Development of an energy analysis tool for data center free cooling technologies modelizzation and comparison in different climate conditions

Mauro Mantovan [a], *Carlo* Bissaro [a], *Fabio* Poletto [a], *Michele* De Carli [b], *Angelo* Zarrella [b]

[a] Hiref S.p.A., Viale Spagna, 31/33, 35020 Tribano PD, Italy. E-mail: mauro.mantovan@hiref.it

[b] Department of Industrial Engineering, University of Padova, Italy. E-mail: angelo.zarrella@unipd.it

Abstract. Data Centers are currently undergoing a great period of change. Developments in business and personal data transfer together with new technologies such as virtualisation and cloud computing are transforming Data centers into dynamic environments with greater power demands unexpectedly. The cooling requirements of the Data Center infrastructure form a large part of the overall power requirements and it is therefore critical to ensure correct optimisation to achieve the desired energy efficiency levels. In Planning data centers for the future, it is imperative that the design matches the infrastructure with greater scalability and integration enabling Data Centrers to evolve to cope with less power demands and lower running costs. This work brings together the main layouts of high efficiency IT cooling systems, highlighting their operation and efficiency in the case of an IT room with a thermal load of 1 MW and three different climatic scenarios. The efficiency of the systems is evaluated through a calculation routine in which all the components of each cooling system are modelled and the regulation logics of the software of these units are implemented. The climatic scenarios for 3 different locations (Palermo, Milan, and Frankfurt) are represented according to the hourly distribution of temperatures and humidity in order to evaluate the seasonal performance of each cooling system. The results give an overview of the consumption referred to each IT cooling technology in relation to the application climate. The calculation routine developed allows to choose the most suitable technology for the climate and the installation considered, also leaving the possibility of a subsequent optimization of the unit design based on the most appropriate technology.

Keywords. Data center, cooling technologies comparison, cooling efficiency, energy analysis tool, energy simulation.
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1. Introduction

Worldwide web, online services, cloud computing are increasing and there is the need for arranging reliable facilities to process, store and transmit these data. This increases the energy consumption of Data Centers: half of the energy is normally consumed by servers while the other half is for electrical power supply and for the cooling system. IT devices also need a close controlled temperature and humidity environment in Data Centers in order to work properly and to provide a reliable and efficient service. Suppliers of servers advise Data Center owners to keep computing rooms within recommended hygrothermal limits throughout their whole working life. As can be seen in Fig. 1, these limits have been constantly widened in recent years, allowing to maximize the annual hours of free cooling, and reducing the consumption of electricity dedicated to the cooling, while ensuring the proper functioning and duration of the servers. The objective of this study is to develop a data center cooling system energy performance evaluation tool that can provide a comparison between different cooling layouts and technologies, driving to an early design choice that should be the best for a particular climate zone considering also installation available footprint and costs of energy and eventually of water when adiabatic cooling is considered.

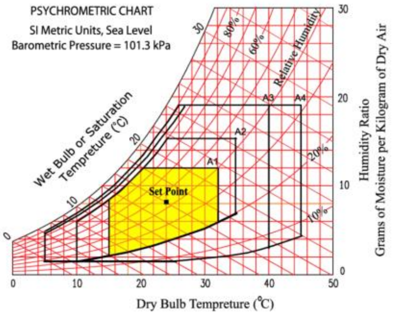

Fig. 1 – Computing rooms hygrothermal limits from class A1 to A4 according to ASHRAE specifications

2. Energy performance in data centers

2.1 Power Usage Effectiveness

Data Center efficiency is measured by DCiE (Data Center infrastructure Efficiency) and PUE (Power

