Comparison of Heat Pump Dryer and Mechanical Steam Compression Dryer

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ABSTRACT

The energy efficiency of domestic dryers is a stake for both manufacturers and regulatory bodies. High efficiency dryers exist by using a heat pump systems. Mechanical steam compression is not used for now but is a promising option. Comparisons of environmental impact and energy efficiency of both systems are performed for standardized conditions.
A detailed description of the mechanical steam compression system developed by the laboratory is presented. Simulations and test results show the energy efficiency that can be reached and also the drying time.
Energy consumption is divided by 2 compared to the actual base line of European dryers and the drying time is also nearly divided by 2.

INTRODUCTION

The Kyoto Protocol resolutions lead to an international effort to reduce the greenhouse gases (GHG) emissions. The carbon dioxide represents 80% of GHGs emissions. The major part of electricity is produced by thermal plants emitting large quantities of carbon dioxide. Therefore, the reduction of the electricity demand and use is primordial to reduce the carbon dioxide emissions. Domestic tumble dryer is one of the most consuming appliance. The forecast of the European market growth is high.
Taking into account these constraints, designers of appliances and component shall look at innovative solutions permitting to improve the energy efficiency of their systems with limited additional costs. Since 1996 the Center for Energy studies has been working on high efficient dryer.
A significant reduction of the energy consumption cannot be reached without energy recovery from the condensation of humidity. The use of the recovered energy implies that the difference between the heat source temperature and the drying temperature is positive and large enough.
Heat pump systems (HP system) or mechanical steam compression systems (MSC) permit to raise the temperature of the recovered heat in order to use it for the drying process. Nevertheless, technical constraints are high for easy integration, cost, environmental impact and easiness for cleaning heat-exchange surfaces.
MSC dryers permit to reach high energy efficiency and short drying time. The following sections present the operation principle of MSC and HP dryers, thermodynamic cycles are described and compared, energy performances of HP and MSC dryers are evaluated based on measurements and simulations.

1- THERMODYNAMIC CYCLE OF TUMBLE DRYERS

Two types of domestic tumble dryers are available on the market :

- Venting dryer
- Condensation dryer.

In the Venting dryer, the air flow is heated at the tumble inlet. Then it is discharged outside the room. This principle is simple and does not permit to develop significant energy efficiency improvement.
The condensation dryer operates with a closed air circuit, including a heat exchanger. Many technical improvements are potentially feasible for this technology in order to reduce the energy consumption.

1.1 Condensation dryer

The internal air circuit (see figure 1) is mainly constituted of 4 components:

- an air filter at the outlet of the tumble
- an air-cooled heat exchanger (condenser)
- a fan
- an electric heater at the tumble inlet.

The air flow blown into the tumble is previously heated. Heat and mass exchanges between the humid linen and the air are activated by the rotation of the tumble. Humid air flow at the outlet is dehumidified in the condenser. cooled by the ambient air flow. The water getting out of the condenser is drained and stocked in a removable tank.

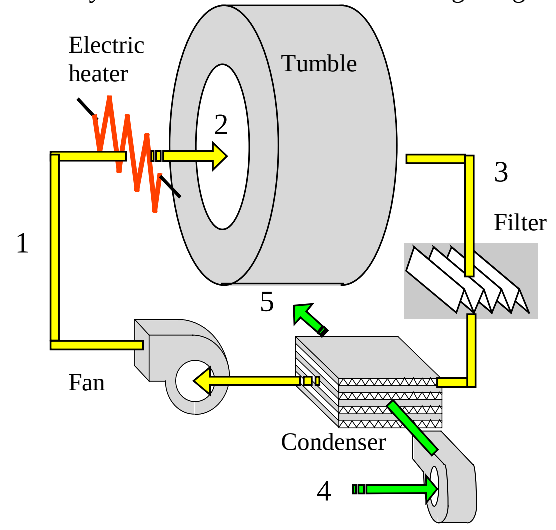

Figure 1: Condensation dryer principle

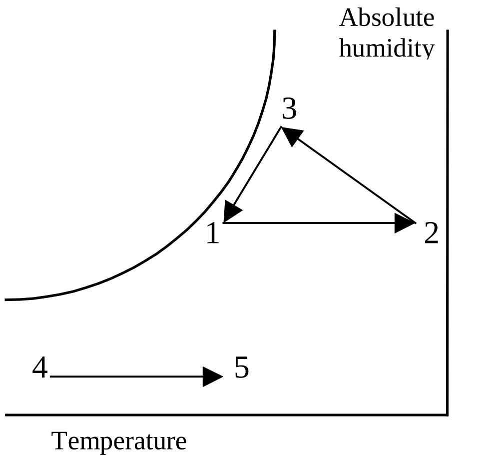

Figure 2: Evolution on psychometric diagram

The heat condensation released at the condenser is extracted outside of the dryer and lost in the cooling air circuit. The evolution on psychometric diagram is shown in figure 2.

