,net})}{\dot{Q}_{des,net}}\right)^2 + \left(\frac{\delta(Drying\ time)}{Drying\ time}\right)^2} \tag{5}$$

Also, the vapor generation rate (i.e., desorption rate) is measured by collecting the condensed water from the condenser module during the drying period.

3.2 Drying test procedure

Standard fabrics were purchased from WFK America LLC. The test fabrics were a blend of 50% cotton and 50% polyester. They were then prepared according to the DOE-D1 clothes drying test procedure (*U.S. DOE federal standards, 10 CFR 430.32 (h), Energy and Water Conservation Standards and Compliance Dates.*, 2013). Next, the sorption system was operated with a LiBr concertation of 45% at the inlet of the desorber module. Then, the inlet oil temperature of the desorber module was set at the desired temperature. Finally, the drum motor and the air blower were turned on to initiate the clothes drying process. The drying time was calculated when the remaining moisture content of fabrics was less than 3.5%. Each experimental data was repeated three times to ensure the repeatability of the data presented.

Table 1: Nominal value, range, experimental error, and uncertainty of main parameters.

Parameter [unit]	Nominal value	Range	Experimental error	Uncertainty
LiBr solution flow rate [g/s]	4	2 - 6	± 0.3	± 0.1 %
LiBr solution density [kg/m^3]	1480	1450 - 1520	± 0.5	± 0.03 %
LiBr solution temperature [°C]	30	25 - 35	± 1	± 0.33 %
Air flow rate [m^3/hr]	212.4	-	± 4	± 2 %
Air relative humidity [%]	60	40 - 70	± 1	± 1.4 %
Air temperature [°C]	45	40 - 85	± 0.5	± 1.1 %
Fabrics/water weight [kg]	2	0-4	± 0.02	± 1 %
Drying time [min]	90	70 - 115	± 0.5	± 0.7 %
Desorber heat input [W]	450	300 - 600	± 19	± 4.2 %
CEF [lbm/kWh]	8	6.75-9.25	± 0.2	± 2.5 %

4. RESULTS AND DISCUSSION

The drying performance of the proposed sorption-based clothes dryer system highly depends on the membrane-based desorption process. The performance of the desorption process is a strong function of its surface temperature. Fig. 2 shows the experimentally-measured desorption rates at different surface temperatures of the desorber module at a constant LiBr flow rate of 4 g/s. As shown in Fig. 2, the desorption rate increases with the desorber temperature. For instance, the desorption rate increases by 160% from 0.1 to 0.26 g/s when the desorber surface temperature increases from 117.5 to 151.5°C. This is attributed to the partial water vapor pressure potential available for the desorption process, which increases at higher temperatures. It can also be observed that the slope of the desorption rate curve increases with the surface temperature. This trend can be related to a shift in the dominant transport mechanism from a single-phase (i.e., direct diffusion) to a two-phase (i.e., flow boiling) regime. At low surface temperatures, the dominant mass transfer process is direct diffusion (Bigham, Nasr Isfahani, & Moghaddam, 2014). However, as the wall temperature increases above the saturation temperature of the LiBr solution, the mass transfer regime changes to boiling with higher desorption rates (i.e., vapor generation rates). Consequently, as shown in Fig. 3, the thermal energy required for the desorption process (i.e., the sum of sensible and latent heat loads) increases at elevated desorber temperatures. Considering the water vapor continuity, the increase in the vapor generation rate at higher surface temperatures indicates a larger amount of humidity captured in the dehumidifier module, thereby shortening the drying time.

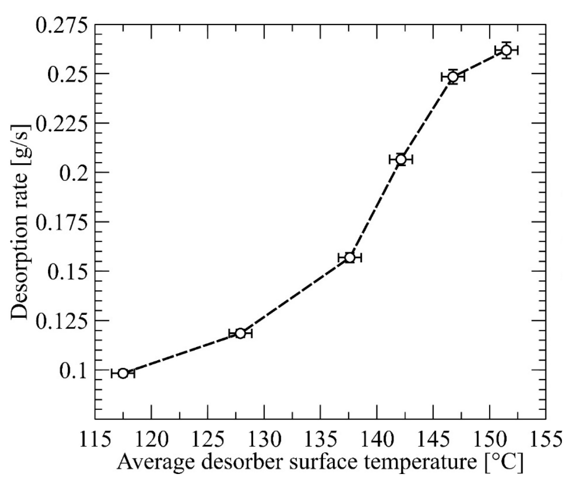

Figure 2: Desorption rate versus desorber surface temperature at a constant LiBr flow rate of 4 g/s.

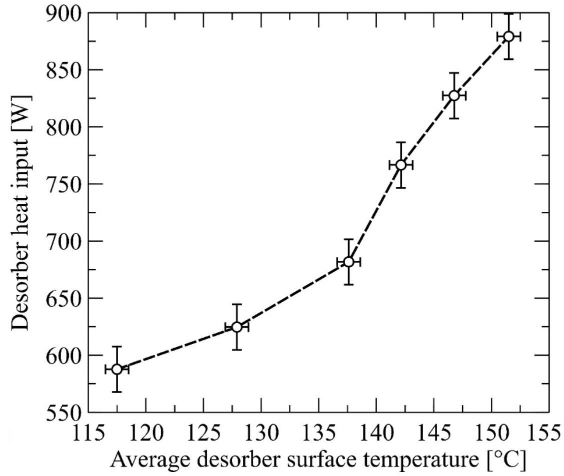

Figure 3: Desorber heat input versus desorber surface temperature at a constant LiBr flow rate of 4 g/s.

