EMERITUS: THE NEW CONDENSER/CO_2 GAS COOLER/DRY COOLER THAT MINIMIZES ENERGY CONSUMPTION

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ABSTRACT

In refrigeration and power cycles processes the use of air as heatsink for condensing, when large quantities of water are not available, is a common practice and even more frequent. Although ambient air has the great advantage of being available everywhere and in unlimited quantity, it also has numerous disadvantages: highly variable temperatures, low exchange coefficients, need to use of large heat exchange surfaces and large air quantities.

To limit these drawbacks, LU-VE has developed an innovative solution named EMERITUS. This technology has a fan-cooled exchanger on which two additional water cooling systems are used in sequence: treated water is sprayed onto the heat exchanger coil and the remaining non-evaporated is collected and used on to the adiabatic panel. This combination of the two techniques has positive effects on both the thermal capacity exchanged and the quantity of water consumed.

The article describes the functional principle of the new EMERITUS and analyses a case study in which the running costs of a water chiller combined with EMERITUS are compared with other traditional solutions.

Keywords: Condenser, CO_2, liquid coolers, heat exchangers, water spray, adiabatic panel

1. INTRODUCTION

Many processes, virtually all closed thermodynamic cycles, both power cycles and inverted cycles, as well as many industrial processes, require the transfer of heat to a heat sink, represented by the environment. The more this is done at low temperature, the better the overall energy performance. In particular, this is true if the heat transfer involves the condensation of the refrigeration cycles and the power cycles: in the first case, it increases the energy efficiency (EER), in the second case the cycle efficiency. The best heat sink to achieve this process is certainly water, due to its excellent heat transfer characteristics and because it is generally available at relatively low temperatures during the entire year. For this reason, most large thermal power plants are located in proximity to seas, lakes or rivers and, wherever it is economically and technically feasible, ground water is used. However, in cases, more and more frequent, in which large amounts of water is unavailable, the thermal exchange must necessarily take place with the ambient air. Sometimes the direct exchange between air and work cycle fluid is preferable, and therefore we speak of "remote fan-cooled condensers". In other cases it is preferred to adopt an intermediate heat transfer fluid (water or water/glycol mixtures), and in those cases we speak of "dry coolers". Faced with the need of a double heat exchange, dry coolers have the advantage of facilitating the adoption of "free cooling" in air conditioning systems, to limit the content of the cooling fluid, to enable a plurality of refrigerating machines, even using different fluids, thereby allowing use of the entire heat exchange capability regardless of the number of activated refrigerating units. While the ambient air has the great advantage of being available anywhere and in infinite quantities, it has several disadvantages, summarised as follows:

- Significantly variable temperatures, both throughout the day/night, and throughout the year;
- Low exchange coefficients, when compared with those of liquids, in particular water;
- Lower density, which involves the need to handle large volumes.

The negative consequences of these features are varied and result in the need to accept, at least in certain periods of the year, the high heat transfer temperatures, to adopt large surfaces of thermal exchange and to handle large air quantities. The energy efficiency of the processes is compromised, thereby increasing the space occupied, the consumption of the electric fans, the sound emissions, and the internal volumes of the refrigerant fluids. To limit these drawbacks, the design of modern dry coolers and remote fan-cooled condensers followed various trend lines:

a) The adoption of increasingly compact and efficient heat exchange matrices obtained by optimising the fin louvre geometry, or by adopting increasingly smaller tube diameters with more efficient groove geometries;
b) The adoption of "V-shape” units, which reduce the footprint;
c) The adoption of fans with vanes of increasingly aerodynamic geometry, and increasingly large diameters, with benefits in terms of efficiency and reduced noise emissions;
d) The adoption of electronic motors that enable high electrical efficiency, even upon variation of the rotation speed, while maintaining a high performance;
e) The adoption of diffusers/silencers which, fan speed being equal, increase efficiency and decrease noise.