1.2 Heat pump dryer

The energy consumption reduction of dryers requires to recover the condensing heat and to use it in the drying process. The use of the recovered energy implies that the difference between the heat source temperature and the drying temperature is positive and large enough.

The HP system permits to raise the temperature of the recovered heat high enough to use it in the drying process. Dehumidification is performed at the evaporator heat exchanger, the heating capacity is provided by the heat pump condenser (see figure 3). The evolution on psychometric diagram is shown in figure 4.

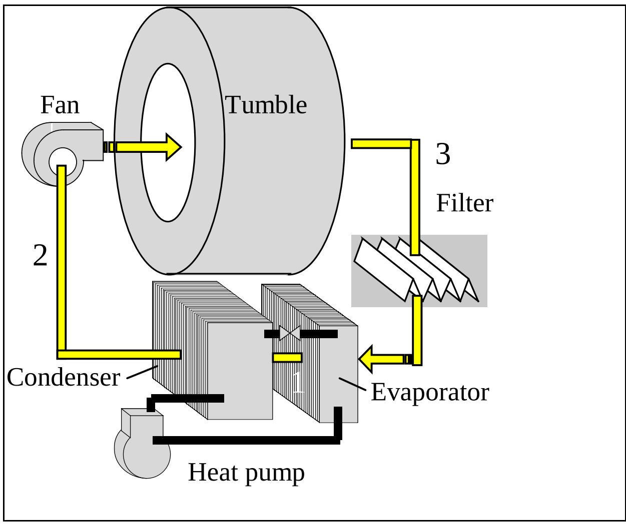

Figure 3: Condensation dryer using a heat pump

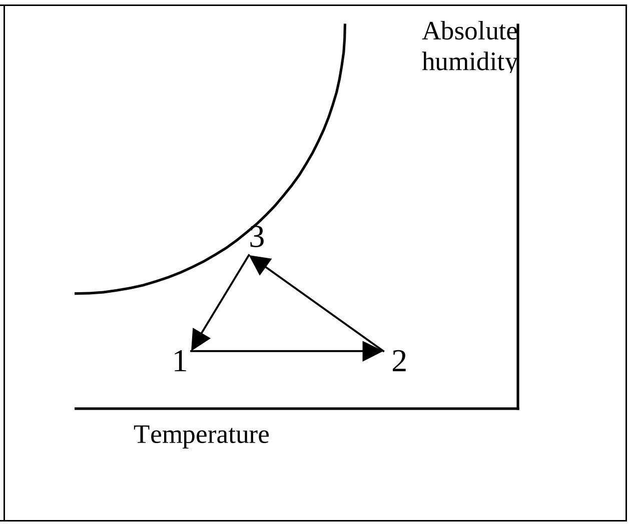

Figure 4: Evolution on psychometric diagram

The heat provided by humidity condensation is then recovered at the evaporator and raised at a higher temperature level at the condenser. HP cycle permits to reduce the energy consumption of the drying cycle by a factor 2 compared to the base-line energy consumption of dryers.
Nevertheless the implementation of a heat pump in a domestic dryer is not an easy process. Some problems have been identified.

- Additional costs are significant: components and integration process;
- Non removable heat exchangers create difficult cleaning. Stuffing deposition on heat exchangers is high and the efficiency decreases rapidly;
- Fluorinated refrigerants imply constraints in terms of management during the manufacturing and at the end of life.

1.3 Super-heated steam (SHS) dryer using mechanical steam compression (MSC)

The Center for Energy studies has developed a drying process using Super-Heated Steam (SHS) in domestic dryers [ARM96], [ARM98]. Compared to air, the SHS drying presents several advantages. The principle is briefly described.

- **SHS drying principle**

The SHS drying process at atmospheric pressure applied to domestic dryers consists of 4 phases.

- Phase 1: temperature raise

Humid linen, circuit and other components are heated to 100°C.

- Phase 2: air purge by steam

The whole circuit is purged by the steam that flushes the air out of the circuit.

