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The Appropriate Choice of Evaporators Type in Refrigeration Systems on the Energy Consumption

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Abstract: This work has as main objective an analysis of the validity of the implementation of a flooded evaporator in a vapor compression refrigerant cycle, the working fluid being the R134a. To achieve this goal, it was used a simulation software, the Pack Calculation Pro. A comparison of the annual energy consumption of the refrigeration system with a flooded evaporator was carried out having as reference the same system with a dry evaporator and working in different situations. In this study, the advantages and disadvantages of using the two types of evaporators, the flooded and dry one, having the system used for situations equal cooling capacity and the possible presence of overheating for the dry evaporator and the presence of the pump in the flooded evaporator was analyzed. It was concluded that the advantage in the implementation of flooded evaporator is directly proportional to the degree of overheating at the exit of the dry evaporator. Also an economic analysis was carried out.

Key words: refrigeration systems, flooded evaporators, dry evaporators, energy use

1. Introduction

Currently, the use of refrigeration systems is indispensable [1]. They play a fundamental role in areas ranging from the preservation of perishable products, the pharmaceutical industry or air conditioning. In fact, uncommon is the house where there are no refrigeration systems installed, be it air conditioner or the refrigerator itself. The scale of applications increases significantly when, instead of considering only domestic applications, it is taken in account industrial, commercial, transportation, among others.

In recent years, with the concept of sustainable development [2], it became clear that changes would have to be made to conventional refrigeration systems trying o increase their efficiency to the maximum, and so, reducing the energy consumed without compromising the cooling effect.

The energy consumption of a refrigeration system is mainly due to the power consumed by the compressor(s), which is responsible for forcing the fluid flow through the system. Components such as the evaporator also influence the energy consumption since the more efficient they are in the absorption of heat, the greater will be the cooling capacity of the entire system, or else, for the same cooling capacity the lower will be the energy consumption [3]. A comparison of the annual energy consumption of the refrigeration system with a flooded evaporator was carried out having as reference the same system with a dry evaporator and working in different situations. Usually in case of the dry evaporator, it presents a useful superheat at its outlet and an unnecessary superheat in flowing to the compressors. So it presents a lower COP due to the increase in the energy consumption of the compressors, being then feasible the inclusion of a flooded evaporator, when the medium/long term system is energetic analysed [4-5]. This is due to the fact the in this type of evaporators the

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refrigerant leaves it in a state of wet vapour (no superheat). In this case, the system has a lower annual energy utilization. From the simulations, made with Pack Calculation Pro 4.2 [6], it was possible to conclude that the relevance of the flooded evaporator implementation is directly proportional to the degree of overheating at the outlet of the dry evaporator.

2. Systems and Methodology

Fig. 1 shows a diagram of both refrigeration systems, one with a dry evaporator and the other with a flooded one.

Table 1 displays the common characteristics of both systems: condensation and evaporation temperatures of the systems, cooling effect, the pump power of the flooded evaporator, as well as, the chosen compressors.

The main difference between them lies in the state of refrigerant at the outlet of the evaporator. In the first one, the dry evaporator, the working fluid leaving the evaporator is superheated vapour (just one phase), while in second one, the working fluid at the outlet is wet vapour (saturated liquid and saturated vapour). It is also need a drum, in parallel to the evaporator, where the two phases are separated. In it, the saturated vapour arriving from the expansion valve and the one coming from the evaporator flows to the internal heat exchanger and then to the compressors. The saturated

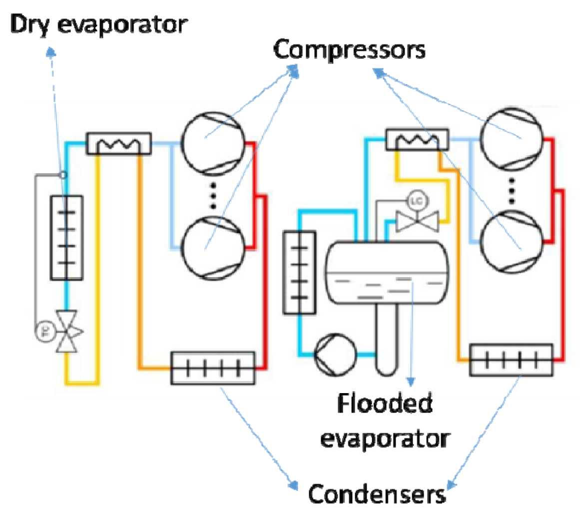

Fig. 1 Refrigeration system with a dry evaporator (left) and with a flooded evaporator (right), Adapted from [6].