2. THE DIFFERENT WAYS OF USING WATER TO ENHANCE HEAT TRANSFER

Conceptually, there are two ways of using water to enhance the heat exchange of condensers or dry coolers:

a) The first consists of running an adiabatic cooling of the air upstream of the heat exchanger, thereby increasing the relative humidity so as to obtain a greater temperature difference between the fluid to be cooled and the air; to obtain high efficiency by this process, make the air pass through a matrix (adiabatic panel) consisting of a set of sheets, typically made of cellulose, characterised by folds with different angles. The top of the matrix is injected with water. In the panel a cross-flow is created which determines an intense contact between air and water, facilitating the evaporation of the latter to the expense of the heat supplied by the air, which therefore decreases its temperature. A significant advantage of this solution is the possibility of using mains water, without wet operating time limits, thanks to the low cost of the evaporating panel and the simplicity of its solution.
b) The second is to spray water directly on the heat exchanger surfaces, that are suitably treated with the dual purpose of preventing deposits and corrosive effects. In this case, the water evaporation removes heat from the heat exchanger walls, which in turn take it from the fluid to be cooled. Experience shows that, in the case of using demineralised water (e.g. from a reverse osmosis system), there are no time duration limits, whereas with softened water it is prudent to limit the annual spraying time.

In both cases, only a fraction of the incoming water flow participates in the process, while the remaining part may be dispersed, or collected in a tank and fed back into the process. In the version proposed here, only the sprayed and unevaporated water (therefore softened or demineralised water) is retrieved and reused in the adiabatic panels, downstream of which the water is dispersed. The innovative solution proposed by LU-VE (patent filed on 07/10/2016) shown in this work involves the use in sequence of water for both the processes described above: treated water is sprayed on the heat exchange coil and unevaporated water is again introduced into the adiabatic panel. This combination of the two practices in sequence (the air passing first through the adiabatic panel and then through the exchanger coil; the water is first sprayed onto the heat exchanger and then injected into the adiabatic panel) has positive effects on both the thermal power exchanged and on water consumption.

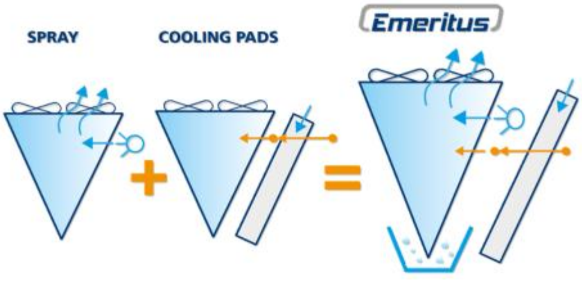

Figure 1. Conceptual diagram of EMERITUS technology: use of water in adiabatic panels and spray in series

3. A COMPARISON BETWEEN NOMINAL PERFORMANCES OF DIFFERENT SET-UPS OF A DRY COOLER AT OPTIMISED FAN SPEEDS

3.1. Comparison at ΔT1 positive (7 K)

Let us consider a large-sized dry cooler, available in three different set-ups:

1. A dry model is a "V-shape" unit with 22 fans of diameter 910 mm; with four-row coils, louvered fins, pitch = 2.1 mm, length 12,800 mm, height 2550 mm.
2. A model similar to the above but equipped with a spray system for wetting the exchanger, with optimised water flow (approximately 3.8 m^3/h, or 175 kg/h per module), and a four-row coil with wavy fins of magnesium aluminium and protected with a special paint, pitch = 2.0 mm (actual spray technology).
3. A model similar to the previous ones, but with both the spray system and the adiabatic panel; the nominal water flow rate sprayed is, as in the previous case, 3.8 m^3/h, while that injected into the adiabatic panel is equal to the fraction not recovered.

For all cases, we consider the following operating conditions:

- Ambient air: dry bulb temperature = 33°C, relative humidity = 42.1% (typical summer conditions in Milan, Italy).
- Fluid to be cooled: water, temperature 40-35°C.

The choice of the operating point for this first comparison (ΔT_1 = 7 K) is such that it allows a comparison between the three versions, and then highlights the advantages permitted by the use of water in the modes described above; subsequently we will illustrate the performance for conditions obtainable only by "boosted" versions with the aid of water ($\Delta T_1 < 0$ K). All models are equipped with fans driven by electrical motors, with a maximum rotational speed of 1000 rpm. The performance dependence of the apparatuses with the rotation speed is different for the various models, as shown in the following figure. It can be noted how the dry version has a steady trend of power as a function of the rotation speed, for which it get maximum power at the maximum fan rpm (1000 rev/min), while in the sprayed versions it is advantageous to limit the speed to lower values (approximately 750 rpm for the sprayed model and 900 rpm for the new model also equipped with an adiabatic panel). The physical explanation of these results lies in a better efficiency of the evaporated water intake upon increasing the residence time of the water droplets in contact with the exchange surfaces.

