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A NEW APPROACH FOR EFFICIENT DEHUMIDIFICATION

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ABSTRACT

Dehumidification of air is an important economic activity responsible for high primary energy use. Several technologies are available that lower both, cost and primary energy use, such as heat pump dehumidification systems, desiccant dehumidification wheels, or other absorption systems. However, the drying efficiency of these technologies is still far below the expected efficiency as prospected by thermodynamic analyses based on the second law. This paper looks into the thermodynamics of drying and proposes a novel dehumidification technology. The proposed system consists of a heat mass exchanger and a mechanical vapour compression unit and is called a vapour heat pump. First, humid air is brought in contact with a hygroscopic salt solution in the exchanger unit and second, the diluted salt solution is reconcentrated by the mechanical vapour compression unit. An analysis of the vapour heat pump indicates a dehumidification efficiency of 6.6 to 9.3. A successful development of the vapour heat pump can have an important effect on the worldwide energy use and sustainability.

INTRODUCTION

Water vapour is a component of air. The mass fraction of water vapor in air at room temperature (20°C) is around 1.5%. Despite this small mass fraction of water vapour in air, it has a large impact on the air properties. Two major processes take place: water vapour can be removed through condensation or added by evaporation. In either case, water undergoes a phase transition, which influences the air temperature. Based on these principles, the energy and/or enthalpy of air is determined by its temperature (sensible heat) and by its vapour content (latent heat).

We need an appropriate vapour content in process air for the different human activities, This could be realized by humidifying or dehumidifying the air. Humidification means adding vapour to the air. As a consequence, the latent heat of the air is also increased. In the case of adiabatic humidification, an increase in latent heat is compensated by a reduction in sensible heat (1st law). Dehumidification means reducing the vapour in the air, and it is the opposite of humidification. However, there is an important thermodynamic difference between both: humidification is a spontaneous process that occurs when liquid water is making contact with unsaturated air. In contrast, dehumidification is not a spontaneous process. Dehumidification is thus more complex process.

Dehumidified air can be used in a wide range of applications like industrial drying or air conditioning. According to [1], drying in the industry is responsible for as much as 15% of its total energy use. [2] mentions that this share for drying increases up to 25% of the total energy required in the developed countries. Dehumidified air for air conditioning is not only important for buildings but also for greenhouses. In Belgium and the Netherlands, for example, dehumidification in greenhouses is responsible for 25% of its energy demand [3]. Greenhouses consume up to 64% of the total energy demand of the agricultural sector in Flanders [4].

The economic importance of dehumidification and the environmental concerns about primary energy saving necessitate the development of efficient drying or dehumidification technologies. Drying or dehumidification, after all, has a high energy demand. Dryer energy efficiency, which is the ratio of the latent heat of evaporated water to the total heat input, typically ranges from 20 to 60% [5]. Much higher efficiencies are theoretically possible because for drying a high quality energy (fossil fuel, electricity) is used to a obtain a low quality result (dehumidified air or a dried product). To that respect, [6] calculated that the maximal theoretical performance for dehumidification of air with 85%RH is 112 (J dehumidification per J exergy input).

In industry, a higher drying performance is achieved when using a superheated steam dryer [7]. In such a system, the product to dry are put in contact with superheated steam. The product adsorbs heat and evaporates. As a consequence, the steam is becoming almost saturated and has a lower drying capacity. To regenerate, a part of the more saturated steam is compressed and then condenses at a higher temperature. This heat of condensation is delivered back to the steam, resulting in the desired strong drying superheated steam. Net energy use in superheated steam dryers is as low as 0.7-1 MJ per kg of evaporated water, which results in a drying efficiency of 2.5 to 3.5.

Despite the economic success of superheated steam dryers, they cannot be widely applied to all products due to the high drying temperatures. Therefore, convective drying techniques are still being used for a lot of products. At present, 85% of the industrial dryers are convective air dryers [5]. Traditionally, such convective air dryers heat air by burning primary energy and vent the humidified air. More efficient air dehumidification techniques are drying heat pumps [2], desiccant drying systems, infra-red drying or a combination of these (hybrid system) [8]. Nevertheless, market penetration of these more efficient convective air dry systems is rather small (Mujumdar, 2007a).

