THE UNIVERSITY *of* EDINBURGH

Efficient drying in washer dryers by combining sorption and heat pumping

Citation for published version:
Cranston, J, Askalany, A & Santori, G 2019, 'Efficient drying in washer dryers by combining sorption and heat pumping', *Energy*. https://doi.org/10.1016/j.energy.2019.06.141

Digital Object Identifier (DOI):
10.1016/j.energy.2019.06.141

Document Version:
Peer reviewed version

Published In:
Energy

Efficient drying in washer dryers by combining sorption and heat pumping

Jonathan Cranston[a], Ahmed Askalany[a,b], Giulio Santori[a]

[a] The University of Edinburgh, School of Engineering, Institute for Materials and Processes, Sanderson Building, The King's Buildings, Robert Stevenson Road, Edinburgh, Scotland, EH9 3FB, UK

[b] Mechanical Engineering Department, Faculty of Industrial Education, Sohag University, Sohag, 82524, Egypt

Abstract

The worldwide need for improved energy efficiency in end use energy demand technologies catalyses the development of advanced household devices. Efficiency in the end use of energy also embraces the development of advanced household technologies with lower energy demand. Wet appliances are among the most energy intensive domestic devices in the domestic sector and accordingly they are a class of devices that require a reduction of their energy intensity. In this research a highly efficient washer-dryer that embeds a heat pump for drying is characterised experimentally and theoretically. With a 3 kg standard load, the heat pump washer-dryer results in 0.83 kWh energy consumption which correspond to 41% of an equivalent Class A device. The energy efficiency can be improved through hybridisation of the technology with a sorption bed. A theoretical assessment of the hybrid sorption/heat pump washer-dryer system shows that it can work with 0.78 kWh and shorter cycle time.

1.Introduction

With global energy demand only expected to increase, the improvement of energy efficiency is the single most effective way of achieving the climate change goals set out by the Paris agreement [1]. Initial investigation into increasing energy efficiency should focus on the most energy intensive technologies. Among these, wet appliances are the second most energy intensive class of household devices in Northern Europe [2–4]. The performance of wet appliances have been significantly improved with the addition of an adsorption bed. The exchange of traditional electrical drying methods with an adsorption bed in dishwashers led to energy savings of 25-41% compared with the standard A class technology [5–7], and the technology is deemed to be mature enough that it has been commercially available since 2012 [8]. Despite the proven success of this technology, the use of adsorption materials in other wet appliances such as washer-dryers is yet to occur. The washer-dryer presents a different challenge. In the dishwasher around 0.1 kg of water is dried during the drying cycle, in the washer-dryer this amount can be as high as 1 kg_{water} $kg_{dry\ load}^{-1}$. A typical washer-dryer load can be up to 6 kg dry load, therefore the required adsorption bed would be too large to fit inside the appliance. This increased demand calls for sorption materials having high water working capacity. Is this study, sorption refers to adsorption and/or absorption of water. Inorganic salt in silica gel matrix composites are sorption materials that have demonstrated water loadings as high as 1 kg_{water} $kg_{sorbent}^{-1}$ [9,10]. However, their use is limited as they are corrosive and have limited hydrothermal stability [11]. These negative properties are mitigated by exchanging the inorganic salt with ionic liquid (IL) [12]. Even with IL-composite providing a higher working capacity of 1 kg_{water} $kg_{sorbent}^{-1}$, a hybrid process is still required due to the amount of water to be dried in the washer-dryer. Therefore, this study introduces the novel concept of integrating an IL-composite sorption bed into the most advanced current washer-dryer technology, a heat pump washer-dryer, to create the hybrid sorption heat pump washer-dryer. The performance of the hybrid system are theoretically predicted from the experimental material properties and the experimental characterization of the device operated with heat pump drying.

2. Description of the processes

The operation of the heat pump in the drying cycle is illustrated in Figure 1a. It involves two closed cycles, one for air and one for the refrigerant. The air cycle is operated by the fan, drawing warm wet air from the drum. This is cooled and dehumidified with the evaporator, and the condensed water leaves the system. The cool dry air is heated by the condenser. The resulting hot dry air re-enters the drum to cause the evaporation of water from the textiles. This process repeats itself until the prescribed time or dryness of textiles is achieved.

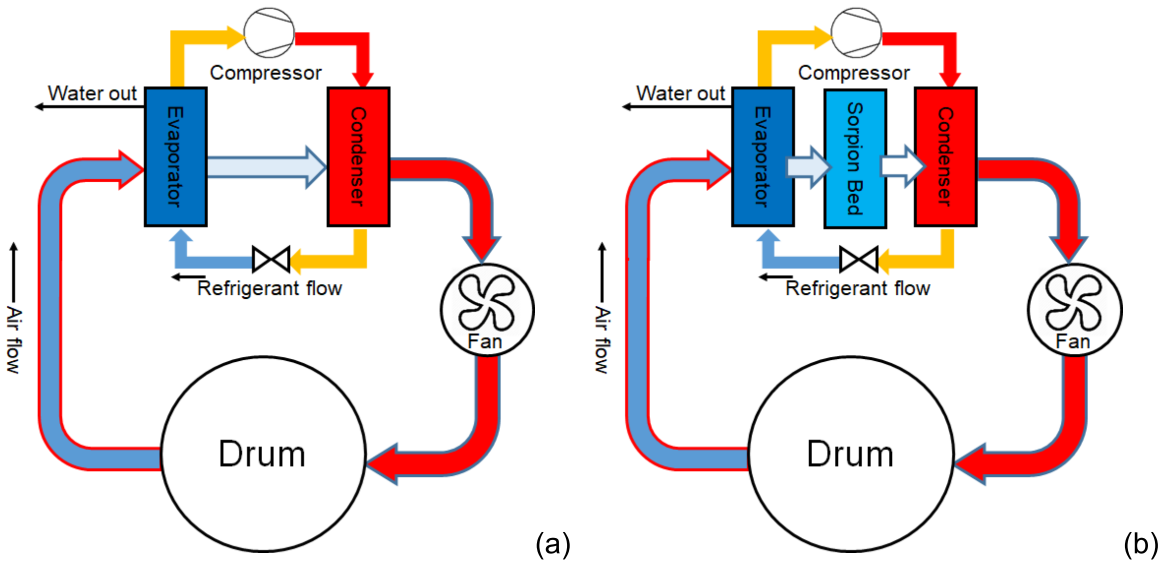

Figure 1: a) Heat pump washer-dryer process schematic (left). b) Hybrid heat pump washer-dryer process schematic (right).

In the hybrid process a sorption bed is fitted between the evaporator and condenser (Figure 1b). In this position the air is at its coldest and highest relative humidity (RH), optimal conditions for sorption. With this set-up the hybrid process works as the non-hybrid process with the exception that the cooled dry air, which is further dried by sorption of water vapour in the bed before it enters the condenser to be heated.