Figure 3 summarises the terms of comparison between the three versions, calculated for the optimum rotational speeds shown in figure 2.

The first group of bars shows the power exchanged in proportion to that in the dry case: it can be seen how the use of water greatly increases the performance. As expected, the best performance is obtained for the solution that combines spray and adiabatic panel, so approximately triple the power is obtained compared to the dry method.

The second group shows the specific electrical power consumed per kW of heat exchanged (i.e. kW_{el}/kW_{th}), always in relation to the machine running dry: it can be noted that the benefits in terms of energy savings, are even higher than the increase of power thanks to the lower number of rotations of the fans.

The third group – which is the power reciprocal per machine shown in the first group of bars – indicates the reduction, at equal thermal power, of a number of important variables, such as:

- Space occupied (footprint);
- Number of electric fans (or modules);
- Weight of the materials (copper and aluminium) of the exchange coil and of the structures (steel) used for the construction of the unit;
- Weight and volume of the equipment to be transported from the manufacturing site to the installation;
- Amount of refrigerant contained in the fluid.

The fourth group indicates the consumption of water specific to the thermal power exchanged: compared to the actual spray solution. In particular, the innovative solution (absolute water consumption being equal) increases the thermal power and therefore decreases the specific water consumption.

The sound power reduction with compared to the dry case, at a set fixed thermal power to be exchanged, is also observed. In all cases there is a significant reduction of the sound level, due to both the smaller number of machines (and therefore of fans) needed and the lower fan rotation speed.

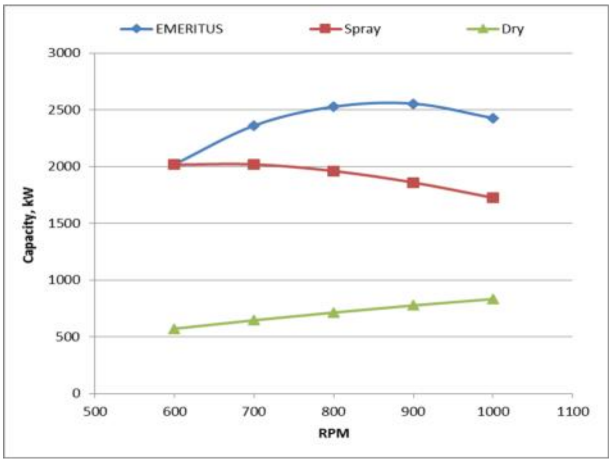

Figure 2. Variation of the thermal power as a function of the fan rpm; comparison of “Dry” heat exchangers, actual “Spray” solution and the new “EMERITUS” technology

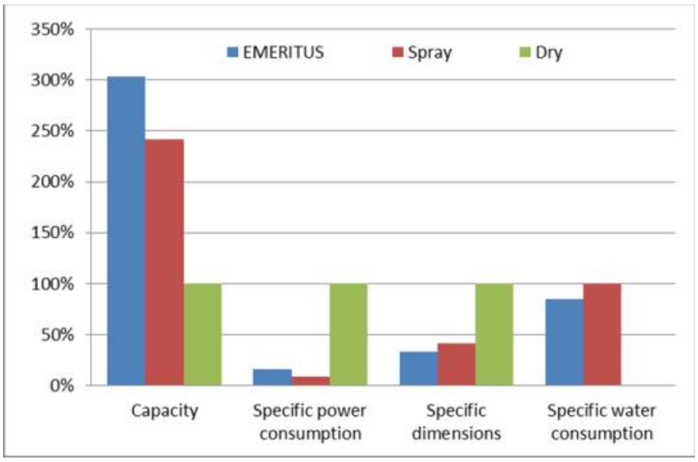

Figure 3. Comparisons between the three versions: the percentages are calculated taking as reference the dry solution, except for the specific consumption of water, which refers to the current "Spray" model

3.2. Comparison upon variation of the ΔT_1

While the comparisons shown in the preceding figures refer to a particular operating specification, in the following figures, maintaining the same ambient conditions of the immediately previous case, the comparison is extended to different operating conditions, in particular by varying the water temperature at the entrance to the exchanger in the range of 33-43°C. Each of the points on the charts below show, as an operating point, the fan speed that maximises the thermal power exchanged, after evaluating performance with a 100 rpm discretization step. If the power increase is less than 2% upon increasing the number of rotations by 100 rpm, the operating point at a lower rpm is preferred.