[8,9] state that an intelligent combination of dryer types is critical for achieving a higher performance . They say that this "intelligent combination" depends on the "creativity" of the researcher. It seems that until now, the creativity of the researchers for developing dryers that operate at moderate temperature is minimal, if you compare the potential of highly efficient dehumidification and the lack of an appropriate technology. In this paper, we propose such an appropriate dehumidification technique, based on the analysis of the irreversibility in a dehumidification process. The efficiency of this dehumidification technique is modelled and presented.

NOMENCLATURE

A	[m²]	Surface
cp	[J/kg/K]	Specific heat
D	[J]	Dehumidification
eqRH	[%]	Equilibrium relative humidity of hygroscopic salt solution
E	[J]	Energy
EX	[J]	Exergy or availability
EXD	[J]	Exergy destruction or loss of exergy
l_{23}	[J/kg]	Heat of phase change of water from liquid to vapour
m	[kg]	Mass of water
n	[mol]	Mols of water
p	[Pa]	pressure
Q	[J]	Heat
r	[s/m]	Transfer resistance
R	[J/mol/K]	Ideal gas constant
RH	[%]	Relative humidity
T	[K]	Temperature
V	[m³]	Volume

Special characters

η	[%]	Efficiency
ρ	[kg/m³]	Density
Δ	[-]	Difference between

Subscripts

a	air
A	condition A
B	condition B
c	condensing
COL	cold surface
COND	the condensation water
cool	cooling
deh	dehumidification
e	environment
FF	falling film
HEX	heat exchanger
HMEX	heat mass exchanger
ht	heat transfer
H2O	water
hum	humidification
i	species i
inp	input
mt	mass transfer
MVC	mechanical vapour compression
out	output
SOR	sorbent
VENT	ventilation
VHP	vapour heat pump

THE EFFICIENCY OF DEHUMIDIFICATION

Dehumidification reduces the water vapour fraction in the air and its latent heat (~2.5 MJ/kg). For adiabatic dehumidification this reduction of latent heat is compensated by a gain in sensible heat, resulting in a constant enthalpy of the system.

The efficiency for dehumidification is

$$\eta_{deh} = \frac{D}{E_{inp}}$$

The energy input can be primary energy or electricity, which is the generic driving force for thermodynamic cycles.

For electricity holds (see [10]):

$$E_{inp} = EX_{inp}$$

and

$$EX_{inp} = EXD + EX_{out}$$

So, the efficiency of dehumidification can be expressed as

$$\boldsymbol{\eta_{deh}} = \frac{\boldsymbol{D}}{\boldsymbol{EXD+EX_{out}}} \tag{1}$$

Equation (1) indicates that the efficiency of dehumidification is inversely correlated to the exergy destruction in its processes and the exergy content of its output (dehumidified air). The output is a setting of the dehumidification device and is not variable. The efficiency of dehumidification can thus only be optimized by minimizing the exergy destruction in its processes.

Let us have a look at the thermodynamics and the different exergy destructions in the processes of dehumidification.

Based on the second law of thermodynamics, the exergy destruction during (spontaneous) humidification or the minimal external exergy input for dehumidification is [6]

$$\boldsymbol{EXD_{hum}} = \Delta\boldsymbol{EX_{deh}} \approx -\boldsymbol{n_{H2O}}.\boldsymbol{R}\,.\boldsymbol{T_e}\,.\ln(\boldsymbol{RH}) \approx -\boldsymbol{m_{H2O}}.\boldsymbol{T_e}\,.\boldsymbol{l_{23}}.\left(\frac{1}{T_a}-\frac{1}{T_c}\right) \qquad (2)$$

This equation takes only the mass transfer process between vapour and liquid water into account. In this process, the heat resulting from a phase change, is transferred to the liquid or solid material. Possible heat transfer processes that simultaneously occur due to difference in temperature between the liquid or solid material and the air are not considered.