3. Experimental test rig

The test rig consists of a washer-dryer that integrates an R134a heat pump for drying. The device features a series of sensors located in the positions indicated in Figure 2. The device is fitted with type T thermocouples (accuracy the greater of ± 1 °C or ± 0.04%), Honeywell HIH-4000 relative humidity sensors (accuracy ± 3.5%), one Sensirion SDP816-500PA (accuracy ± 3%) differential pressure sensor fitted to a Pitot tube to measure the air flow rate and an ammeter fitted to the washer-dryers main electricity cable to determine electricity usage.

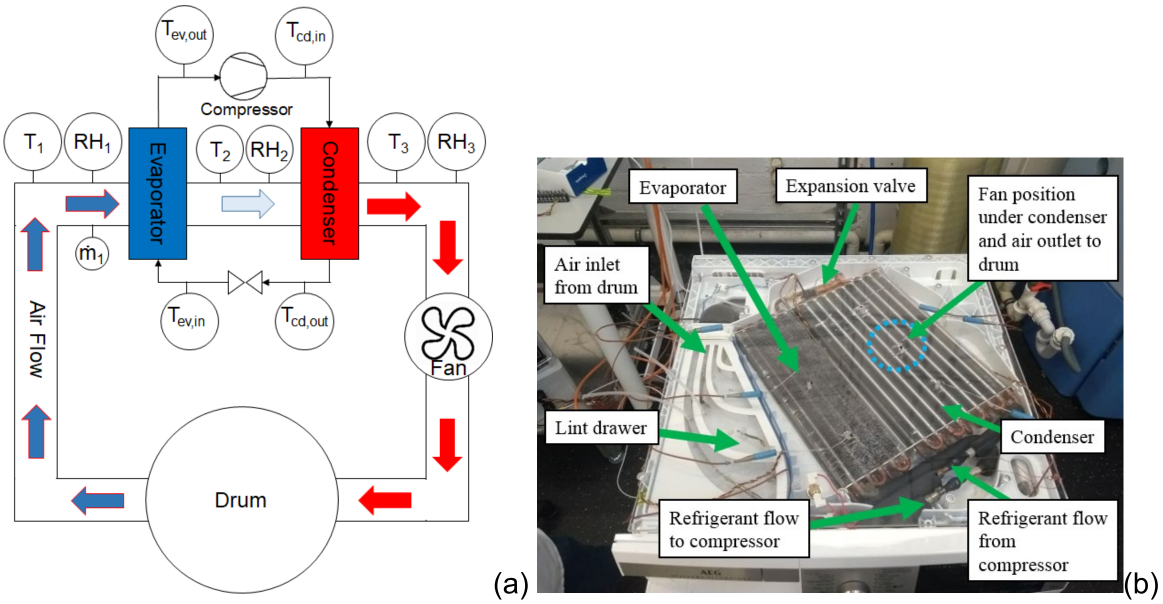

Figure 2: a) Schematic of heat pump washer-dryer with locations of sensors. T_1 and RH_1 detect the air conditions before the evaporator. T_2 and RH_2 sense the air conditions after the evaporator, while T_3 and RH_3 after the condenser. The mass flow is measured before the evaporator ($\dot{m}_1$). $T_{ev,in}$ and $T_{ev,out}$ detect the temperatures of the refrigerant before and after the evaporator respectively. $T_{cd,in}$ and $T_{cd,out}$ detect the temperatures of the refrigerant before and after the condenser. b) Upper view of the heat pump washer-dryer, where some of the heat pump details are visible along with some of the sensors and the air ducts.

A 3 kg pure cotton load following British and European Standards EN 61121:2013 and a standard test with the parameters listed in Table 1 are used with clothes considered dry when they reach 'Cotton Iron Dry' under the EN61121:2013 standards [13].

Table 1: EN61121:2013 standard test parameters used for characterisation [13]

Test Parameter	Standard Test Setting
Load mass	3 kg bone dry
Load material	Cotton
Washing programme	Rinse
Spin speed	1200 RPM
Drying programme	Cotton Dry
Moisture level when classified dry	12 % of dry mass

The performance of the system is evaluated during experimental tests and model simulation with four different measures, the moisture extraction rate (MER), the specific moisture extraction rate (SMER), the total energy required for drying (E_{cycle}) and the time required for drying (t_{dry}):

$$MER = \frac{m_w(t_0) - m_w(t_{dry})}{t_{dry}} \quad (1)$$

$$E_{cycle} = \int_{t_0}^{t_{dry}} P_{washer\ dryer}\, dt \quad (2)$$

$$SMER = \frac{m_w(t_0) - m_w(t_{dry})}{E_{cycle}} \quad (3)$$

4. Experimental characterization of the heat pump cycle

At steady state, the reverse vapour compression cycle followed by the R134a heat pump operates at compressor discharge temperature of 72°C, condenser temperature of 45°C, evaporator temperature of 15°C and compressor suction temperature of 25°C (Figure 3), that correspond to the pressures and reverse vapour compression cycle performance of Table 2.

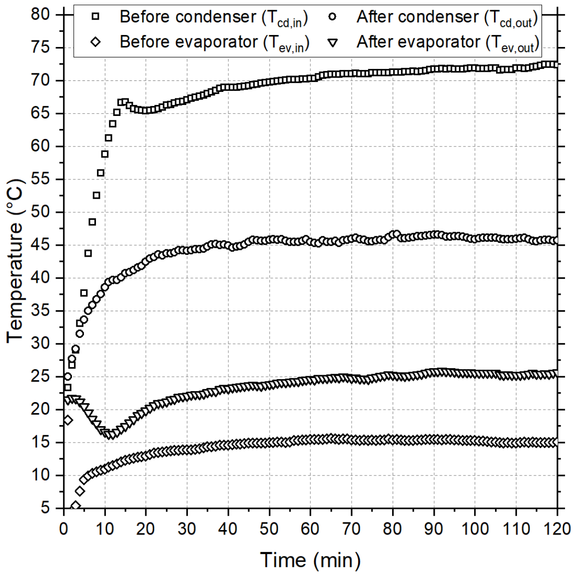

Figure 3: Average heat pump cycle temperatures throughout 120-minute drying cycles of standard load. Average deviation in measurements $T_{evap,in}$ ± 0.3%, $T_{evap,out}$ ± 0.3 %, $T_{cond,in}$ ± 0.2 %, $T_{cond,out}$ ± 0.4 %. Positions of sensors are in Figure 2.