- Phase 3: drying phase with SHS.

The internal atmosphere is now pure water vapor. At the tumble inlet the steam flow is superheated. Water in the linen is vaporized at 100°C and at atmospheric pressure.

- Phase 4: Cooling phase

External air is introduced at the end of the cycle in order to cool the circuit and the dry linen.

- **SHS drying advantages**

Compared to humid air drying, superheated steam drying is more energy efficient.

- Sensible heat losses are nil during the condensation process, because the water vapor is in saturated state.
- Heat and mass transfers are higher with steam because there is no more air resistance.
- The thermal capacity (Cp) of steam is about twice high compared to the air one permitting either to decrease the steam mass flow rate or to increase the heating capacity at constant mass flow rate.

- **Mechanical Steam Compression (MSC)**

The open cycle using mechanical compression uses the vapor extracted from the linen as the working fluid of the thermodynamic cycle. The evaporating phase does not take place in the heat exchanger but, directly in the linen. Since the temperature difference at the evaporator does not exist, the cycle energy efficiency is improved. This operating mode is then associated to a drying cycle using SHS [ARM98].

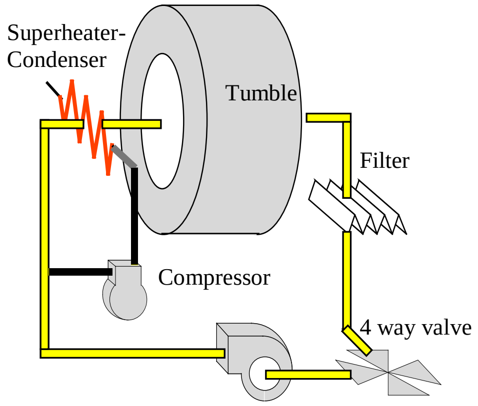

Figure 5: Mechanical Steam Compression Dryer

A MSC drier needs a limited number of additional components, at a limited cost (see figure 5):
- the compressor,
- only one heat exchanger : the superheater – condenser.

Moreover the process presents several advantages
- the thermodynamic fluid is water recovered from linen,
- the open cycle implies less leakage constraint,
- the simple air circuit avoids additional air cooling circuit,
- the condenser is removable for cleaning.

2- REFRIGERATION CYCLE COMPARISONS

A heat pump dryer has been tested [AEG00]. The sensors have been located both in the air circuit and in the refrigerant circuit. The thermodynamic system is run with R-134a. Thermodynamic cycles of the heat pump and the MSC are compared. Operating conditions are summarized in table 1.

Table 1: Operating conditions

	Heat pump	MSC
Drying temperature	40°C	100°C
Condensation temperature	60°C	120°C
Evaporation temperature	15°C	100°C

For both systems the difference between the condensation temperature and the drying temperature is equal (20K). Because of direct water vaporization from the linen, the drying temperature and the evaporation temperature are the same in the MSC dryer.

2.1 Refrigerant properties

Table 2: Thermodynamic and thermophysical properties of R-134a and R-718 (Water)

		R-134a				R-718			
		Vap.	Liq.	Vap.	Liq.	Vap.	Liq.	Vap.	Liq.
Temperature	°C	15		60		100		120	
Pressure	kPa	488		1680		101		198	
Lv	kJ/kg	185.3		138.5		2256		2202	
ρ	kg/m^3	23.8	1243	87.4	1053	0.6	958.4	1.12	943.1
cp	kJ/kg.K	0.97	1.39	1.39	1.66	2.07	4.22	2.17	4.24
μ	.10^{-6} Pa.s	11.4	224.3	13.8	124.2	12.3	281.8	13.0	232.1
λ	.10^{-3}W/m.K	13	85.4	18	66	30	680	30	680

Figure 6 compares the pressure ratio and the pressure difference of R-134a and R-718. These values indicate that R-718 presents better operating conditions for the compressor.
Figure 7 compares the thermal conductivity of liquid and vapor phases for the two refrigerants. These figures also indicate that water characteristics favor higher internal heat-exchange coefficient.