From Equation (2), we conclude that

- Dehumidification needs only a small exergy input (20kJ/kg water at 85%RH, 90kJ/kg water at 50%RH). This illustrates the high potential for efficient dehumidification.
- The minimal exergy input for dehumidification depends on the drying depth (RH). Strong drying requires a logarithmically higher input.

The external driving force for dehumidification is provided by (see Figure 1)

- Cooling: The humid air is exposed to a cold surface at a temperature below its condensing temperature, and the vapour in the air condenses on that surface.
- Sorption: A liquid or fixed sorbent that has the capacity to adsorb vapour of unsaturated air is put in contact with the air. depends on The drying state of the sorbent is determinant for its affinity to adsorb vapour.

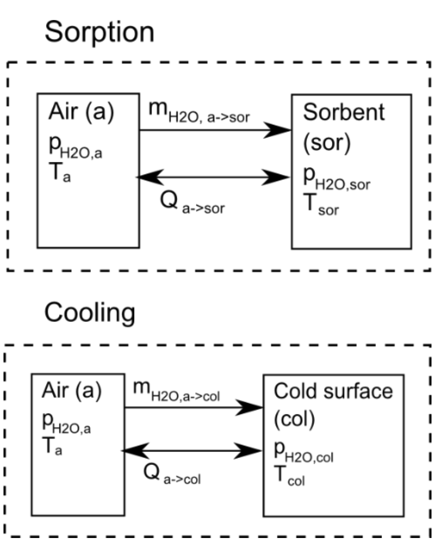

Figure 1 Schematic representation of dehumidification through sorption and cooling. There is a mass flow at a higher to a lower pressure. The heat flow depends on the temperatures. The regeneration of the sorbent and the cold surface are not illustrated.

For dehumidification by cooling, the following processes take place

1. Cooling of the air until its condensing temperature (T_c) is reached.
2. Further cooling of the air under its condensing temperature.
3. Simultaneous mass transfer of water vapour to liquid (condensation).

The equation for the loss of exergy during dehumidification by cooling, is (see [6,10])

$$\boldsymbol{EXD_{deh,cool}} = -\int \boldsymbol{n_{H2O,a\to col}}\,\boldsymbol{R}\,\boldsymbol{T_e}\,\ln\left(\frac{p_{H2O,col}}{p_{H2O,a}}\right) - \int \boldsymbol{Q_{a\to col}}\,\boldsymbol{T_e}\left(\frac{1}{T_a}-\frac{1}{T_{col}}\right) \qquad (3)$$

For dehumidification by sorption, the following processes take place:

1. Mass transfer of water vapour at a higher pressure $p_{H2O,a}$ to the sorbent at a lower pressure $p_{H2O,sor}$. The sorbent is absorbing the energy of the phase change.
2. Depending on the temperature of the sorbent, also heat exchange ($Q_{a,sor}$) can take place to some extent.

The equation for the loss of exergy during dehumidification by sorption, is

$$\boldsymbol{EXD_{deh,sor}} = -\int \boldsymbol{n_{H2O,a\to sor}}\,\boldsymbol{R}\,\boldsymbol{T_e}\,\ln\left(\frac{p_{H2O,sor}}{p_{H2O,a}}\right) - \int \boldsymbol{Q_{a\to sor}}\,\boldsymbol{T_e}\left(\frac{1}{T_a}-\frac{1}{T_{sor}}\right) \qquad (4)$$

The first term in both equations describes the dehumidification, while the second term describes the heat transfer.

Some characteristics of the different systems are here listed:

- For dehumidification by cooling, the heat transfer term is high. In contrast, this term is minimal during sorption or can be zero in case the temperatures of the sorbent and the air are equal.
- The proportion in exergy destruction by heat transfer compared to mass transfer for dehumidification by cooling depends on the conditions. Exergy destruction due to heat transfer will become more important when the air is dryer and at a lower temperature.
- For “adiabatic dehumidification” (for a description, see above), the dehumidified air needs to be heated. For “sorption dehumidification”, only the heat of phase change needs to be transferred to the air. However, for “cooling dehumidification”, also the sensible heat of the cooling needs to be retransferred to the air, resulting in an additional exergy destruction.