Table 2: average heat pump performance throughout the 120 minute of drying of the standard load

Symbol	Description	Unit	Value
COP	Coefficient of performance		5.55
H	Compressor isentropic efficiency		0.60
p_{evap}	Pressure of refrigerant before evaporator	kPa	480
p_{cond}	Pressure of refrigerant before condenser	kPa	1195
Q_{evap}	Evaporator specific enthalpy difference	kJ kg^{-1}	149.05
Q_{cond}	Condenser specific enthalpy difference	kJ kg^{-1}	181.80
ΔT_{sh}	Superheating of the compressor suction	°C	9
$\dot{m}_{ref}$	Mass flow refrigerant (steady state)	kg s^{-1}	0.00495

The evolution of the electrical power absorbed during one cycle is illustrated in Figure 4. A steady state value of 0.485 kW is achieved after 10 minutes. This corresponds to the simultaneous operation of the heat pump compressor, air fan and drum motor. The power absorption increases to 0.519 kW for 30 seconds every 10 minutes when the pump needs to remove the water condensed by the evaporator.

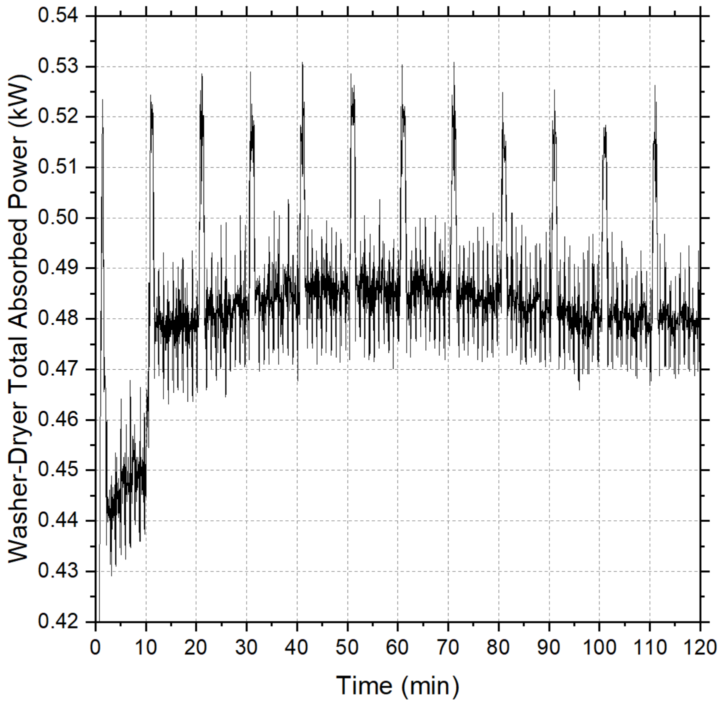

Figure 4: Electrical power absorbed by the washer-dryer during 120-minute standard load cycle. The contributions are from the evaporator drain pump (P_{pump}=0.034 kW), heat pump compressor (P_{compr}=0.360 kW), fan (P_{fan}=0.068 kW) and drum motor (P_{drum}=0.057 kW).

5. Lumped parameters dynamic model of the heat pump washer-dryer

To support the understanding of the process a lumped parameters dynamic model of the heat pump washer-dryer is developed and validated. The model is based on the following main assumptions:

- The heat pump cycle is ideal with the exception of the isentropic efficiency and superheating of the compressor suction which are constant;
- Pressure drops are neglected;
- All the air flows homogeneusly through the condenser or evaporator (no by-pass);
- Heat losses occur only from the drum and condenser;

- The relative humidity after the evaporator is always 100%;
- All water in the drum is in liquid phase initially;
- Air mass flow rate is constant;
- Temperature of the outlet air is identical to the temperature of the drum;
- There are no changes in air conditions between sections.

The energy balance equations of the model are collected in Table 3.

Table 3: energy balance equations of the heat pump washer-dryer

Evaporator	
$\dot{m}_1\left[Cp_{m,1}(T_1 - T_2) + \Delta H_{w,vap}(x_1 - x_2)\right] = \dot{m}_{ref}\left(h_{ev,out} - h_{ev,in}\right)$	(4)
$\dot{m}_1\left[\Delta H_{w,vap}(x_1 - x_2)\right] = (1 - SHR)\dot{m}_{ref}\left(\Delta H_{ref,vap} - c_{p,ref}\Delta T_{sh}\right)$	(5)
$SHR = Q_{sens}/(Q_{lat} + Q_{sens})$	(6)
$Q_{sens} = \dot{m}_1 c_{P,m,1}(T_1 - T_2)$	(7)
$Q_{lat} = \dot{m}_1 \Delta H_{w,vap}(x_1 - x_2)$	(8)
$RH_2 = p_{w,2}/p_{wsat,2} = 1$	(9)
Condenser	
$x_2 = x_3$	(10)
$\dot{m}_1 c_{p,m,2}(T_2 - T_3) = \dot{m}_{ref}\left(h_{cond,in} - h_{cond,out}\right) + k_c A_c (T_3 - T_{amb})$	(11)
Drum	
$\left(m_{tx}c_{p,tx} + m_d c_{p,d} + m_w c_{p,w}\right)\frac{dT_d}{dt} + k_d A_d (T_d - T_{amb}) = \dot{m}_3(h_3 - h_2) - \dot{m}_w \Delta H_{w,vap}$	(12)
$\dot{m}_w = \psi\left(p_{w,tx} - p_{w,3}\right)$	(13)
$\frac{p_{w,tx}}{p_{wsat,d}} = 1 - (\beta X_{tx} + \delta)/(1 + \delta^{(\gamma X_{tx})})$	(14)
$X_{tx} = (m_{water} - \int_0^t \dot{m}_w dt)/m_{tx}$	(15)
Total Energy Usage	
$E_{cycle} = \int_0^{t_{dry}}\left(P_{compr} + P_{fan} + P_{drum}\right)dt + \int_0^{t_{pump}} P_{pump} dt$	(16)

Note: SHR was obtained from a preliminary experimental characterization of the evaporator targeted to define it. Results have shown the following linear correlation between SHR and RH_1: SHR= 0.59 RH_1+0.81

This set of differential-algebraic equations was solved in Matlab by using the Levenberg-Marquardt algorithm, the parameters in Table 4 and the information gathered in the previous characterization of the heat pump cycle. All initial values for the air cycle temperatures are assumed equal to the ambient air (22 °C). Similarly, the initial relative humidity is assumed at 60%.