Fig. 4 shows variations of the drying time versus the desorber temperature at a constant LiBr flow rate of 4 g/s. As shown, the drying time of the proposed sorption-based drying system decreases at higher surface temperatures. This is because the desorption rate increases at higher desorber surface temperatures as discussed in Fig. 2. For example, the drying time decreases from 115 to 70 minutes when the desorber surface temperature increases from 117.5 to 151.5˚C. A higher desorption rate shortens the drying time in two different ways. First, a higher desorption rate translates to a higher dehumidification rate, thereby capturing a larger humidity content at a shorter time. Second, a larger amount of condensation latent heat is generated at higher desorption rates. This further increases the air temperature entering the drum unit, thus facilitating the clothes drying process. Fig. 5 shows the CEF/SMER improves as the regeneration temperature increases. At a desorber temperature of 151.5˚C, the CEF is 8.25 $lbm_{dry\ clothes}$/kWh (a SMER of 2.02 kg_{water}/kWh), a 150% improvement compared with the standard gas clothes dryers with a CEF of 3.3 $lbm_{dry\ clothes}$/kWh (a SMER of 0.81 kg_{water}/kWh). The CEF/SMER depends on both the desorber heat input and drying time. At higher desorber surface temperatures, the desorber heat input increases but the drying time decreases. It is evident that a shorter drying time has a more pronounced effect on the CEF than a higher desorber heat input at higher temperatures.

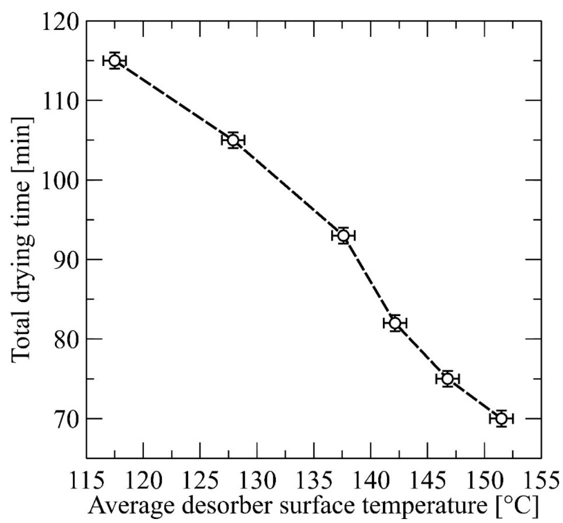

Figure 4: Variations of the drying time versus desorber surface temperature at a constant LiBr flow rate of 4 g/s.

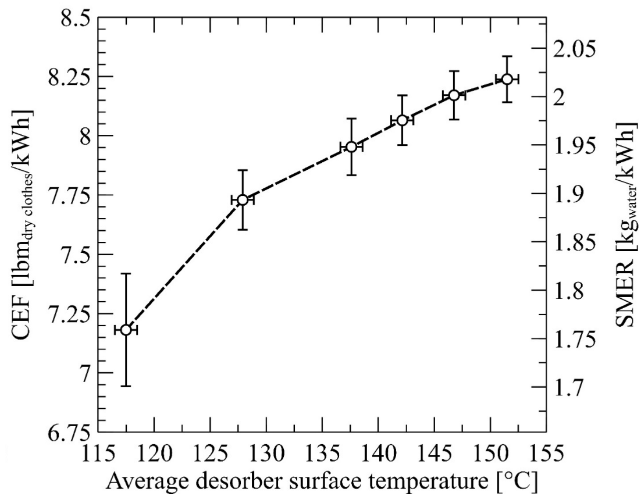

Figure 5: Variations of the CEF/SMER versus desorber surface temperature at a constant LiBr flow rate of 4 g/s.

5. CONCLUSIONS

This study experimentally examined the drying performance of a novel sorption-based clothes drying system integrated with a commercial tumble drum unit. The proposed sorption-based heat pump dryer is designed to recuperate both latent and sensible heat loads of the air leaving the drum unit. The humidity of the air leaving the drum is first captured by a liquid desiccant solution in an adiabatic dehumidifier module at high temperatures (i.e., no sensible heat load waste). The air is then heated by the condensation heat of the vapor released during the desorption process. An experimental study was conducted to evaluate the overall energy performance and drying time of the proposed sorption-based clothes dryer system. The experimental measurements showed that the CEF of the sorption-based heat pump clothes dryer is 8.25 lbm$_{dry\ clothes}$/kWh (a SMER of 2.02 kg$_{water}$/kWh), a 150% improvement compared with the standard gas clothes dryers with a CEF of 3.3 lbm$_{dry\ clothes}$/kwh (a SMER of 0.81 kg$_{water}$/kWh). Increasing the regeneration temperature from 117.5 to 151.5°C increases the CEF by 15% while reducing the drying time by 39%. The demonstrated drying metrics of the sorption-based heat pump dryer show the promise of the hygroscopic materials to improve the energy efficiency of fuel-driven residential clothes dryings.

NOMENCLATURE

VCR	Vapor compression refrigeration	(-)
CEF	Combined energy factor	(lbm/kWh)
m	mass	(kg)
RMC	Remaining moisture content	(%)
$\dot{Q}$	Heat input	(W)
$\dot{m}$	mass flow rate	(kg/s)
T	Temperature	(°C)
C_p	Heat capacity	(J/g°C)
$\dot{W}$	Work	(W)

Subscript

in	inlet
out	outlet
des	desorber

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