We conclude that dehumidification by sorption is more attractive because it results in a lower quantity of heat transfer and thus a lower exergy destruction.

The exergy loss (EXD) is not only proportional to the number of processes involved (quantity), it is also proportional to a quality difference ($\ln(p_1/p_2)$ or $(1/T_1-1/T_2)$). The smaller that difference, the less exergy is lost.

This quality difference is related to the driving force of the process, as described by the following equations:

$$Q_{B\to A} = \frac{\rho\ \ cp\ A}{r_{ht}}(T_B - T_A\ ) \quad (5)$$

$$\boldsymbol{m_{i,B\to A}} = \frac{\boldsymbol{A}}{\boldsymbol{r_{mt}}}\ (\boldsymbol{\rho_{i,B}} - \boldsymbol{\rho_{i,A}}\ ) \quad (6)$$

Based on the equations 3 to 6, a sufficient process speed with a minimal exergy destruction can be realized through a minimal resistance factor for mass (r_m) and heat (r_h) transfer in combination with a maximal surface (A). Indeed, this will result in minimal temperature differences or vapour pressure differences.

Another factor that determines the exergy efficiency of the dehumidification device is its pressure drop:

$$\boldsymbol{EXD} = -\boldsymbol{V} * \boldsymbol{\Delta p} \quad (7)$$

Integration of equation 7, combined with the ideal gas law, yields the equation for exergy destruction through mass transfer ($n\ R\ T\ \ln(p_1/p_2)$). Those similarities are there because both processes have the same driving force.

In the next section, we propose an efficient dehumidification device starting from these analyses. The device is called a “vapour heat pump”, because it upgrades the energy in vapour to energy in sensible heat. The name is chosen based on the analogy with a classic heat pump that upgrades sensible heat at a lower temperature into sensible heat at a higher temperature.

THE DESIGN OF AN EFFICIENT DEHUMIDIFICATION DEVICE: THE VAPOUR HEAT PUMP

The design of the vapour heat pump is based on the principles described in the previous section. It consists of (Fig.2)

- a counter flow heat mass exchanger (HMEX) between the air and the liquid desiccant solution (such as a $CaCl_2$ or LiCl solution), and,
- a mechanical vapour compression (MVC) unit to reconcentrate the diluted salt solution.

Here are some more details on the vapour heat pump:

- The counter flow HMEX consist of
  - a distribution unit of concentrated desiccant solution on the top
  - a matrix material through which the salt solution flows by gravity
  - a drain unit for the diluted hygroscopic salt solution
  - an air inlet at the bottom and an air outlet at the top
- Humid air is entering the HMEX at the bottom and is flowing through the matrix. The matrix surface is covered with a thin layer (~0.05mm) of a hygroscopic salt solution that flows down by gravity and has intensive contact with the upward flowing air (counter flow).
- For an efficient counter flow design of the HMEX, the hygroscopic capacity of the air stream and salt solution stream must be similar. The hygroscopic capacity of a stream (kg/s) is defined as the mass of absorbed water, per unity change of the (equilibrium) relative humidity and per mass of substance multiplied with its flow rate. For such a similar hygroscopic capacity, the mass ratio between the salt solution and the air flow is small and the HMEX is called “low flow” ([11,12,13,14]).
- Part of the vapour in the air is absorbed by the hygroscopic salt solution. During that process, the latent heat of evaporation (~2.5 MJ/kg) and the differential enthalpy of dilution (~50-300kJ/kg, see [15]) are transformed into sensible heat, which is absorbed by the salt solution. Most of this sensible heat, however, is transferred to the air (approximating adiabatic dehumidification) because of the low thermal capacity of the salt solution flow compared to the air flow.
- The dried and heated air is then transferred to the drying unit, and the diluted salt solution to the MVC unit.
- The general principle of MVC is as follows: A liquid is boiling in contact with a surface. The produced vapour is compressed. This compressed vapour is then brought in contact with the opposite side of the surface (“thermal contact”). The vapour is condensing and transferring the heat of that phase change to the surface, a process that allows the liquid at the other side to continue boiling.
- Several design possibilities exist for MVC-units, for example bundle boiling, flow boiling in evaporation tubes, and vertical or horizontal falling films (see [16,17]). An optimal efficiency of the vapour heat pump will depend on an optimal design of the MVC-unit.
- A heat exchanger is exchanging the heat between the incoming and the outgoing salt solution (Fig.2).
- In such a vapour heat pump, the hygroscopic salt solution is the “refrigerant” of this open system.
- An additional advantage of the proposed system is that it can perform well in a corrosive environment such as for wood drying. The coils of the evaporator of a drying heat pump will typically have corrosion problems.