Table 1 Common characteristics of both systems.

	Dry evaporator	Flooded evaporator
Te	-11°C	
Te	48°C	
Compressors	Bitzer OSK 8561 50 Hz [1] (2x)	
Power of the pump	-29W	
Cooling effect	200 kW	

liquid is recirculated to the evaporator. In this case, the liquid from the drum can flow by gravity to the evaporator or, if the pressure losses are significant, it is necessary to use a circulating pump. So it was also simulated the possibility of using a circulation pump to feed the evaporator. In both systems, it was used two compressors and an internal heat exchanger.

The methodology used for the simulations was as follow:

• equal cooling capacity and the temperatures of evaporation and condensation fixed;

• addition of a pump to carry out forced circulation of the flooded evaporator;

• regarding the dry evaporator, it was considered an unnecessary overheating.

In order to carry out an economic analysis of the systems, the following data is necessary: the energy costs, based on current tariffs, is 0.14 €/kWh. Regarding equipment, the compressors of Bitzer OSK were considered and they have a cost of 20 k€ [7] (for safety two equal compressors were chosen working in parallel), the cost of the dry evaporator for a cooling capacity of 200 kW is 7 k€ [8] and the flooded evaporator was considered to have a cost 25% higher [3]. It was admitted a lifetime for both systems of 10 years.

The city chosen for the simulations was Oporto, Portugal. For the simulations, the location of the city is mandatory because of the annual variability of the climate during de year, as can be seen in Figs. 2-6 where the monthly outside temperature is displayed.

3. Results and Discussion

3.1 Dry Evaporator without Overheating vs Flooded Evaporator by Gravity (without Pump)

Fig. 2 shows the energy consumption per month of both systems regarding the compressors with dry and flooded evaporators and fans. The fans are used in the evaporator and condenser to exchange the heat more efficiently. When the systems stop, the fans are also stopped.