Table 4: parameters of heat pump washer-dryer model

Symbol	Description	Value	Units
β	Water desorption isotherm constant [a]	1	
δ	Water desorption isotherm constant [a]	2	
γ	Water desorption isotherm constant [a]	11	
$c_{p,d}$	Specific heat capacity of the drum (stainless steel)	0.4608	kJ kg^{-1} K^{-1}
$c_{p,ref}$	Specific heat capacity of the saturated liquid refrigerant	0.923	kJ kg^{-1} K^{-1}
$c_{p,tx}$	Specific heat capacity of textiles (cotton) [b]	1.210	kJ kg^{-1} K^{-1}
$c_{p,w}$	Specific heat capacity of liquid water	4.910	kJ kg^{-1} K^{-1}
$\Delta H_{ref,vap}$	Heat of vaporisation of refrigerant [c]	187.6	kJ kg^{-1}
$\Delta H_{w,vap}$	Heat of vaporisation of water [c]	2263	kJ kg^{-1}
Ψ	Mass transfer coefficient of water from textile to air[a]	0.00001	kg s^{-1} kPa^{-1}
k_cA_c	Thermal conductance for heat loss from condenser[a]	0.0065	kJ s^{-1} K^{-1}
k_dA_d	Thermal conductance for heat loss from drum[a]	0.059	kJ s^{-1} K^{-1}
m_d	Mass of drum	2	kg
m_{tx}	Mass of dry textile [d]	3	kg
m_{water}	Mass of water in the textile [d]	1.3	kg
$\dot{m}$	Mass flow rate of moist air [d]	0.024	kg s^{-1}

Note:
[a] from fitting of the model on the experimental data
[b] from [14]
[c] from [15]
[d] Experimentally determined with preliminary tests on the system

6. Experimental tests on the heat pump washer-dryer and model validation

In a standard drying step, the steady state air flow rate is 0.024 kg s^{-1} ± 0.002 kg s^{-1}. The drum relative humidity (RH_1) drops steadily throughout the drying cycle as clothes become drier. The relative humidity of the air after the evaporator (RH_2) is fully saturated demonstrating the capabilities of the heat pump to cool the air to its dew point continuously. After a few minutes the air after the condenser reaches a low relative humidity below 20%. The temperature of the air before the evaporator (T_1) increases as it becomes dryer (Figure 5). The temperature after the evaporator increases steadily throughout the cycle (T_2). The start-up period is around 20 minutes and after this initial period, the air follows the thermodynamic cycles illustrated in the psychrometric chart of Figure 6.

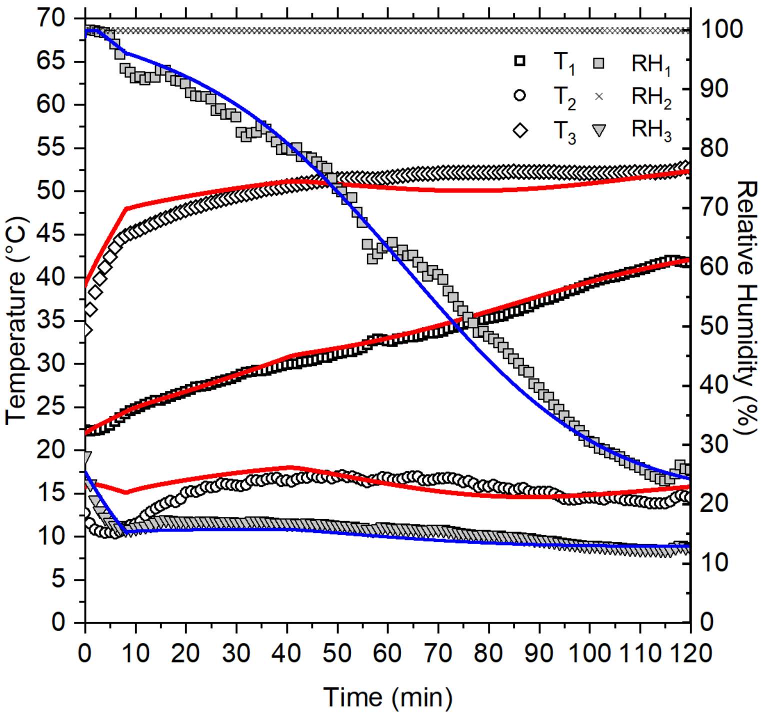

Figure 5. Average temperature and relative humidity during a drying cycle in the heat pump washer-dryer for 3kg standard load. (T_1; RH_1) and (T_2; RH_2) are the temperatures and relative humidity before and after the evaporator respectively. (T_3; RH_3) is the temperature and relative humidity after the condenser. Average deviations in measurements were as follows: $T_1 \pm 0.3$ %, $T_2 \pm 0.3$ %,$T_3 \pm 0.3$, $RH_1 \pm 2.0$ %, $RH_2 \pm 3.2$% and $RH_3 \pm 1.1$%. Sensor locations are illustrated in Figure 1. The comparison of experimental data (symbols) with calculated temperature (red solid lines) and relative humidity (blue solid lines) is also included. Start-up is modelled by increasing the flow of refrigerant until its steady state value (achieved after 500s) and increasing the condenser heating power until its steady state (achieved after 2400s).

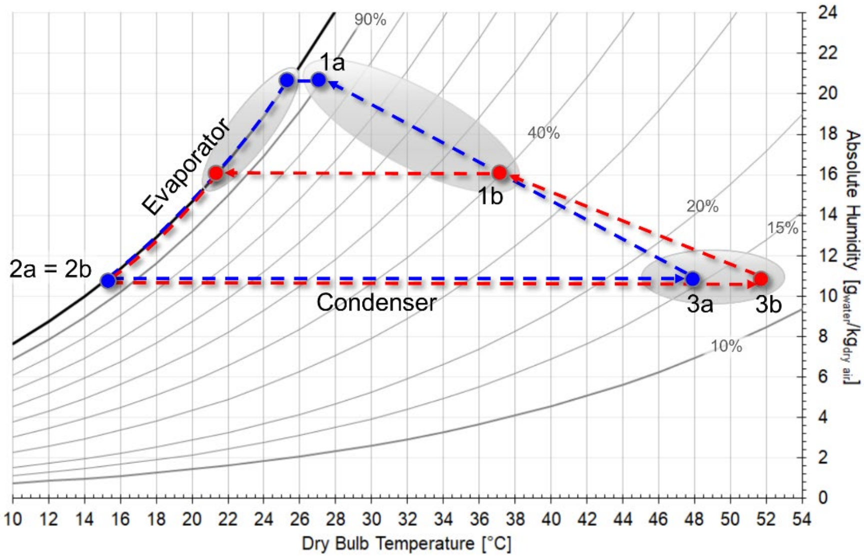

Figure 6: Psychrometric chart illustrating the air cycle at 30 minutes (red cycle – a) and 90 minutes (blue cycle – b) of a 3 kg standard load. Positions 1, 2 and 3 are in Figure 2.