The superiority of the solutions that use water is evident throughout the range: for example, the solution that combines adiabatic panel and spray is able, at ΔT_1 = 0 K, to provide a thermal power equal to that of the dry apparatus at ΔT_1 = 10 K. Such superiority is also confirmed by the results in figure 5, which shows the specific power consumption upon varying the ΔT_1. While dry case see a significant increase in the electric consumption upon the reduction of the ΔT_1, this does not happen for the sprayed machine. For these, in fact, at low ΔT_1 it is preferable to reduce the speed of the fans and benefit from the increased evaporation efficiency that occurs upon reduction of the air speed.

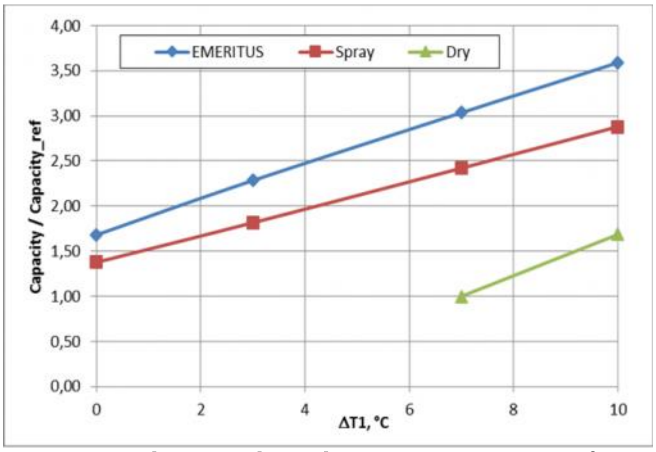

Figure 4. Change in thermal power upon variation of ΔT_1: the powers are non-dimensionalised compared to the reference case (ΔT_1 =7 K, dry solution)

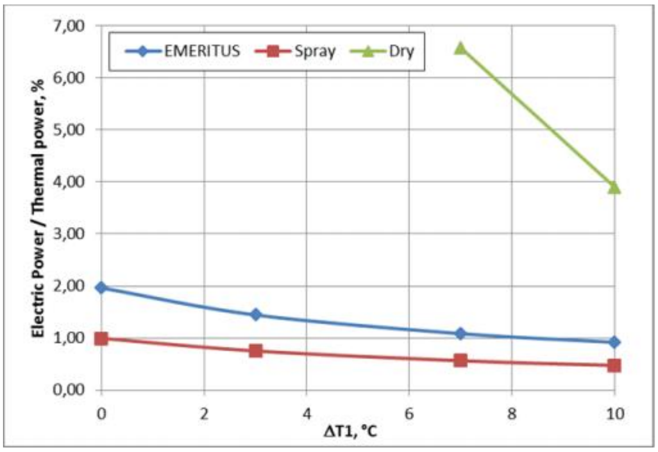

Figure 5. Specific fans consumption variation as a function of the ΔT_1

Another significant behaviour is about the specific water consumption. The machine equipped with adiabatic panels has specific consumption lower than those of the solution sprayed (-15 %). The recovery of the water sprayed and not evaporated to power the adiabatic panel allows, thanks to the increase of thermal power that follows, a decrease of the specific water consumption.

4. COMPARISONS AT EQUAL THERMAL AND SOUND POWER

In the previous graphs we put forth a hypothesis of managing units by actuating the fans at a rotation speed optimised for each configuration, a hypothesis that is translated, into a sound power that is appreciably different among the various solutions. If the comparison is conducted with the overall sound power being equal (in the specific case, 85 dB(A) per machine), for each solution the fan speed must be set to correspond to the target sound power, again at equal operating conditions and equal thermal power.

The following figures show the same magnitudes as those shown previously for ΔT_1=7 K (Figure 6) and 0°C (Figure 7). In the first case, as in the previous case, the dry mode (100% of the performance) was hypothesised. In the second case, where the dry apparatus cannot be hypothesized, the highest performing apparatus which combines adiabatic panel and spray was hypothesised.

