NEW CO_2 GAS COOLER FOR DRY AND WET OPERATION

S. Filippini [(*)], G. Mariani [(**)], L. Perrotta [(***)], U. Merlo [(****)]

LU-VE Group

[(*)] stefano.filippini@luvegroup.com; [(**)] giovanni.mariani@luvegroup.com; [(***)] livio.perrotta@luvegroup.com; [(****)] umberto.merlo@luvegroup.com

1. INTRODUCTION

Conceptually, there are two ways of using water to enhance the heat exchange of CO_2 gas 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, the air is made to 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. A cross-flow is created in the panel which determines an intense contact between air and water, facilitating the evaporation of the latter at 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 onto the heat exchanger surfaces, which are suitably treated for 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 shown in this work involves the use in sequence of water for <u>both</u> 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.

2. THE CASE STUDY

An industrial refrigeration plant working in transcritical/subcritical CO_2 operation is considered. Design data: refrigeration capacity required: 250 kW, evaporation temperature -9 °C, recovered thermal capacity (winter season): 200 kW max.

A simple cycle with a heat recuperator and flash gas valve is considered. The low and intermediate pressures of the cycle are fixed; the high pressure is variable with the outdoor temperature and according to the heating and/or refrigeration load requested. When operating in transcritical regime, it is established with iterative calculations the pressure that maximize the COP. A rack of equal compressors working with fixed frequency is considered. The isentropic efficiency is a function of the pressure ratio; the relation is extrapolated from the data of the compressor manufacturer. During the winter season, when the outdoor temperature is below 16 °C, the system also has to supply energy for heating. The minimum CO_2 temperature acceptable in the recuperator outlet is 40 °C. In the summer season, the recuperator is switched off (by-passed). The CO_2 outlet temperature is reduced to the lowest achievable value to maximise cycle performance. In this way, the liquid quality is also reduced and the refrigerant flow to the evaporator is maximized. In the COP definition, the evaporator capacity (constant) as well as the capacity requested from the heating load that it is variable during the season are considered as useful effects.

An annual balance simulation to calculate cycle performance and operating costs is conducted. Climatic data of three European cities are used representative of a cold zone (Stockholm), average zone (Paris) and warm zone (Trapani, South Italy).

Table 1. Location data assumption

Location	*Ta design, °C*	*HR, %*	*Cost of electricity, €/kWh*	*Cost of water, €/m³*	*Working pressure, bar*	*n° of fans*
Stockholm	26	39	0.07	0.83	86	8
Paris	32	32	0.10	1.54	89	10
Trapani	36	28	0.15	0.95	91	12

Four technological solutions are compared:

1. **DRY** A dry model is a "V-shape" unit with number of fans variable from 8 to 12, depending on the design location (standard technology).
2. **SPRAY** A model similar to the above but equipped with a spray system for wetting the exchanger, with optimised water flow (current spray technology).
3. **AP** A model similar to DRY but equipped with adiabatic panels kept wet with a water flow rate.
4. **EMERITUS** A model similar to the previous ones, but with both the spray system and the adiabatic panel, the water injected into the adiabatic panel is equal to the fraction not recovered.

With wet solutions the COP improves by 60% (fig. 2); this allows, refrigeration capacity being equal, a reduction of the size of the compressor and compensates for the extra cost of the gas cooler. The yearly running costs include the compressors power consumption and all the costs of the gas cooler: power consumption of the fans, water used for the wet systems, operation and maintenance costs. Electricity and water costs are assumed as in table 1.

3. RESULTS

For each location, the annual balance results are presented both in graphical and table form. The average climatic zone is presented first as reference simulation.

Fig. 1 shows the temperature T_3 in function of the ambient temperature. When the heat exchanger operates in "dry" mode, up to 17 °C, the outlet temperature is the same for all technologies, 3 K above the ambient temperature. The minimum value of T_3 is equal to the saturation temperature corresponding to the pressure in the receiver, fixed during the simulation. The DRY model keeps this approach for the entire year. The SPRAY model keeps this approach up to 24 °C, after that an approach of 4 K (3 K in EMERITUS configuration) is maintained, not compared to the air dry bulb temperature, but compared to the wet bulb; in this way it is possible to operate with lower values of T_3 and increase the cycle efficiency. The AP and EMERITUS models are the same as the above technology, however the adiabatic panel activation permits the reduction of T_3 starting from 17 °C.

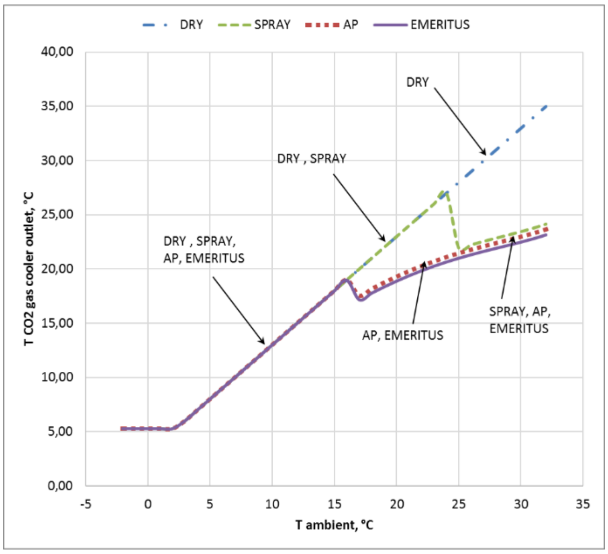

Figure 1. CO_2 outlet temp. (T_3) vs. ambient temp.