The model correlates the steady state experimental data with sufficient accuracy (Table 5) but shows deviations when compared with the start-up transient. However, this does not have a significant influence overall, as the percentage mean absolute errors remain <1.6%, well within the bounds indicated in similar studies [16–18]. Therefore, approaching the description of the system with a dynamic model is appropriate for the overall assessment of the performance of the heat pump washer-dryer with standard load.

Table 5: error between experimental and simulated data at steady state.

Parameter	Mean Absolute Deviation
RH_1	2.25 %
RH_2	0.00 %
RH_3	1.09 %
T_1	0.65 °C
T_2	0.91 °C
T_3	1.19 °C

The model is compared with the experimental data also in terms of mass of water in the textile and water evaporation rate (Figure 7). While the mass of water in the drum is followed precisely by the model, the correlation of the evaporation rate is correct only in the middle part of the drying.

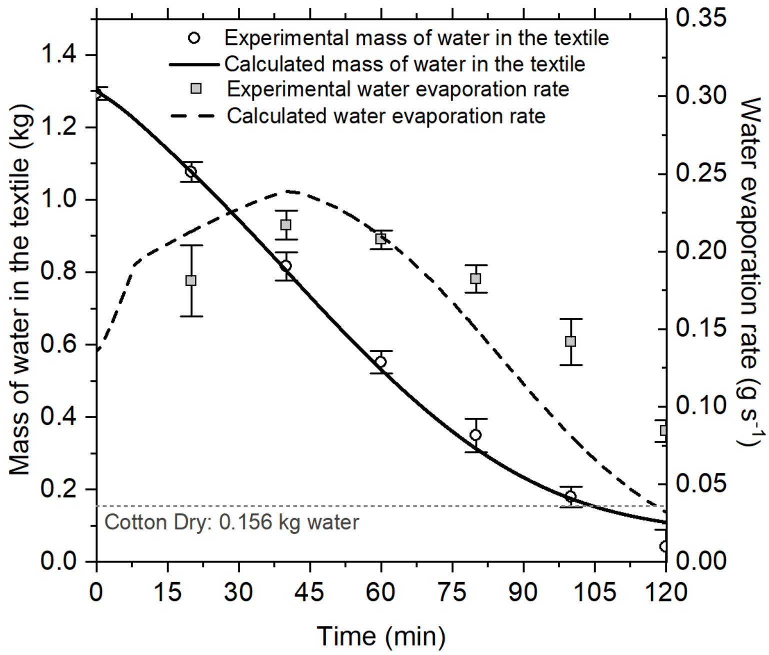

Figure 7: Mass of water in textile and water evaporation rate of experimental (symbols) compared to simulated results (solid lines and dashed lines) for standard 120-minute load of heat pump washer-dryer

Table 6 reports the values of the main performance indicators for the device. The time required to reach ‘cotton iron dry’ is 103.5 minutes, the total energy consumed in the drying cycle is 0.828 kWh and the MER and SMER are higher than the values commonly observed with traditional dryers [19]. These performance demonstrate the benefit of the heat pump in terms of energy saving.

Table 6: Performance results of the standard load to reach ‘cotton iron dry’ condition. Comparison of calculated and experimentally measured indicators for the standard load.

Symbol	Description	Unit	Exp.	Calc.	Error %
E_{cycle}	Total energy consumed to reach ‘cotton iron dry’ state	kWh	0.828	0.013	1.57 %
MER	Moisture evaporation rate	kg h^{-1}	0.663	0.673	1.52 %
SMER	Specific moisture evaporation rate	kg kWh^{-1}	1.381	1.360	1.52 %
t_{dry}	Time required to reach ‘cotton dry’ condition	min	103.5	104.1	0.06 %

The integration of an adsorption bed is an option available to alleviate the heating and cooling duties of the heat pump. This allows also to store water which can be used in the subsequent cycle. In dishwashers, a similar energy and water storage strategy has been proved to enable significant energy savings.

7. Integration of sorption and heat pumping drying

The limiting factor in the dryer of the washer-dryer is the slow evaporation rate of water from the drum resulting in long drying times. The driving force for this rate is the difference in relative humidity of water vapour on the textile surface and the relative humidity of the inlet drying air [16,20,21]. To reduce the time of drying, the relative humidity of the air entering the drum has to be low. The role of the sorbent bed is therefore primarily to decrease the relative humidity of the air. A reduction in drying time does not necessarily lead to an energy saving as the bed must be regenerated, but the presence of the heat pump in the process makes the regeneration much more efficient than by using an electrical heater embedded in the sorption bed. The optimal position of the sorption bed is after the evaporator (Figure 1b). In this position the sorption material can benefit of a stream with relative humidity close to 100%, at temperatures less than 20 °C. These operating conditions are ideal for water sorption since materials show their maximal water capacity at low temperature and high relative humidity.

Therefore, the previous model was complemented with a set of equations describing the dynamics and equilibrium of a sorption bed (see equations in Table 7) to check if there is a theoretical gain when a sorption bed is integrated within the heat pump drying system. The additional equations follow the assumptions:

1) Pressure drop across the sorption bed is negligible;
2) Thermal equilibrium between across the bed and between the gas and solid;
3) The flow through the bed is homogeneous.

Table 7: equations of the sorption bed

$\left(m_{bed}c_{p,bed}+m_{bed}c_{p,w}W\right)\frac{dT_{bed}}{dt} = m_{bed}H_{st}\frac{dW}{dt} - \dot{m}_2 c_{p,m}\left(T_{2,bed,out} - T_{2,bed,in}\right)$	(17)
$W = \frac{W_0}{v_a} exp\left[-\left(\frac{RT}{E} ln\left(\frac{1}{RH}\right)\right)^n\right]$	(18)
$v_a = -\left(B\,T + \frac{1}{v_w}\right)^{-1}$	(19)
$\frac{dW}{dt} = \frac{F_0 D_s}{{R_p}^2}\left(W_{eq} - W\right)$	(20)
$D_s = D_{so} exp\left(-\frac{E_a}{RT}\right)$	(21)
$H_{st} = \left[\Delta H_{w,vap} + E\left[ln\left(\frac{W_0}{Wv_a}\right)\right]^{\frac{1}{n}} + \frac{ET\alpha}{n}\left[ln\left(\frac{W_0}{Wv_a}\right)\right]^{\frac{1-n}{n}}\right]$	(22)
$\alpha = v_a\left(B - \frac{\alpha_w}{v_w}\right)$	(23)

Table 8 includes equilibrium and kinetics parameters of the bed made of the novel sorption composite material [emim][CH_3SO_3]/Syloid AL1FP prepared at The University of Edinburgh and already extensively characterized elsewhere [12]. In this material the [emim][CH_3SO_3] ionic liquid is confined in Syloid AL 1FP silica pores.