Usage Effectiveness), as defined by The Green Grid, a global consortium of IT professionals aiming to increasing the energy efficiency of Data Centers. The biggest challenge for IT organizations to manage Data Centers is the reduction of energy for cooling and for power supply: this is the only way to let Data Centers grow. Efficient Data Centers let IT providers better manage the increasing demands on the network, computing, and storage requirements with lower energy costs, thus with lower running costs (operating expense). A higher efficiency in the end leads to more competitiveness and readiness in answering to the market demands. As can be seen in Eq. (1) Power Usage Effectiveness (PUE) is a measure of how efficiently a Data Center uses the input energy:

$$PUE = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} \qquad (1)$$

In particular, it shows how much energy is used for the IT System compared to that used for Cooling and Power Supply. The DCiE is the reciprocal of PUE:

$$DCiE = \frac{1}{PUE} \qquad (2)$$

The ideal PUE of a data center should be 1.0, which means that all the energy consumed by the facility is used to power ICT (Information and Comunication Techonology) equipment. In real applications, as shown in Fig. 2, the total power consumption, the electricity used (by ICT equipment, cooling, lighting, etc.) need to be measured to calculate the effectiveness.

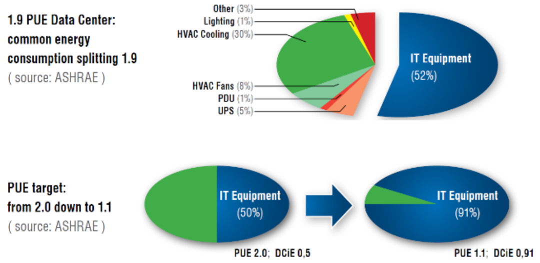

Fig. 2 – Data center energy consumption splitting example.

2.2 Water usage effectiveness

Another index to consider in the case of adiabatic cooling systems is the WUE (Water Usage Effectiveness), that has received increasing interest with increasing usage of adiabatic cooling systems, where a large amount of water evaporates to get the desired cooling effect. WUE is a measure of the amount of water used in the Data Center per unit of IT equipment energy:

$$WUE = \frac{Annual\ site\ water\ usage}{IT\ Equipment\ Energy} \qquad (3)$$

The ideal WUE of a data center should be 0.0, but if the goal is to minimize water use at a global level, then a low WUE can have an adverse impact that needs to be considered. In fact electricity generation needs a significant amount of water that depends on the generation method used, but the majority of electricity generation today is still very water intensive. So reducing water use at the site may increase electricity use, which will likely result in increased water use at the power-generation source. Depending on many factors like location, business strategy, and financial considerations, increasing water use and decreasing energy use may be the desired outcome, or increasing energy use and decreasing water use (as in a desert location) may be the desired outcome. Regardless of the outcome, PUE and WUE are helpful tools to guide business decisions.

3. Free Cooling

As temperature limits inside computer rooms have increased in the last years, many more places around the world can achieve the needed cooling capacity for the servers as Free-Cooling capacity, using (directly or indirectly) fresh air from outside. The cooling system can work in Free-Cooling operation when the outdoor temperature is below that o fthe computer room. The required cooling can be achieved by letting the outdoor air directly into the racks (direct Free-Cooling) or exchanging heat between outside and indoor air (indirect Free-Cooling) or between the outside air and the chilled water circuit (indirect water Free-Cooling). A larger operation field in terms of indoor hygrothermal conditions lead to a larger number of hours for Free-Cooling, a larger number of countries where Free-Cooling is achievable and higher chilled water temperatures for CRAC units, thus more indirect Free-Cooling hours.

3.1 Air quality and direct free cooling

When in direct Free-Cooling operation a Data Center uses outside fresh air which is directly blown into the server room, so outside air quality strongly affects the IT devices performances and behaviour.