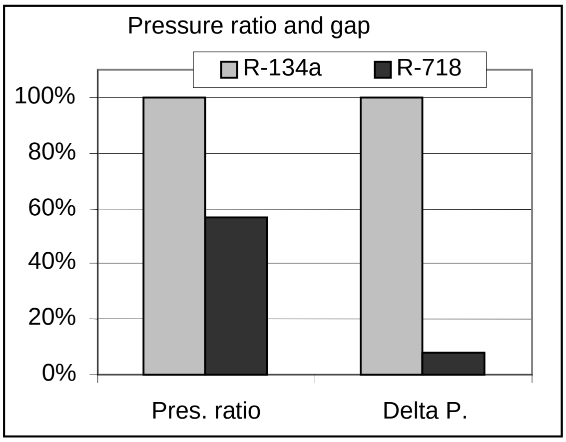

Figure 6: Operating condition - Pressure

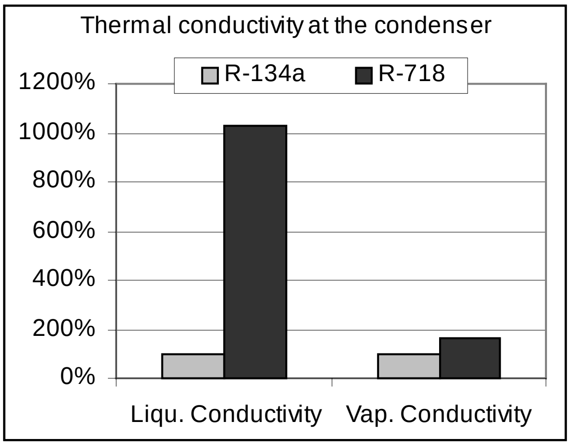

Figure 7: Thermal conductivity of the refrigerant

2.2 Refrigerant cycle

For a constant difference between the blowing temperature (Tb) and the drying temperature (Td), the open cycle benefits from a lower compression because the evaporating temperature is the drying temperature (see figure 10). Moreover, the total heat dissipated at the condenser can be used for the drying process, contrary to the heat pump cycle (see figure 8) where part of it shall be extracted to compensate the compression excess.
Figures 9 and 11 present two thermodynamic cycles in a H. logP diagram.

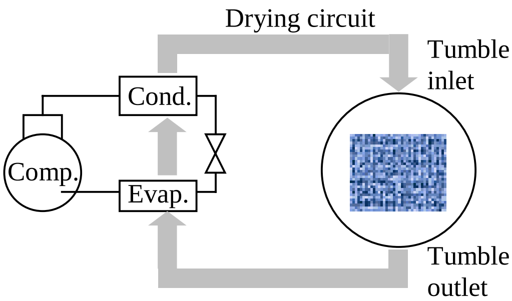

Figure 8: Schematic circuit

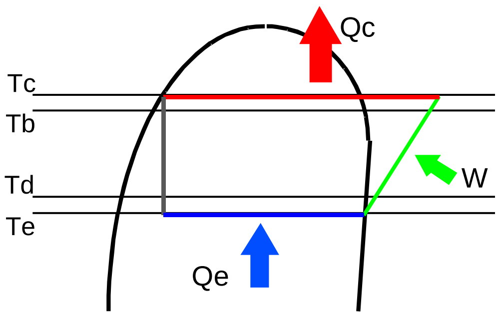

Figure 9: R-134a closed cycle

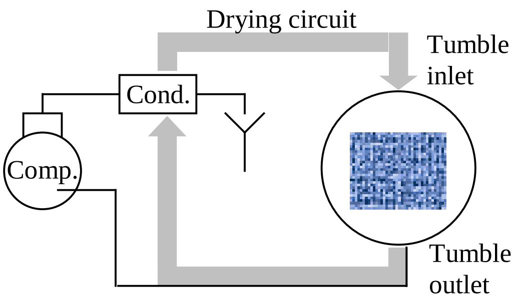

Figure 10: Schematic circuit

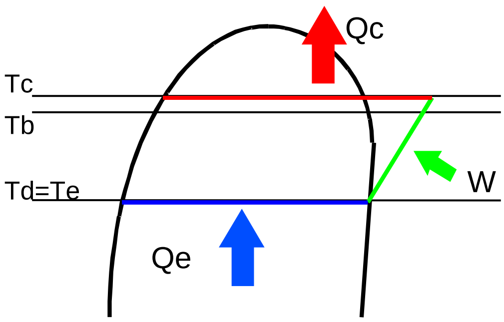

Figure 11: R-718 open cycle

The closed cycle (see Figure 9) is implemented in a heat pump dryer using R-134a as a working fluid
The humid air at drying temperature (Td) is dehumidified on the evaporator at the evaporating temperature Te, that exchanges a cooling capacity (Qe), with Te < Td.