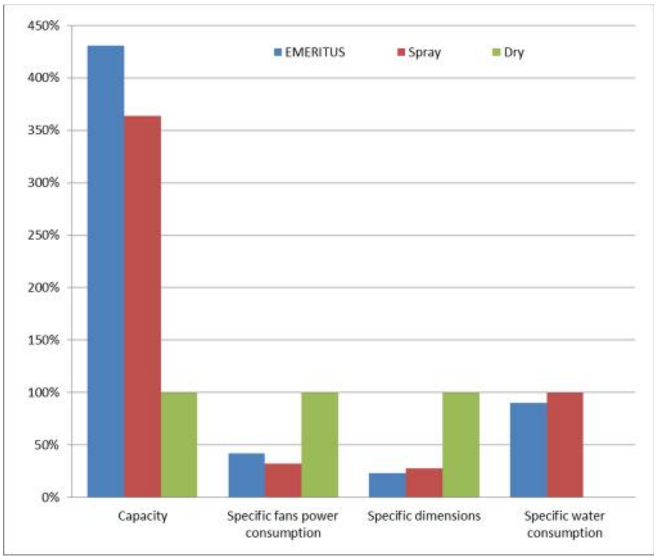

Figure 6. Comparison of different solutions (ΔT_1 =7 K), sound power equal

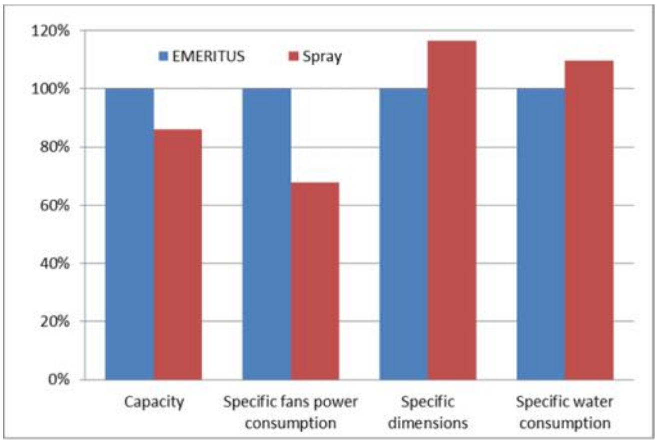

Figure 7. Comparison of EMERITUS and actual Spray solutions (ΔT_1 =0 K), sound power equal

The figure shows once again the notable benefits permitted by the use of water: in particular, the highest performing solution (adiabatic panel + spray) allows a reduction, noise and thermal power being equal, more than four times the specific dimensions compared to the dry apparatus. The figure also shows how the combination of the adiabatic panel and the spray allows the specific dimensions of the apparatus to be reduced (with all the resulting advantages) to values from about 20%.

5. AN EXAMPLE APPLICATION: AN AIR CONDITIONING SYSTEM

Among the many types of dry cooler applications, let us consider the following case, highlighting the advantages of the solutions that increase performance by using water.

The comparison between the different solutions for heat transfer to the environment was conducted for an air conditioning system in Milan, Italy, operating only in the summer, between three different solutions:

1) EMERITUS (for softened water)
2) Spray (line pre-existing to the new EMERITUS line)
3) Dry

The comparison is conducted assuming the same footprint for all solutions and the same sound power (basically, the same apparatus is always used, the same heat exchange coils, same fans, same control system), only varying the type of fins (louvered fins for the unsprayed solutions, wavy fins with protective paint for the others) and the presence or absence of spray systems and/or adiabatic panels.

5.1. Assumptions common to the various alternatives

We make the following assumptions, common to all the solutions, for sizing under nominal conditions:

- T_{amb} = 35°C, Relative Humidity = 41%
- T_{eva} = 3°C (for cooling icy water 5-12°C)
- DT superheating to evaporator = 5°C
- DT sub-cooling to condenser = 2°C
- Cooling capacity under nominal conditions: 1900kW$_f$;

and the following operating modes:

- T_{cond} = variable, depending on the operating conditions and the potential of the dry cooler, down to a minimum value of 20°C;
- Cooling capacity required by the user: linear variation as a function of the ambient temperature, from 100% to 33°C to 40% at 23°C;
- Turning the chiller off at ambient temperature under 23°C;
- Speed control of the electric fans and water flow rate as managed by the software.