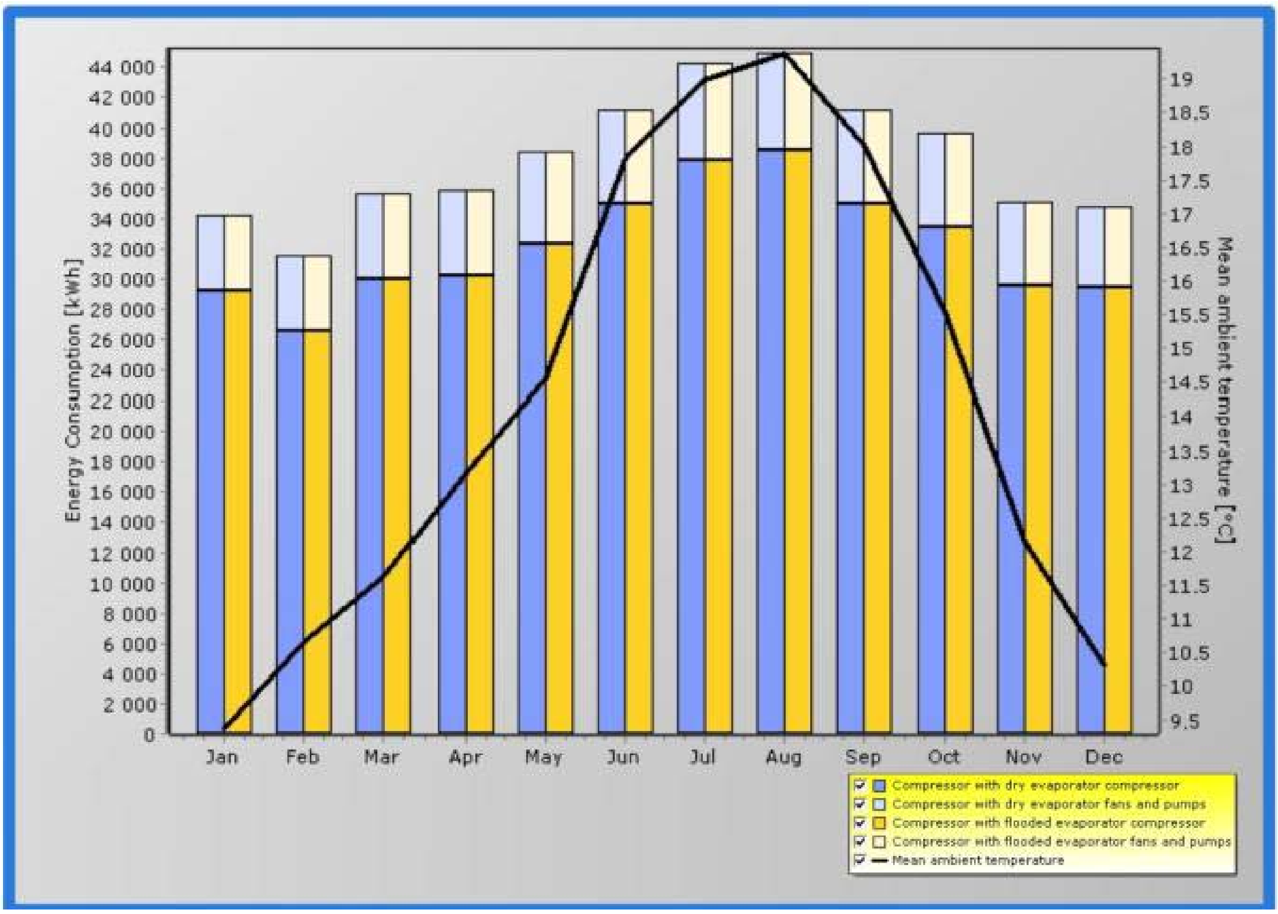

Fig. 2 Monthly energy consumption for the equipment used in both systems.

The left axis represents the monthly energy consumption of the components of the systems while the right axis represents the monthly average temperature of Oporto city. The horizontal axis represents the month of a typical year.

As can be seen from Fig. 2, the monthly energy used by each individual component varies along the year as a function of the local weather, accompanying the ambient external temperature. When it increases the electrical energy consumption to run the systems increases and vice versa. Usually this does not take into account when designing such kind of systems or heat pumps. The energy used by the fans along the year corresponds to the evaporator and condenser.

In the other Figs. 3-5, only left axis will change according to the electrical energy consumption per month.

Table 2 displays for the same year the global energy used in both evaporators.

The COP value displayed in Table 2 is the average COP of the systems along the year. They vary from month to month due to fact that for the same cooling effect, the energy used also varies. It can be concluded that in this case there are no energetic advantages from one evaporator over the other. This is due to the fact that in this case the vapour entering the compressor is saturated. This can also be observed in Fig. 2, the height of the bars is the same.

Table 2 Annual energy consumption for both systems.

	Dry evaporator	Flooded evaporator
COP	3.39	3.39
Energy consumption		
Fans and pumps (kWh)	69535	69535
Compressors (kWh)	386847	386847
Total (kWh)	456382	456382

It was also calculated the lifetime of both systems as shown in Table 3 in which IRR is the Internal Rate of Return and Inf stands for infinity.

The difference between the total annual cost of the main equipment (compressors and evaporators) is due to the piping, directional and expansion valves, other accessories needed for the system, as well as, the labour for the installation. As expected, the energy used in both systems is the same, because the pump of the flooded evaporator is not running. However, the lifetime costs of the flooded evaporator are higher.

Based on the results obtained for the refrigeration cycle with dry evaporator without overheating and flooded evaporator by gravity, it is visible that the running costs of the two systems are all identical. This information is shown in Table 3. Taking in account that the working fluid enters exactly in the same thermodynamic state in both evaporators, such behaviour would be expected and leaves always in saturated vapour.

3.2 Dry Evaporator without Overheating vs Flooded Evaporator with Pump

Considering the use of a circulation pump, it is expected that energy consumption increases compared to the previous condition of the flooded evaporator.

In Fig. 3 it is shown the energy consumption per month of both systems for the equipment used. As can be seen the trend of the graph is similar to the one shown in Fig. 2, exception for the energy used.

Table 3 Lifetime costs.