The condenser heats the air from temperature (Td) to temperature (Tb) (with Tb < Tc). The heat capacity to be extracted (Qc) is the sum of the cooling capacity (Qe) plus the compressor input power (W).
The excess of heat, equivalent to the mechanical compression power, is not useful for the drying process and shall be extracted from the dryer.

The open cycle (see Fig.11) is the cycle used in the dryer using MSC, and where the steam is the working fluid.

The water evaporated from the linen is directly sucked by the compressor. Since there is no evaporator, the evaporating temperature (Te) is equal to the drying temperature (Td).
The steam condensation supplies the heating capacity necessary to raise the temperature at the tumble inlet. The open thermodynamic cycle permits to use 100% of the evaporating latent heat, and the formula Qc = Qe + W does not apply. The heat excess is much lower than the compression, and is compensated by the dryer heat losses. The drying process benefits better from the supplied heat.

- **High temperature of the thermodynamic cycle**

Reminder : Cycle Coefficient Of Performance (COP)

Heating COP

$$COP_{carnot} = \frac{T_c}{T_c - T_e} \quad [1]$$

$$COP = \frac{Q_c}{W} \quad [3]$$

Cooling COP

$$COP_{carnot} = \frac{T_e}{T_c - T_e} \quad [2]$$

$$COP = \frac{Q_e}{W} \quad [4]$$

$$\eta_c = \frac{COP}{COP_{carnot}} \quad [5]$$

The heating COP [1] is the ratio between the condenser heating capacity and the electric power consumed by the moto compressor. The equation of the COP can be linked to the cycle condensing and evaporating temperatures [2]. The cycle efficiency (η_{cy}) indicates the degradation of the real cycle compared to the theoretical Carnot cycle. The COP is related directly to the condensing temperature when the temperature difference ($T_c - T_e$) is constant. The thermodynamic cycle efficiency is higher when the drying temperature raises.

Table 3: Coefficient of performance

	R-134a cycle		R-718 cycle	
	Heating	Cooling	Heating	Cooling
COP carnot	7.4	6.4	19.65	18.65
COP	3.35	2.64	8.78	8.78
η_{cy}	45%	41%	47%	47%

Direct evaporation in R-718 open cycle permits to reduce the temperature difference between the condenser and the evaporator. Moreover the adiabatic expansion in R-134a cycle decreases the cycle efficiency (η_{cy}) with a lower cooling effect (liquid flash).

3- DRYING CYCLE COMPARISON

A dryer demonstrator using mechanical steam compression is under development at the Center for Energy Studies. In order to obtain the best evaluation of the performances, tests have been performed on the main component of the system: the compressor.
Additional tests performed on condensation dryers existing on the market have permitted to measure the electric consumption of other motors. Based on these different experimental results, a numerical model has been developed. The psychometric chart equations are implemented in the model. It permits to simulate the operation of the MSC dryer under various conditions.

3.1 Assumptions

- Temperature at condenser outlet: 145°C
- Condensation pressure: 500kPa
- Compressor swept volume: $12m^3/h$
- Fan volume flow rate: $250m^3/h$
- Compressor volumetric efficiency: 75%
- Compressor global efficiency: 65%.

3.2 Drying cycle with HP and MSC

The operating conditions are in accordance with the European standard CES/IEC 61121/1997 [NOR97]. Figures 12 and 13 present for each cycle heating capacity and global COP evolutions during the drying cycle.

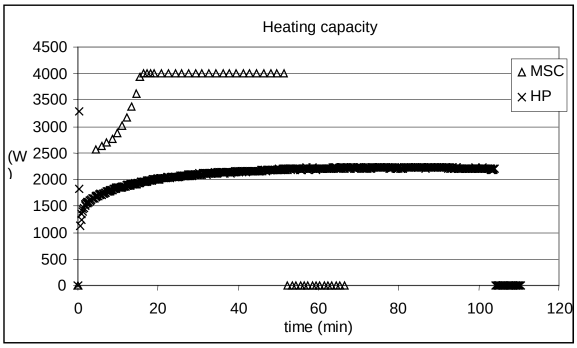

Figure 12: Heating capacity

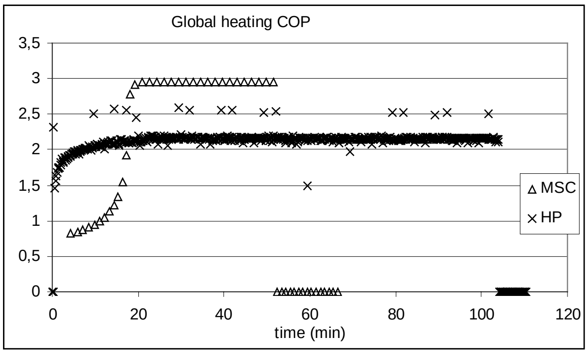

Figure 13: Global heating COP

The global heating COP takes into account the electric consumption of auxiliary motors (fan and tumble). Consequently it is lower than the COP defined in [3].