A dehumidification device as described above, is currently being developed in our lab. An appropriate matrix material has been chosen [18] for the HMEX. A pilot for the MVC of the hygroscopic salt solution is under construction.

The next section is presenting the modelling of the vapour heat pump’s dehumidification efficiency.

difference, see Equation 1) and for higher temperatures (higher quantity, see equation 1).

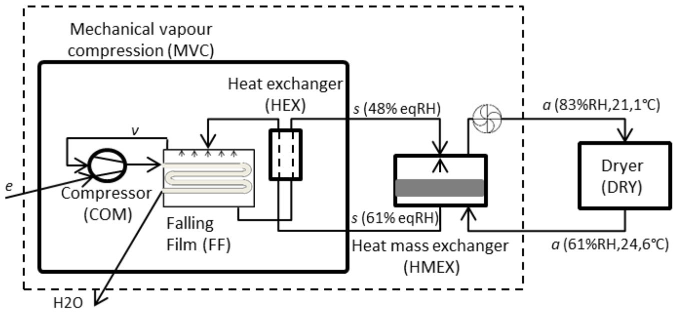

Figure 2 Representation of the basic principles of a vapour heat pump. The indicated values for air and salt solution are typical values for greenhouse dehumidification and vary depending on the application. The dashed line is the boundary for the exergy analysis of the dehumidification device. *a* stands for air, *e* for electricity, *H2O* for liquid water, *s* for liquid hygroscopic salt solution and *v* for vapour.

EFFICIENCY ANALYSES OF THE VAPOUR HEAT PUMP

Technical data and calculation method

Six different air conditions are modelled (see Table 1). The air outlet conditions in Table 1 are given for adiabatic drying conditions (see section Thermodynamics of dehumidification). This is an approximation: adiabatic drying is not a spontaneous process, some additional exergy input is required and will result in somewhat higher output temperatures.

The vapour heat pump is modelled under the following conditions:

- The characteristics of the HMEX are studied in our lab and will be published later. The average driving force for the heat transfer is around 2°C. For the mass transfer, a RH difference of 10-20% is used, depending on the drying rates. The pressure drop is small and approximates 20 Pa. Exergy destruction is calculated according to Equations 3 and 4.
- The heat transfer in a MVC-unit is around 15kW/m² for a 4°C temperature difference.
- The heat exchanger (HEX) between the incoming and outgoing salt solution is supposed to have an average temperature difference of 5°C.
- Isentropic efficiency of the compressor is 70% (see Groll, 2012).
- Axial fans are used. Their exergetic efficiency is 40% based on values of the commercial supplier Ventomatic.
- For calculation equations that are not mentioned, refer to a general thermodynamic handbook (e.g. Moran and Shapiro, 1998).
- Air values are calculated per kg dry air.

Results and discussion

Table 1 displays the air characteristics per kg dry air under different drying conditions. The exergy difference between the dried and humid air is higher for lower RHs, (higher quality

Table 1: Six different air conditions as used in the analyses of the vapour heat pump. The air outlet conditions are calculated for an adiabatic system. Values are expressed for 1 kg of dry air.

	$T_{a,inp}$ (K)	$RH_{a,inp}$	$T_{a,out}$ (K)	$RH_{a,out}$	D (J)	Δm_{H2O} (kg)	ΔEX (J)
1	293	0.9	299	0.5	6166	-0.0025	138
2	293	0.6	299	0.3	5941	-0.0024	276
3	305	0.9	313	0.5	8240	-0.0034	206
4	305	0.6	314	0.3	8479	-0.0035	419
5	325	0.9	336	0.5	11941	-0.0050	378
6	325	0.6	338	0.3	12852	-0.0054	723

Table 2 depicts the corresponding exergy destructions and efficiency of the vapour heat pump for the air conditions.