For the highest performing solution (EMERITUS) the following temperatures are assumed in nominal conditions:

- T_{water} = 30-35°C (at lower ambient temperatures, the water temperatures decrease)

The flow rate of circulating water in the machine is constant, for which the variations in power exchanged are reflected on the variations of the ΔT of the water in the dry cooler. For other configurations (Spray and Dry) the water temperatures in the nominal conditions are higher, due to the lower performance that characterises these solutions. The complex of the compressors is dimensioned according to the nominal condensing temperature, which increases with the decrease of the dry cooler performance.

5.2. Assumptions on the refrigerator compressor

The consumption of the refrigeration cycle compressor is a function of the evaporator load and the condensing temperature. A system solution with a high number of compressors is assumed, which therefore operate at a load always near the nominal value. The ratio for the compressor at nominal load is obtained by a linear interpolation between the values in the table.

Table 1. Compressor data

Condensing temperature, °C	60	50	40	30
COP	2.30	3.24	4.43	5.99

5.3. Sizing at nominal conditions

From the previous assumptions these are machines with the following dimensions:

Table 2. Models data

	EMERITUS	*Spray*	*Dry*
ΔT_1, K	7	10.4	23.8
Condensing temperature, °C	45	48.4	61.8
RPM	715	620	720
Sound power, dB(A)	85	84.2	85
Thermal power, kW	2408	2460	2752
Electric fan power, kW	19.5	12.54	20.14
COP chiller	3.76	3.40	2.23
Total nominal electrical power of the compressors, kW	506	560	852

The benefits of water-enhanced models compared to the dry model are manifested in terms of higher COP and consequently to lower overall power of the compressors and they are maximum for the EMERITUS model.

5.4. Annual simulation results

If a simulation extended to the entire summer is run, the results shown in the table below in reference to the unit cooling capacity at nominal conditions are obtained:

Table 3. Simulations results

	EMERITUS	*Spray*	*Dry*
Total annual operating costs, €/kW/year	49.4	51.2	59.4
Energy saving compared to dry machine	21.2%	16.5%	0
Number of hours per year for wet operating	2402	838	-
Change in operating costs compared to dry machine	-16.9%	-13.8%	0
Annual operating costs of chiller electricity, €/kW/year	43.4	46.8	56.0
Annual operating costs of fan electricity, €/kW/year	3.3	2.8	3.4
Annual operating costs of water, €/kW/year	2.6	1.6	0

From the tables it is apparent that:

- EMERITUS allows energy savings of more than 20% compared to the dry solution.
- The saving rate is a little lower in terms of management costs, since operating costs linked to the use of water are small compared to the costs for electricity consumption, predominately for the compressor.
- In absolute terms, the savings for the higher performing solution is approximately 19,000 €/year (an underestimate because it does not take into account the savings made by the reduced power consumption).
- In terms of investment, at the higher costs resulting from the adoption of a model equipped with adiabatic panels, the spray system and the water quality monitoring (totalling, for the considered model, about €15,000) and the need to install a softener, (estimated at €9,000) we must subtract the savings achieved from the reduction in size (over 40% smaller) of the compressor and its condenser. This would reduce the additional investment in the solution to values that could be amortised in a short time, in fact in just one year of operation.

5.5. Simulation details

The graphs below show the most significant curves. The values refer to the cooling capacity of the project, which is 1900 kW in all cases considered.