Table 8: Parameters used in sorption bed model

Symbol	Description	Value	Units
B	Sorbed phase specific volume fitting constant	-0.74	
$c_{p,bed}$	Specific heat capacity of IL-composite bed	0.924*	kJ kg^{-1} K^{-1}
D_{so}	Pre-exponential constant	4.41 10^{-13}	m^2 s^{-1}
E	Characteristic energy	12.8	kJ kmol^{-1}
E_a	Activation Energy	5307	kJ kmol^{-1}
F_0	Geometric parameter describing sorbent	0.02	
n	Dubinin-Astakhov fitting parameter	0.27	
R_p	Radius of sorbent particles	2.5 10^{-6}	m
W_0	Saturation uptake	38.78	cm^3 g^{-1}

Note: *assumed

Model results show that the introduction of a sorption bed in a heat pump drying system causes a significant improvement in the drying time (Figure 8) thanks to the increased water evaporation rate from the textile. Consequently, the time required to reach 'Cotton dry' is reduced by 19 minutes compared with only heat pump drying.

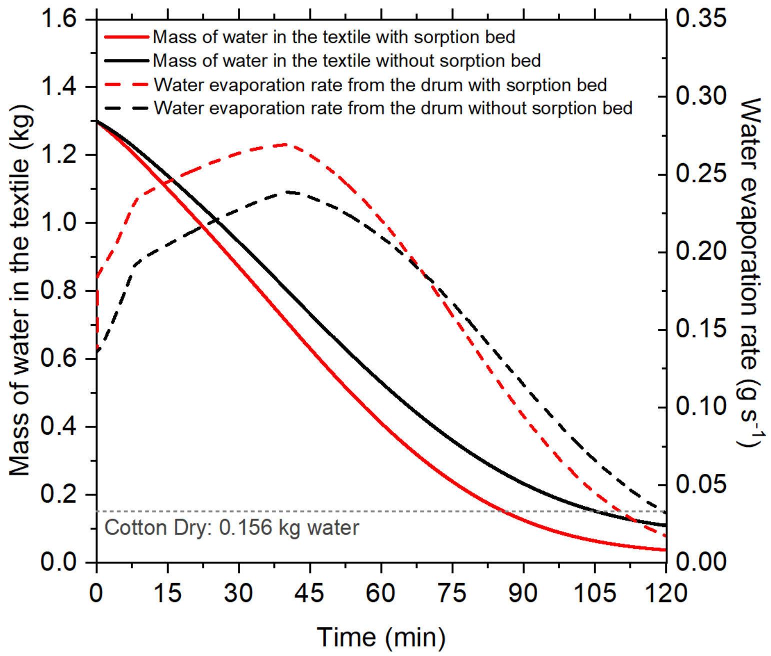

Figure 8: Simulated 0.5 kg silica-supported ionic liquid sorption bed (red lines) after evaporator compared to simulation without bed (black lines) for water evaporation rate and mass of water in textile.

However, the temperature change of air throughout the system is negligible and the main effect of the sorption bed consequently consists of a ~25% reduction of the relative humidity after the evaporator (Figure 9 and 10). This reduction causes the absolute humidity after the condenser to be significantly lower than the absolute humidity at the evaporator outlet.

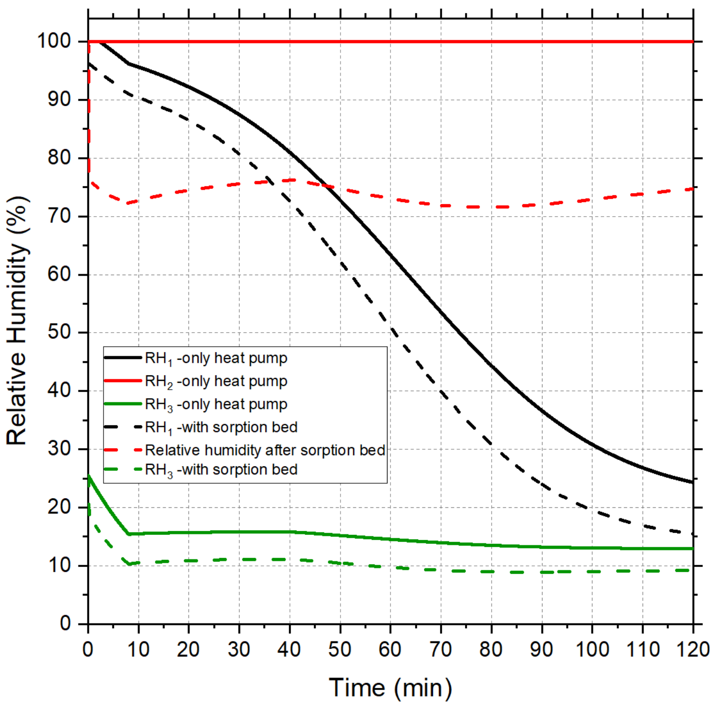

Figure 9: Comparison between calculated 0.5 kg silica-supported ionic liquid bed relative humidity (dashed lines) and relative humidity without sorption bed (solid lines).

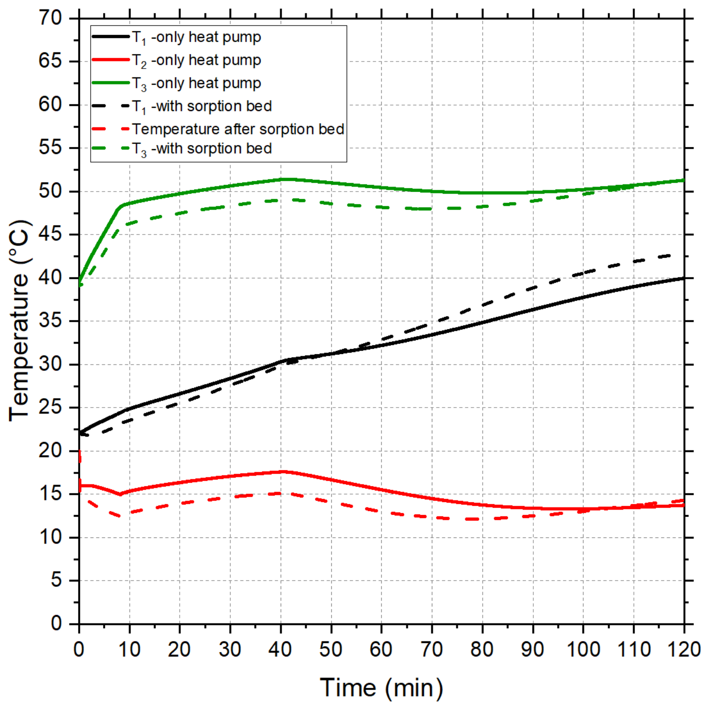

Figure 10: Comparison between calculated 0.5 kg silica-supported ionic liquid bed temperatures (dashed lines) and temperatures without sorption bed (solid lines).