Due to the high coefficient of performance of the MSC dryer, and to the high evaporating temperature, the heating capacity can be significantly increased for a constant input power permitting to reduce significantly the drying cycle duration.

Figure 12 shows that **cycle duration is limited to about 1 hour with MSC dryer**, compared to 1h50 with HP dryer. During the drying phase the COP is 50 % higher with MSC (see Figure 13).

The energy consumption (see figure 14) of MSC and HP dryers are in the same range: 1730Wh/cycle for 5kg of cotton. These performances represent more than 55% of energy saving compared to usual condensation dryers.
Because of its higher drying temperature, the temperature raise phase consumes more energy with MSC dryer. Nevertheless the drying phase is more efficient and globally performances are equal.
The main additional interest of MSC dryer compared to HP dryer is the 40% reduction of the cycle time.

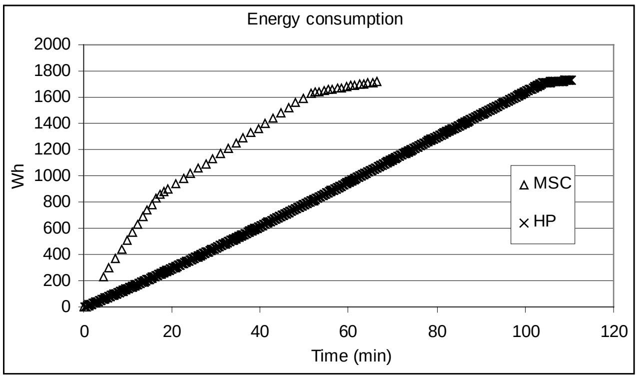

Figure 14: Energy consumption

4 CONCLUSIONS

HP and MSC dryers permit to divide by 2 the energy consumption of usual drying cycle. The development of these technologies in drying appliances shall take into account a number of constraints in order to make the dryer attractive, reliable and energy efficient. Two technologies are evaluated: R-718 mechanical compression and R-134a heat pump. The MSC dryer offers an added value by reducing to about 1 hour the drying cycle duration compared to 2 hours for most of usual dryers. The energy consumption is reduced to 45% of the actual base-line. Additional costs are limited with a small number of additional components. The refrigerant used, water, is environment-friendly and offers good performances. Because of the open cycle configuration, the heat exchanger is removable for cleaning, essential condition for high energy efficiency preservation.

NOMENCLATURE

MSC	Mechanical Steam Compression	
SHS	Super-Heated Steam	
HP	Heat Pump	
COP	Coefficient of performance	
Q	Capacity	W
W	Mechanical power	W
Lv	Latent vaporization heat	kJ/kg
T	temperature	K
cp	thermal capacity	kJ/kg.K

Greek letters

η	efficiency	
ρ	density	kg/m^3
μ	cinematic viscosity	Pa.s
λ	thermal conductivity	W/m.K

Subscripts

cy	cycle
b	blown
d	drying
e	evaporator
c	condenser

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COMPARAISON D'UN SECHE-LINGE AVEC POMPE A CHALEUR ET UN SECHE-LINGE A RE-COMPRESSION MECANIQUE DE VAPEUR D'EAU

L'efficacité energétique des sèche-linge domestiques est un enjeu à la fois pour les constructeurs et les autorités réglementaires européennes. Des solutions à haute efficacité énergétique existent en utilisant une pompe à chaleur. La re-compression mécanique de vapeur d'eau n'est pas encore utilisée à ce jour mais constitue une option technique prometteuse. L'impact environemental et l'efficacité énergétique de ces deux systèmes sont comparés dans les conditions de fonctionnement normalisées. Une description détaillée du procédé de séchage par re-compression mécanique de vapeur d'eau développé par le laboratoire est présentée. Les résultats expérimentaux et de simulation montrent que la consommation énergétique peut être réduite de plus de 50 % comparée à la base actuelle des sèche-linge du marché, la durée du cycle est presque divisée par 2.