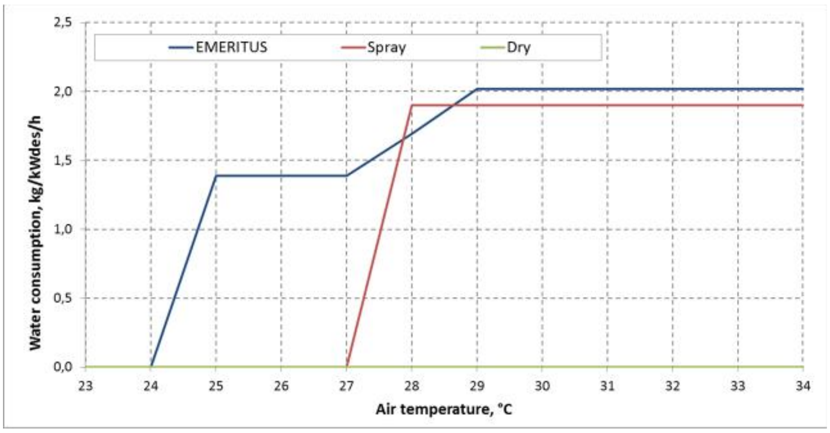

Figure 8. The figure illustrates the logic of using water for the various alternatives: the sprayed solutions use water on the coil only for ambient temperatures above 28°C in order to respect the limit of hours with a wet coil. The solutions with an adiabatic panel extend the use of water up to temperatures of 24°C.

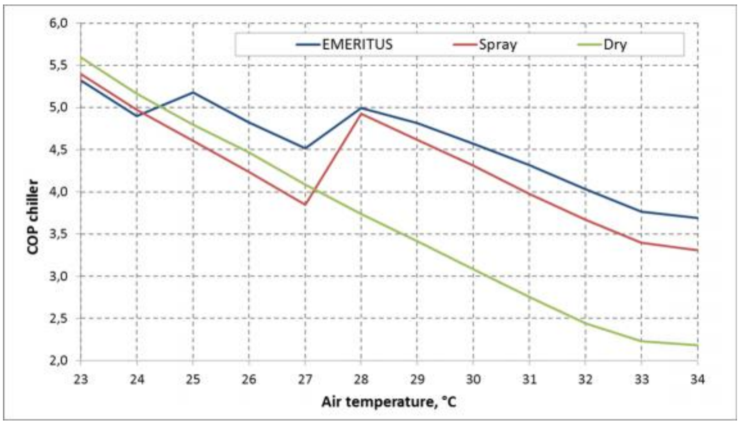

Figure 9. The performance of the chiller COP demonstrates how the EMERITUS solution provides superior values in all operating conditions, thanks to the reduction of the condensing temperature.

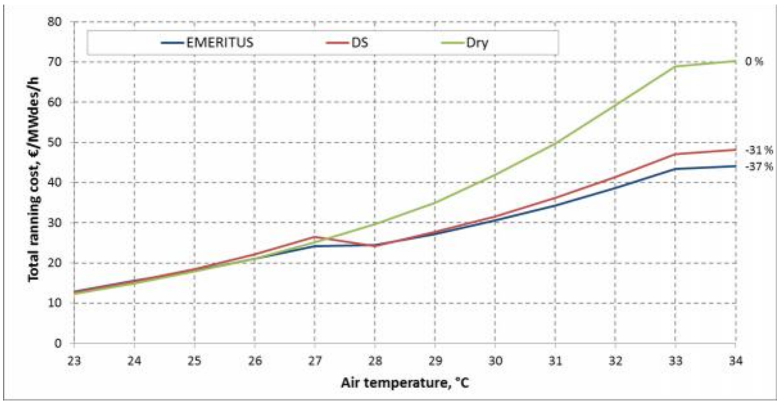

Figure 10 The final result, in terms of total operating costs, is represented in this diagram: For all ambient temperatures above 27°C, the systems that spray the coil have much lower operating costs and EMERITUS model remains the best.

CONCLUSIONS

The analysis shows the potentiality of water "chill boosted" systems in air fin-and-tube heat exchangers. While the use of water spray on the coil or the use of humidification with adiabatic panel are well known applications, the synergetic use of both systems (named EMERITUS) is a new technology. The results highlight the improvement in terms of capacity and annual energy savings of this solution. In comparison to the "dry" configuration, the capacity of EMERITUS is about three time greater, with footprint equal; likewise with EMERITUS it is possible to obtain the same capacity of the dry system at much lower ΔT_1, obtaining in this way a significant reduction of the condensing temperature of the refrigeration machine. A case study has been analysed. The final result is a reduction of overall power consumption of 21% compared to a dry solution. EMERITUS heat exchanger can enable the CO2 system to work in subcritical regime during the year longer than with conventional gas coolers, helping the CO2 systems to be more efficient.

NOMENCLATURE

ΔT_1 difference between internal fluid inlet temperature and ambient air inlet temperature

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