Due to reduced relative humidity after the condenser, the evaporation of the water from the drum and consequently the evaporation rate increases. Even at increased evaporation rates, the relative humidity in the drum decreases due to the dryer air which enters the drum. Since RH_1 is reduced the SHR parameter (see definition in Table 3) increases and the heat exchanger can operate by exchanging a larger quantity of sensible heat than in the design without sorption bed. This reduction in the drying time results in an increase in the overall performance compared to the washer-dryer model without the sorption bed (comparison in Table 9). The effect of this improvement in the overall performance and energy consumption in the drying stage, with an increase in MER and SMER.

Table 9: calculation of the effect of 0.5 kg sorption bed on the performance indicators of a heat pump washer-dryer with standard load. Sorption bed regeneration is not accounted.

Performance Measure	Without sorption bed	With Sorption bed	% Improvement
E_{cycle} (kWh)	0.841	0.688	18.2 %
MER (kg h^{-1})	0.673	0.807	19.9 %
SMER (kg kWh^{-1})	1.360	1.662	26.6 %
t_{dry} (min)	104.1	85.1	18.3 %

The heat pump is then used for regeneration. Sorption bed regeneration is an energy expense for the system as fan and heat pump are operating to heat up the bed. If the time of regeneration is the same as the time saved, then the energy benefit to the system consists only of the limited use of the drum motor. However, the power consumption of the drum is minimal compared to the compressor of the heat pump. In order to achieve a significant energy benefit the regeneration time must be less than the time saved during drying by addition of the bed. To determine if this is the case, the regeneration is modelled by reversing the heat pump cycle with a four way valve as usually happens in domestic heat pumps, where evaporator and condenser are swapped [22]. The results from this calculation show that the bed takes 13.4 minutes to regenerate reducing the overall time required for drying by 5.6 minutes and consequently the overall energy consumption by 6.9%. Table 10 collects the new performance indicators showing also an increase in the energy efficiency.

Table 10: calculation of the effect of 0.5 kg sorption bed on the performance indicators of a heat pump washer-dryer with standard load. Sorption bed regeneration is accounted.

Performance Measure	Without sorption bed	With sorption bed including regeneration	% Improvement
MER (kg h^{-1})	0.673	0.697	3.44 %
SMER (kg kWh^{-1})	1.360	1.461	8.23 %
$t_{tot,sorption}$	104.1	98.5	5.38 %
Total energy consumption (kWh)	0.841	0.783	6.90 %

Conclusions

The combination of sorption and heat pump drying can theoretically reduce the overall energy consumption by 6.9% in a standard washer-dryer with 3 kg load. This theoretical figure is inclusive of the energy used for the sorption bed regeneration. Without regeneration the system takes 19 minutes less to dry the clothes, resulting in an overall energy reduction of 18.3%. The hybrid sorption/heat pump system uses a silica-supported ionic liquid composite material located in between evaporator and condenser of the heat pump. This leads to a reduction of the relative humidity of the air entering the drum that leads to an enhanced driving force for the evaporation of water from the textile. The water evaporation rate in the drum is the limiting factor during the drying phase. In addition, the increasing of the evaporation rate leads to a decrease in drying time compared with a standard heat-pump washer dryer. The results show that for a larger increase of the energy efficiency, the water vapour released from the sorption bed during regeneration has to be used during the washing.

Acknowledgment

The research leading to these results has received funding from the EPSRC “Micro-scale energy storage for super-efficient wet appliances” project EP/P010954/1.

Nomenclature

Symbol	Description	Units
α	Thermal expansion coefficient of water in the sorbed phase	K^{-1}
α_w	Thermal expansion coefficient of water in the vapour bulk phase	K^{-1}
COP	Coefficient of performance	
$c_{p,bed}$	Specific heat capacity of the sorbent	$kJ\ kg^{-1}\ K^{-1}$
$c_{p,d}$	Specific heat capacity of the drum	$kJ\ kg^{-1}\ K^{-1}$
$c_{p,m}$	Specific heat capacity of moist air	$kJ\ kg^{-1}\ K^{-1}$
$c_{p,ref}$	Specific heat capacity of refrigerant	$kJ\ kg^{-1}\ K^{-1}$
$c_{p,tx}$	Specific heat capacity of textiles	$kJ\ kg^{-1}\ K^{-1}$
$c_{p,w}$	Specific heat capacity of liquid water	$kJ\ kg^{-1}\ K^{-1}$
D_s	Surface diffusivity	$m^2\ s^{-1}$
D_{s0}	Pre-exponential kinetic constant	$m^2\ s^{-1}$
E	Characteristic energy of sorption	$kJ\ kmol^{-1}$
E_a	Activation energy	$kJ\ kmol^{-1}$
E_{cycle}	Energy consumed during drying cycle	kWh
F_0	Geometric parameter describing sorbent particle shape	
$\Delta H_{ref,vap}$	Heat of vaporisation of refrigerant	$kJ\ kg^{-1}$
$\Delta H_{w,vap}$	Heat of vaporisation of water	$kJ\ kg^{-1}$
H_{st}	Isosteric Heat of sorption	$kJ\ kg^{-1}$
h	Specific Enthalpy	$kJ\ kg^{-1}$
Ψ	Coefficient of water mass transfer from textiles to air	$kg\ s^{-1}\ kPa^{-1}$
k_cA_c	Thermal conductance for heat loss from condenser	$kJ\ s^{-1}\ K^{-1}$
k_dA_d	Thermal conductance for heat loss from drum	$kJ\ s^{-1}\ K^{-1}$
MER	Moisture evaporation rate	$kg_{water}\ h^{-1}$
m_{bed}	Mass of sorption bed	kg
m_d	Mass of drum	kg
m_{tx}	Mass of dry textiles	kg
m_w	Mass of water in clothes	kg
$\dot{m}$	Mass flow rate of moist air	$kg\ s^{-1}$
$\dot{m}_{ref}$	Mass flow rate of refrigerant	$kg\ s^{-1}$
$\dot{m}_w$	Evaporation rate of water from drum	$kg\ s^{-1}$
m_{water}	Initial mass of water in the textile	$kg\ s^{-1}$
η	Compressor isentropic efficiency	%
n	Dubinin-Astakhov fitting parameter	
P_{compr}	Compressor power	kW
P_{drum}	Power absorbed by the drum motor	kW
P_{fan}	Power absorbed by the fan	kW
P_{pump}	Power absorbed by the pump	kW
$P_{washer\ dryer}$	Total power absorbed by the washer-dryer	kW
p_w	Partial pressure of water	kPa
p_{wsat}	Water saturation pressure	kPa
Q_{lat}	Latent thermal power of the evaporator	kW
Q_{sens}	Sensible thermal power of the evaporator	kW
R	Ideal gas constant	$kJ\ kmol^{-1}K$
RH	Relative humidity	%
R_p	Sorbent particle radius	m
SHR	Sensible heat ratio	
$SMER$	Specific moisture extraction rate	$kg\ kJ^{-1}$
T	Temperature	°C
ΔT_{sh}	Superheating of the compressor suction	°C
t	Time	s
t_0	Start time of drying cycle	s
t_{dry}	End time of drying cycle	s
t_{pump}	Time pump is operational during drying	s
$t_{tot,sorption}$	Time for drying and regeneration with sorbent bed	s
v_a	Sorbed phase specific volume	$m^3\ kg^{-1}$