ASHRAE recommends, besides hygrothermal values, particulate contamination limits and gaseous contamination limits. The reference norm for particulate contamination is ISO 14644-1: the quality of the air is defined by nine different classes (1 to 9 ISO class) as the number of particles in each cubic meter of air. Each particle is considered with its size. ASHRAE claims that air filters used must achieve ISO 8 class cleanliness. According to ANSI/ASHRAE Standard 127-2007 the indoor air must have filtration class MERV8, while the air entering the Data Center must have filtration class MERV11/MERV13 depending on the outdoor air quality and specific computer room conditions. When dedicated measurements show that outdoor air can not be directly used for cooling purposes (ISO class greater than class 8) then specific filters with a high efficiency must be used.

The reference standard for gaseous contamination is ANSI/ISA S71.04-1985: different corrosivity levels (from G1 to Gx) define each gas reactivity level according to concentration. ASHRAE's book "Particulate and Gaseous Contamination in Datacom Environments" of 2009 recommends level G1 for Data Centers. In the end direct Free-Cooling is the best solution thermodynamically, but the following aspects must be considered:

- high efficiency filtration causes high air pressure drops, therefore the fans' energy consumption may reduce the global efficiency of the system.
- the replacement of old filters may be expensive
- a strict control of gaseous contamination with chemical filters is necessary
- the upper humidity limit must be controlled (dehumidification may be needed)
- the lower humidity limit must be controlled (humidification may be needed)

4. Evaluated Cooling technologies

In the current work all the considered cooling units are equipped with free cooling modules comparing performances of direct free cooling CRAC, Indirect Free Cooling CRAC, Indirect Evaporative Cooler, Free Coolig Chiller and Adiabatic Free Coolig Chiller, with typical return air condition for a compartmentalized room of 36°C and RH 27%. While CRAC units and Indirect Evaporative Cooler are working directly on data centre indoor air, chillers are producing chilled water that is supplied to dedicated free fans CRAC units. For each cooling technology a data hall with a thermal load of 1 MW and (n+1) redundancy have been considered.

4.1 Direct free cooling CRAC – Case 1

This layout consists in a typical close control unit used for perimetral cooling in data center rooms where the free cooling is obtained by means of the regulation of a damper which allows to select if recirculate return air from hot aisle, let external ambient air enter the data center or have a mix of these two airflows to match the target supply air temperature. When the free cooling is not available or insufficient, mechanical cooling guarantee the maintenance of the set point. Units are equipped with a remote condenser, and condensation control is achieved by partialization of the condenser ventilation. Standard refrigerant R410A is considered, 2 scroll compressors are installed in 2 separated circuits (one On-Off compressor and one inverter driven compressor), (9+1) redundancy has been adopted for seasonal energy analysis.

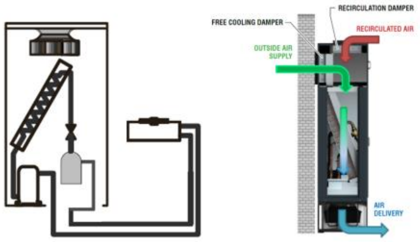

Fig. 3 – Direct free cooling CRAC principle scheme and direct free cooling damper.

4.2 Indirect Evaporative Cooler – Case 2

These units are based on the use of a cross flow heat exchanger that keeps internal and external airflows separated. The evaporative system, by cooling down external air all along his path through the recovery system, increases the heat exchange capacity of the recovery system, thus allowing indirect free cooling to be extended to a wider range of external thermo-hygrometric conditions reducing the field of action of mechanical cooling. Extra costs due to the increase in water consumption and water treatment and pumping requirements are compensated by limited compressor operation. These units can be installed on the external perimeter of the data center or on the roof, taking zero indoor space. Standard refrigerant R410A is considered, 2 scroll compressors are installed in a single circuit (one On-Off compressor and one inverter driven compressor), (5+1) redundancy has been adopted for seasonal energy analysis.