	Dry evaporator	Flooded evaporator
Cost of equipment (€)	47500	49365
IRR (%)	-	100
Total annual costs (€)	64259	64259
Payback period (years)	-	Inf
Energy (kWh)	578394	578394
Lifetime costs (€)	625894	627759

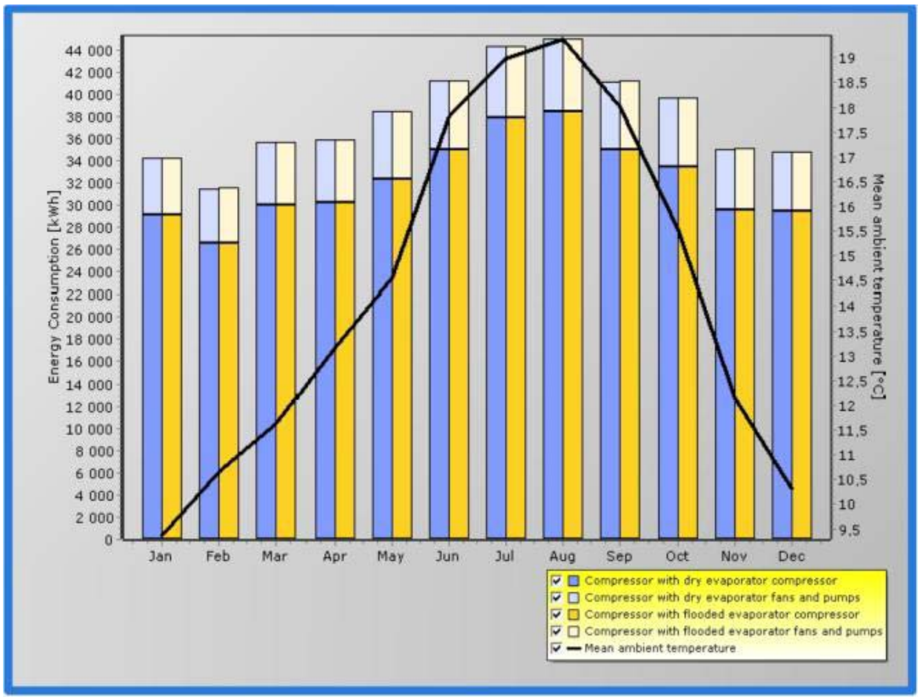

Fig. 3 Monthly energy consumption for the equipment used in both systems.

Table 4 displays, for the same year, the global energy used.

The COP values of both systems are very similar because the energy used by the pump is very small. The compressors also use the same amount of energy because they are working in the same conditions.

However, the total energy used by the flooded evaporator is higher, due the pump, which corresponds to an increase of 224 kWh in energy consumed annually when compared to the system with dry evaporator.

It was also calculated the lifetime of both systems as shown in Table 5.

The inclusion of a circulating pump in the flooded evaporator, if necessary, implies a higher lifetime costs of 2129 €.

3.3 Dry Evaporator with Useless Overheating (3 and 6K) vs Flooded Evaporator by Gravity (without Pump)

The presence of unnecessary overheating is very common in cycles with dry evaporators, since from the exit of the evaporator to the inlet of the compressor, due to the piping length (which may be long), absorbs heat from the environment, which results in an increase in the compression work for the same refrigeration power.

Considering the presence of unnecessary overheating of 3K at the inlet of the compressor, the monthly energy consumption results are shown in Fig. 4.

Table 4 Annual energy consumption for both systems.

	Dry evaporator	Flooded evaporator
COP (average)	3.39	3.4
Energy consumption		
Fans and pumps (kWh)	69535	69759
Compressors (kWh)	386847	386847
Total (kWh)	456382	456606
Savings		
Annual savings (kWh)	224	-
Annual savings (%)	-	-

Table 5 Lifetime costs.

	Dry evaporator	Flooded evaporator
Cost of equipment (€)	47500	49365
IRR (%)	-	100
Total annual costs (€)	64259	64259 (+31)
Payback period (years)	-	59
Energy (kWh)	578394	578678
Lifetime costs (€)	625894	628043 (+2149)