v_w	Vapour phase-specific saturated volume	$m^3\ kg^{-1}$
W	Water uptake in sorbent	$kg_{water}\ kg_{sorbent}^{-1}$
W_0	Water saturation uptake in sorbent	$m^3\ kg^{-1}$
W_{eq}	Equilibrium water uptake of sorbent bed	$kg_{water}\ kg_{sorbent}^{-1}$
X_{tx}	Water content per kg of dry textile	$kg_{water}\ kg_{textiles}^{-1}$
x	Specific humidity	$kg_{water}\ kg_{dry\ air}^{-1}$

Subscripts

1	Air condition before evaporator
2	Air condition after evaporator
3	Air condition after condenser
amb	Ambient conditions
bed,in	Air conditions into sorption bed
bed,out	Air conditions out of sorption bed
bed	Sorption bed
cond,in	Refrigerant condition before condenser
cond,out	Refrigerant condition after condenser
D	Drum
ev,in	Refrigerant condition before evaporator
ev,out	Refrigerant condition after evaporator
ref	Refrigerant
wsat	Water saturation
tx	Textiles

References

[1] WEO 2017 n.d. https://www.iea.org/weo2017/#section-1-1 (accessed March 28, 2019).

[2] Energy consumption in the UK - GOV.UK n.d. https://www.gov.uk/government/statistics/energy-consumption-in-the-uk (accessed March 28, 2019).

[3] Bengtsson P, Eikevik T. Reducing the global warming impact of a household heat pump dishwasher using hydrocarbon refrigerants. Appl Therm Eng 2016;99:1295–302. doi:10.1016/J.APPLTHERMALENG.2016.02.018.

[4] Bengtsson P, Berghel J. Study of using a capillary tube in a heat pump dishwasher with transient heating. Int J Refrig 2016;67:1–9. doi:10.1016/J.IJREFRIG.2016.04.006.

[5] Hauer A, Fischer F. Open Adsorption System for an Energy Efficient Dishwasher. Chemie Ing Tech 2011;83:61–6. doi:10.1002/cite.201000197.

[6] Santori G, Frazzica A, Freni A, Galieni M, Bonaccorsi L, Polonara F, et al. Optimization and testing on an adsorption dishwasher. Energy 2013;50:170–6. doi:10.1016/j.energy.2012.11.031.

[7] Erdogan M, Graf S, Bau U, Lanzerath F, Bardow A. Simple two-step assessment of novel adsorbents for drying: The trade-off between adsorber size and drying time. Appl Therm Eng 2017;125:1075–82. doi:10.1016/J.APPLTHERMALENG.2017.07.014.

[8] PerfectDry Dishwasher 60cm Freestanding, Zeolith - Energy efficient and perfect drying results - Serie | 6 - SMS67MW00G | BOSCH n.d. https://www.bosch-home.co.uk/product-list/dishwashers/freestanding-dishwashers/freestanding-dishwashers-with-60cm-width/SMS67MW00G (accessed March 28, 2019).

[9] Aristov YI. Novel Materials for Adsorptive Heat Pumping and Storage: Screening and Nanotailoring of Sorption Properties. J Chem Eng JAPAN 2007;40:1242–51. doi:10.1252/jcej.07WE228.

[10] Mrowiec-Białoń J, Jarzębski AB, Lachowski AI, Malinowski JJ, Aristov YI. Effective Inorganic Hybrid Adsorbents of Water Vapor by the Sol-Gel Method. Chem Mater 1997;9:2486–90. doi:10.1021/cm9703280.

[11] Aristov YI. New family of solid sorbents for adsorptive cooling: Material scientist approach. J Eng Thermophys 2007;16:63–72. doi:10.1134/S1810232807020026.

[12] Askalany AA, Freni A, Santori G. Supported ionic liquid water sorbent for high throughput desalination and drying. Desalination 2019;452:258–64. doi:10.1016/J.DESAL.2018.11.002.

[13] BS EN 61121:2013 - Tumble dryers for household use. Methods for measuring the

performance n.d. https://shop.bsigroup.com/ProductDetail/?pid=000000000030243719 (accessed March 28, 2019).

[14] Morton WE (William E, Hearle JWS, Textile Institute (Manchester E. Physical properties of textile fibres. CRC Press; 2008.

[15] Lemmon EW, Huber ML, McLinden MO. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties (REFPROP), Version 9.0 2010. doi:10.1234/12345678.

[16] Deans J. The modelling of a domestic tumbler dryer. Appl Therm Eng 2001;21:977–90. doi:10.1016/S1359-4311(00)00092-2.

[17] Saensabai P, Prasertsan S. Effects of Component Arrangement and Ambient and Drying Conditions on the Performance of Heat Pump Dryers. Dry Technol 2003;21:103–27. doi:10.1081/DRT-120017286.

[18] Sarkar J, Bhattacharyya S, Gopal MR. Transcritical CO_2 Heat Pump Dryer: Part 1. Mathematical Model and Simulation. Dry Technol 2006;24:1583–91. doi:10.1080/07373930601030903.

[19] Stawreberg L, Nilsson L. Potential energy savings made by using a specific control strategy when tumble drying small loads. Appl Energy 2013;102:484–91. doi:10.1016/J.APENERGY.2012.07.045.

[20] Bansal PK, Braun JE, Groll EA. Improving the energy efficiency of conventional tumbler clothes drying systems. Int J Energy Res 2001;25:1315–32. doi:10.1002/er.752.

[21] Huelsz G, Urbiola-Soto L, López-Alquicira F, Rechtman R, Hernández-Cruz G. Total Energy Balance Method for Venting Electric Clothes Dryers. Dry Technol 2013;31:576–86. doi:10.1080/07373937.2012.746977.

[22] Siepmann S, Witte O, Bau U, Erdogan M, Lazerath F, Bardow A. WASHING AND DRYING MACHINE. DE102016107884 (A1), 2017.