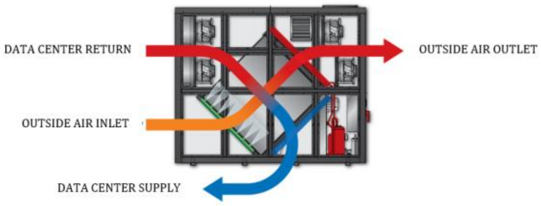

Fig. 4 – Indirect evaporative cooler principle scheme

4.3 Adiabatic Free Coolig Chiller + CW CRAC – Case 3

This case scenario is based on a traditional air cooled liquid chiller with V shaped condenser coils. In these units are also installed free cooling coils with the same V shape and a 3 way valve regulating the amount of water flow in the free cooling module. Upstream of the free cooling coils, evaporative pads are installed which allow the outside air temperature to be lowered by adiabatic saturation, increasing the number of free cooling hours per year and reducing consumption. Standard refrigerant R134a is considered, 2 screw compressors are installed in 2 separated circuits (one On-Off compressor and one inverter driven compressor), (3+1) redundancy has been adopted for seasonal energy analysis. Chilled water on supply is sent to an indoor CRAC free fan unit working with (9+1) redundancy.

Fig. 5 – Evaporative free cooling chiller and free cooling module principle scheme

4.4 Free Coolig Chiller + CW CRAC - Case 4

Same scenario of Case 3 without adopting evaporative pads.

4.5 Indirect Free Cooling CRAC - Case 5

Indirect Free Cooling CRAC provide free cooling by cooling glycol water through an external dry cooler if the external air temperature allows it. The cooled water is sent to the indoor unit in a finned coil dedicated to cooling the return air from the datacentre. If free cooling is not available or sufficient, mechanical cooling guarantees the maintenance of the set point, using the water leaving the free cooling coil for condensation on a dedicated plate condenser. In the case of negligible contribution from free cooling, a 3-way valve diverts the water arriving from the dry cooler directly to the plate condenser, reducing the pressure drops of the hydraulic circuit. Condensation control is guaranteed by means of a flooding valve which allows a reduction of the exchange surface of the condenser by flooding a portion on the refrigerant side. Standard refrigerant R410A is considered, 2 scroll compressors are installed in 2 separated circuits (one On-Off compressor and one inverter driven compressor), (9+1) redundancy has been adopted for seasonal energy analysis.

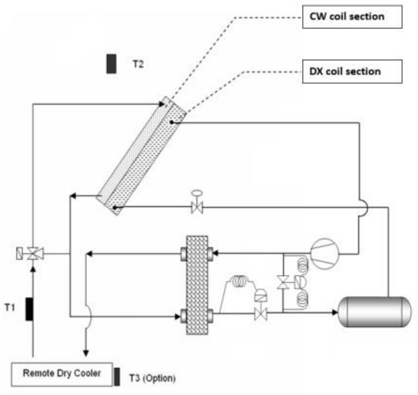

Fig. 6 – Indirect Free Cooling CRAC principle scheme

5. Cooling unit's components and numerical modelling

All the units considered are equipped with a free cooling module and a backup/integration mechanical cooling system. The components are sized in order to guarantee the necessary cooling capacity in the worst climatic conditions with a unit in failure/maintenance, while the energy analyzes are conducted on the assumption that all the units are active with load partialization. Below are the main components common to all the layouts that make up the free cooling and mechanical cooling modules, describing their numerical implementation in the seasonal energy analysis routine.

5.1 Compressors

Regardless of the type, compressors behaviour is always modelled according to the polynomials provided by the manufacturer in order to predict the cooling capacity, the electrical absorption, and the thermal power to be disposed off to the condenser according to a given number of rpm and given temperatures of evaporation and condensation. The adopted polynomials have a standardized form exposed in Eq. (4).

$$y = c1 + c2 * to + c3 * tc + c4 * to^2 + c5 * to * tc + c6 * tc^2 + c7 * to^3 + c8 * tc * to^2 + c9 * to * tc^2 + c10 * tc^3 \quad (4)$$