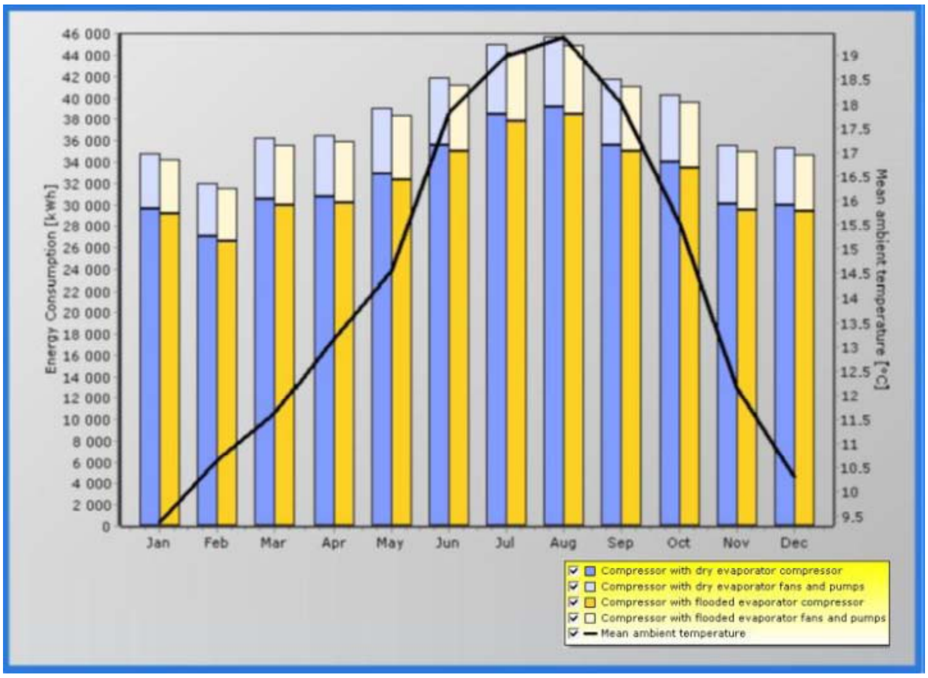

Fig. 4 Monthly energy consumption for the equipment used in both systems (3K useless overheating).

Table 6 displays, for the same year, the global energy used as well as the COP.

As can be seen, the flooded evaporator can save 1.7% of the energy in the whole system when compared to the dry evaporator. It was also calculated the lifetime of both systems as shown in Table 7.

As displayed, the payback period when using the flooded evaporator is 1.7 years if the dry evaporator has 3K of overheating.

Considering the unnecessary overheating of 6K at the inlet of the compressor, the following results were obtained.

In Fig. 5 it is show the energy consumption per month of both systems for the equipment used. Table 8 displays, for the same year, the global energy used.

Table 6 Global energy costs.

	Dry evaporator	Flooded evaporator
COP (average)	3.33	3.39
Energy consumption		
Fans and pumps (kWh)	70521	69535
Compressors (kWh)	393680	386847
Total (kWh)	464201	456382
Savings		
Annual savings (kWh)	-	7819
Annual savings (%)	-	1.7

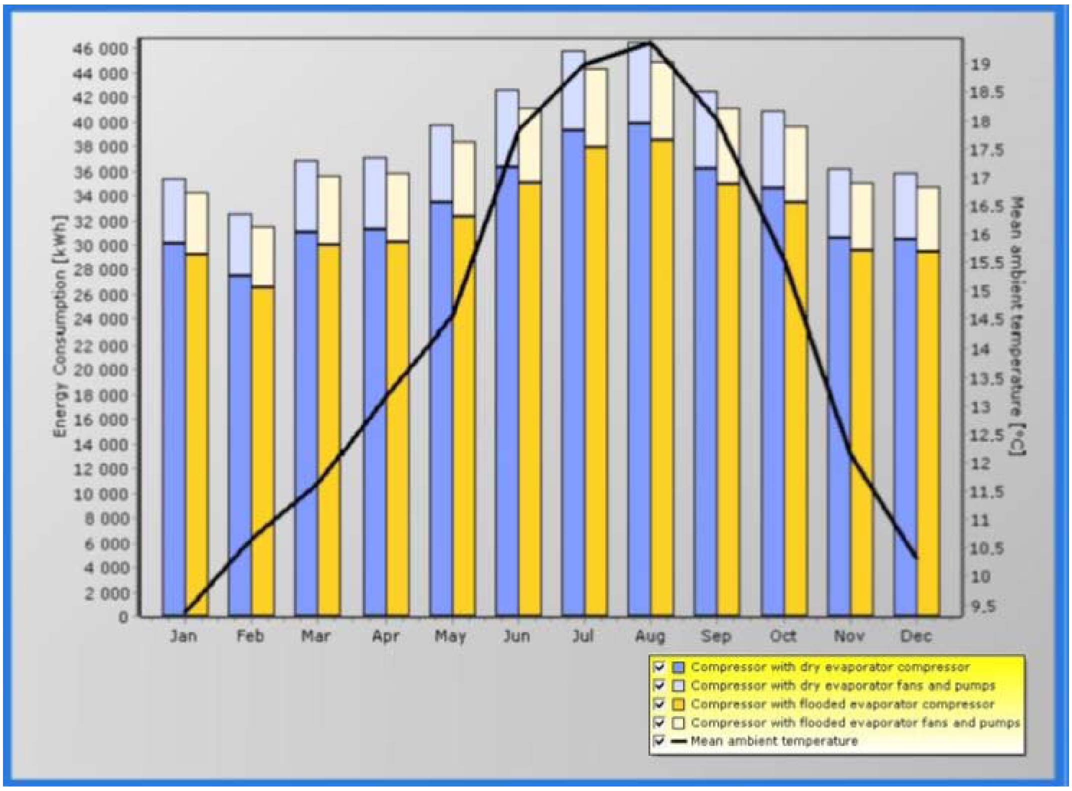

Fig. 5 Monthly energy consumption for the equipment used in both systems (3K useless overheating).