Table 2: Simulated exergy loss (EXD) of the different components of the vapour heat pump as described in Fig. 2 and its dehumidification efficiency (η_{deh}). The numbering 1 to 6 refers to the air conditions in Table 1. The EXD of the pressure drop in the HMEX and in the ventilator is summed in the group VENT. Σ represent the summation of the exergy destruction of the different processes in the concerning device.

	HMEX	VENT	Σ HMEX	FF	COM	HEX	COND	Σ MVC	Σ VHP	η_{deh}
1	152	41	193	50	100	54	110	314	507	9.6
2	200	41	242	48	145	70	106	369	611	6.7
3	201	41	242	66	135	73	149	424	666	9.5
4	285	41	326	68	209	101	154	532	858	6.6
5	287	41	328	96	200	107	221	624	952	9.0
6	429	41	470	104	323	156	238	820	1291	6.4

From the table, we can conclude that

- The MVC-unit is responsible for the largest part of the exergy destruction.
- In the presented design, the heat of the condense water dissipates to the environment during cooling. This results in exergy losses (column COND in Table 2). For a vapour heat pump, the recuperation of the sensible heat of both fluxes is thus important. However, the possibilities will also depend on the energy balances of the MVC unit (inputs are the diluted salt solution and electricity of the compressor, outputs are the concentrated salt solution and liquid water) which are not integrated in this simulation study.
- The efficiency (η_{deh}) is only slightly influenced by the air temperature. In contrast, the impact of the relative humidity is more pronounced, as expected: stronger drying needs will result in a lower dehumidification efficiency.
- The average calculated efficiency for dehumidification is 9.3 for humid conditions (RH 0.9→0.5) and 6.6 for dry conditions (RH 0.6→0.3).

For comparison, the actual efficiencies of moderate temperature dryers in industry are:

- Conventional air dryers have efficiencies of 0.2 to 0.6 [5].

- Advanced air dryers like heat pump dryers have efficiencies of 1 to 3 [2]; desiccant wheel assisted dryers have efficiencies close to 1 [8].

Compared to those values, the proposed vapour heat pump has the potential to cause a massive improvement in industrial drying efficiency. Furthermore, because drying processes take up as much as 15% of the total energy, used by industry [1], a successful development of the vapour heat pump can significantly reduce the energy use worldwide. A successful economic implementation will depend on the combination of energy savings, minimal costs, and a good reliability.

CONCLUSIONS

Based on second law analyses, efficient dehumidification is feasible. However, even the best available technology still has a low dehumidification efficiency. A comprehensive thermodynamic analysis was performed to explain that discrepancy.

Dehumidification by sorption, in contrast to cooling, is more attractive for an efficient dehumidification device because the processes of sensible cooling and redistributing the heat to the air are avoided. Of course, the regeneration of the sorbent should also be efficient.

This paper presents a novel dehumidification device with a higher efficiency. The device consists of a heat mass exchanger, containing a salt solution that absorbs the water vapour in the humid air during intensive contact with the air. The diluted salt solution is regenerated or reconcentrated in a mechanical vapour compression unit, in which the salt solution boils. The produced vapour is compressed and condenses at a higher temperature, thereby producing heat for the boiling process. Such a system will be called a vapour heat pump.

The performance of the vapour heat pump is modelled by studying and modelling all processes that take place in the heat mass exchanger and in the mechanical vapour compression unit.

The dehumidification efficiency of the vapour heat pump is on average 9.3 for humid air conditions (RH from 0.9 to 0.5) and 6.6 for dry air conditions (RH from 0.6 to 0.3). This means a huge efficiency improvement compared to traditional drying techniques (η_{deh}~0.2-0.6) and advanced drying technologies like heat pump drying (η_{deh}~1-3) and desiccant wheel dryers (η_{deh}~1).

A successful development of the vapour heat pump can have a considerable impact on the global energy use and the overall sustainability due to the large share of drying in the global energy consumption.

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