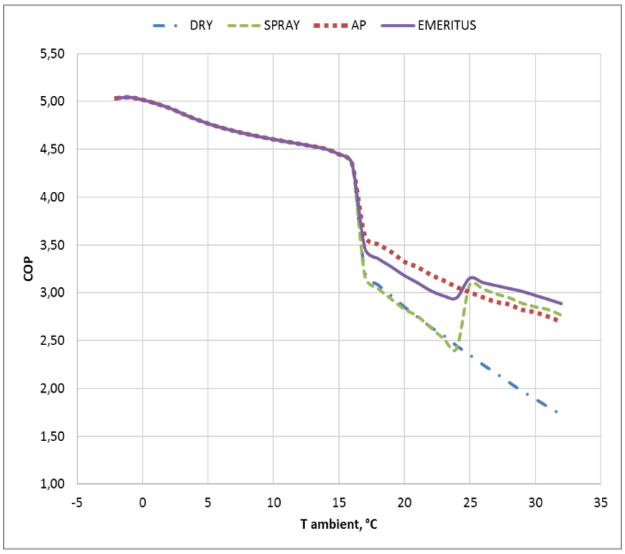

Figure 2. COP

Figure 2 shows the COP of the cycle. During the winter season (Ta<17 °C), the performance declines due to the rising ambient temperature. The drop in performance at 17 °C is due to the absence of recovery heat as useful effect. The units with wet resource allow lower operating pressure and therefore better performance, EMERITUS configuration in this example, always operates in subcritical conditions. It is interesting to point out that the maximum electric power necessary with the wet solutions is about half the power required by the wet solutions. This is an advantage in terms of installation and power plant costs.

Table 2 summarizes the annual relative costs; the reference is the total cost of the DRY solution. The energy cost of the compressors; it is the greatest component of the total cost, more than 90%. The fans energy consumption is limited, also for all the solutions. The water cost in the solution with the greatest exploitation of wet solution is around 3.8% of the total. The operating and maintenance costs are negligible. Compared to the DRY solution, the EMERITUS and AP have savings on the yearly running costs of 5% and 3%; in this case the SPRAY configuration does not increase the annual performance.

Table 2. Annual cost, Paris

	compressor	*fans*	*water*	*O&M (*)*	*total*	*saving, €/year*
DRY	98.6%	1.39%	0.00%	0.05%	100.0%	-
SPRAY	97.4%	1.37%	0.97%	0.34%	100.1%	-98
AP	91.6%	1.43%	3.57%	0.27%	96.9%	3162
EMERITUS	89.3%	1.39%	3.88%	0.49%	95.1%	5033

The same analysis was done for the "warm" and "cold" locations. The general considerations are the same as the average zone. In the cold zone all the solutions are very similar. The wet systems do not bring significant advantages and probably the DRY configuration is advisable.

Table 3. Annual cost, Stockholm

	compressor	*fans*	*water*	*O&M (*)*	*total*
DRY	99.0%	0.96%	0.00%	0.07%	100.0%
SPRAY	98.2%	0.96%	0.66%	0.50%	100.3%
AP	96.7%	0.98%	1.18%	0.40%	99.2%
EMERITUS	96.4%	0.96%	1.39%	0.71%	99.4%

In the warm zone, the wet systems have the greatest benefits. The EMERITUS solution saves up to 9% of the yearly costs. The cost of water is greatly exceeded by the saving of the compressor. The benefit of the wet systems is a yearly saving of about 50 €/kW of refrigeration capacity.

Table 4. Annual cost, Trapani

	compressor	*fans*	*water*	*O&M (*)*	*total*	*saving, €/year*
DRY	97.5%	2.52%	0.00%	0.03%	100.0%	-
SPRAY	95.4%	2.48%	0.40%	0.21%	98.5%	2467
AP	88.2%	2.61%	2.66%	0.17%	93.6%	10581
EMERITUS	85.6%	2.51%	2.78%	0.30%	91.2%	14685

(*): O&M: operation and maintenance

CONCLUSIONS

The analysis shows the potential of water "chill boosted" systems in air fin-and-tube CO_2 gas coolers. While the use of water spray on the coil or the use of humidification with adiabatic panels are well known applications, the synergetic use of both systems (named EMERITUS) is new technology. The results show that the use of more advanced technologies is a worthwhile solution to reduce the total running cost of the plant. The use of gas coolers with wet systems makes the CO_2 cycles efficient also in ambient with average and warm annual temperatures. The case study has analysed three European climatic areas: cold, warm and moderate; savings of 5% in Paris and of 9% in Trapani are shown.

The implementation of this solution, moreover, allows the significant reduction of the size of the compressor and maximum electric power installed.