Table 7 Lifetime costs.

	Dry evaporator	Flooded evaporator
Cost of equipment (€)	47500	49365
IRR (%)	-	117.58
Total annual costs (€)	65360	64259 (-2194)
Payback period (years)	-	1.7
Energy (kWh)	588304	578394
Lifetime costs (€)	635804	627759 (-17882)

As a consequence, of the increase in the useless overheating of 6K in the dry evaporator, the annual energy savings are now 3.3% when compared with the dry evaporator.

It was also calculated the lifetime of both systems as shown in Table 9.

Table 8 Global energy costs.

	Dry evaporator	Flooded evaporator
COP (average)	3.28	3.39
Energy consumption		
Fans and pumps (kWh)	71494	69535
Compressors (kWh)	400469	386847
Total (kWh)	471963	456382
Savings		
Annual savings (kWh)	-	15581
Annual savings (%)	-	3.3

Table 9 Lifetime costs.

	Dry evaporator	Flooded evaporator
Cost of equipment (€)	47500	49365
IRR (%)	-	117.58
Total annual costs (€)	66452	64259 (-2194)
Payback period (years)	-	0.9
Energy (kWh)	598141	578394
Lifetime costs (€)	645641	627759 (-17882)

As can be seen now, the payback period is only of 0.9 years.

It must be noticed, that in this case, the refrigerant flowing from the drum of the flooded evaporator, as saturated vapour, can also have a useless superheat until it reached the compressors. However, when comparing with the dry evaporator, the total superheat is always lower (with the dry evaporator the total superheat is the sum of the useful and useless superheat). So the energy use is always lower.

4. Conclusions

In this work it was done a comparison between refrigeration systems based on vapour compression cycle using dry and flooded evaporators. An energy and economic analysis was carried out in order to evaluate when to use one or another. The main conclusions that can be withdrawn are:

• During the design phase of refrigeration systems, care must be taken in account with the monthly average temperature of the local where the systems are to be installed. The local affects the ambient external temperature, and thus the energy used. When the environment temperature increases, the electrical energy consumption to run the system increases and vice-versa.

• Dry evaporator without overheating vs flooded evaporator by gravity (without pump) — it can be concluded that in this case there are no energetic advantages installing one over the other evaporator. However, the lifetime costs of the flooded evaporator is higher due to the higher initial cost of the flooded evaporator.

• Dry evaporator without overheating vs flooded evaporator with pump — the COP values of both systems are very similar because the energy used by the pump is very small. The compressors also use the same amount of energy because they are working in the same conditions. However, the total energy used by the flooded evaporator is higher, due the pump, which corresponds to an excess of used energy of 224 kWh when compared to the system with dry evaporator. The inclusion of a circulating pump in the flooded evaporator, if necessary, implies a higher lifetime costs of 2129 €.

• Dry evaporator with useless overheating of 3K vs flooded evaporator by gravity (without pump) — in this situation the flooded evaporator can save 1.7% of the annual energy in the whole system when compared to the dry evaporator and the payback period is 1.7 years. The lifetime costs are also benefited.

• Dry evaporator with useless overheating of 6K vs flooded evaporator by gravity (without pump): in this situation, the flooded evaporator can save 3.3% of the annual energy in the whole system when compared to the dry evaporator and the payback period is 0.9 years. The lifetime costs are also benefited.

• The refrigerant flowing from the drum of the flooded evaporator, as saturated vapour, can also have a useless superheat until it reached the compressors. However, when comparing with the dry evaporator, the total superheat is always lower (with the dry evaporator the total superheat is the sum of the useful and useless superheat). So the energy use is always lower.

• This analysis was done only for one system. In the world there are millions of systems similar to the ones simulated. As can be easily seen, just with a multiplication, how many MWh can be saved contributing in this way for a sustainable development of the world.

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