5.2 Finned Coils

Finned coils are used as evaporators, condensers, chilled water-cooling coil, and dry cooler's/free cooling heating coil on modelled units. Refrigerant fluid properties are evaluated by literature available equations, while air properties are evaluated through standard psychrometric relations for humid air. Fins and tubes geometries and spacing are the inputs of the model with airflow rate, air temperature and humidity, and evaporation/condensation temperatures. The finned coil model provides an iterative method that converge matching refrigerant side and air side exchanged power, solving heat transfer on each side with empirical correlations developed by units constructor. The synthetic flow chart shown in Fig. 7 groups the main steps of the calculation model. The various functioning modes of the finned coil share the same calculation method with evaluation of refrigerant's properties, and formulation of the heat transfer coefficients dedicated to the specific case.

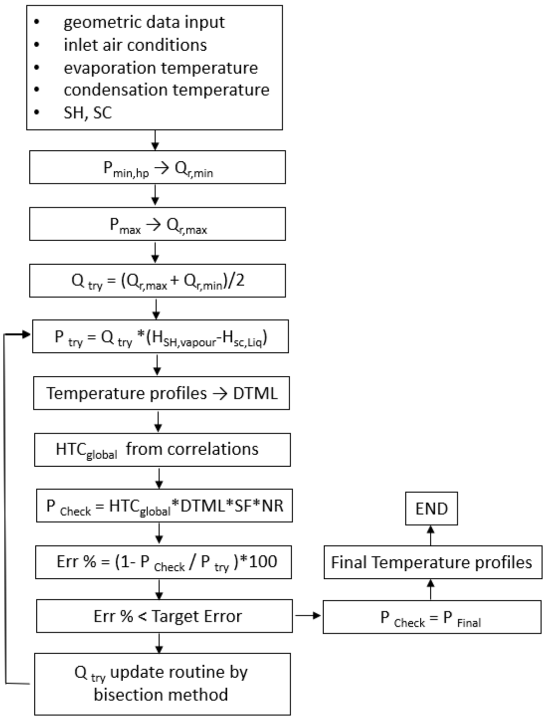

Fig. 7 – Finned coils general flow chart

5.3 Plate heat exchangers

Plate heat exchangers are used as water cooled condensers on modelled CRAC units. Compressor discharge temperature, refrigerant properties, and water/glycol mixtures properties are evaluated through the use of Refprop. Plates geometry and spacing, exchanged power, condensation temperature, water inlet temperature and water volumetric flow are the inputs of the model. Water channel is modelled with standard correlation for parallel plates flow, while refrigerant side is solved with empirical correlations. The output of the model is the margin of the exchanger over required working conditions.

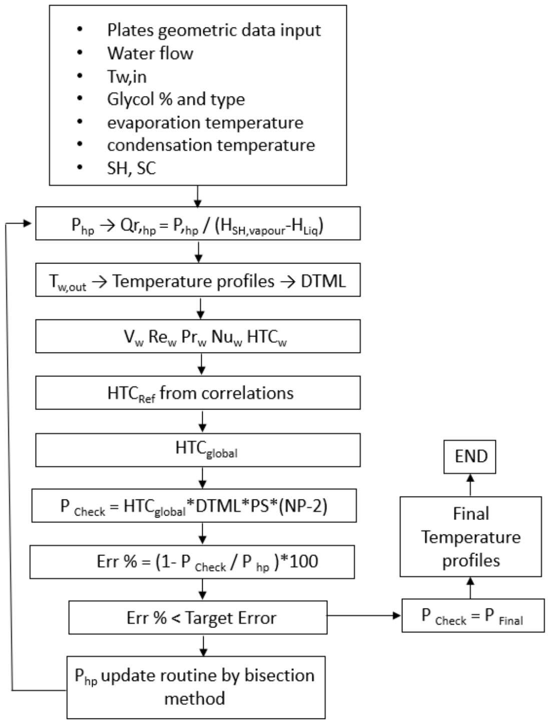

Fig. 8 – Finned coils general flow chart

5.4 Radial and axial fans

Fans are modelled using constructor 's data for head and absorbed power at full speed, scaling performances at variable rpm with affinity laws indicated in Eq. (5, 6, 7).

$$Q2 = Q1 * \left(\frac{N2}{N1}\right) \tag{5}$$

$$H2 = H1 * \left(\frac{N2}{N1}\right)^2 \tag{6}$$

$$HP2 = HP1 * \left(\frac{N2}{N1}\right)^3 \tag{7}$$

5.5 Wetted Cross flow heat exchanger

Calculations are based on a Finite Element Method, that starts from boundary conditions to solve mass and energy balance of each element of the recuperator. Calculation are based on NTU (number of transfer units) that are calibrated with the constructor polynomials for a given working condition and water evaporation on external air side is accounted through heat and mass transfer analogy with dedicated Lewis number evaluation and surface wettability factor. For heat transfer mechanism between internal and external air is schematized in Figures 9 and 10.

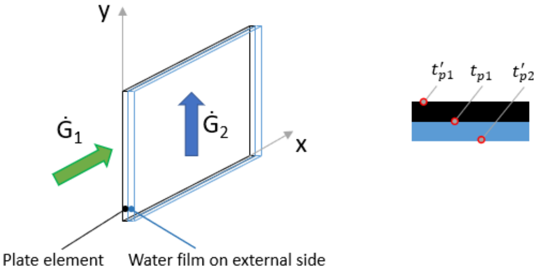

Fig. 9 – Heat exchanger plate – water film interface in crossflow heat exchanger model

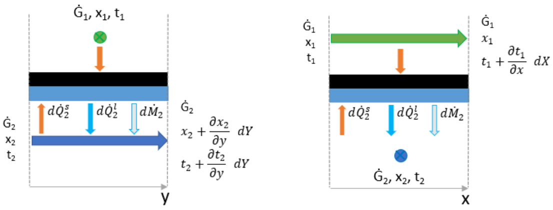

Fig. 10 – Differential control element of the crossflow heat exchanger model

Governing equations for external airflow are listed in Eq. (8, 9) while internal airflow is described by Eq. (12). Energy balance between internal and external flows is guarantee by Eq. (10, 11).

$$\frac{dt_2^{(k,l)}}{d\bar{Y}} = NTU_2'[((t_2^{(k,l-1)})' - t_2^{(k,l-1)}) + \left(\frac{\sigma_p}{Le}\right)_2 \left(\frac{c_g}{c_p}\right)_2 ((t_2^{(k,l-1)})' - t_2^{(k,l-1)}) ((x_{p2}^{(k,l-1)})' - x_2^{(k,l-1)}) \tag{8}$$

$$\frac{dx_2^{(k,l)}}{d\bar{Y}} = NTU_2' \left(\frac{1}{Le_2}\right) \sigma_{p2} ((x_{p2}^{(k,l-1)})' - x_2^{(k,l-1)}) \tag{9}$$

$$\left(\frac{W_1}{W_2}\right) NTU_1(t_{p1}^{(k,l-1)} - t_1^{(k,l-1)}) + NTU_2((t_2^{(k,l-1)})' - t_2^{(k,l-1)}) + NTU_2 \left(\frac{\sigma_p r_0}{c_p Le}\right)_2 ((x_{p2}^{(k,l-1)})' - x_2^{(k,l-1)}) = 0 \tag{10}$$

$$\left(\frac{\lambda_{plt}}{\delta_{plt}}\right)\left(t_{p1}^{(k,l-1)} - \left(t_{p2}^{(k,l-1)}\right)'\right) = \alpha_1(t_1^{(k,l-1)} - t_{p1}^{(k,l-1)}) \tag{11}$$

$$\frac{dt_1^{(k,l)}}{d\bar{X}} = NTU_1 \left(\frac{t_{p1}^{(k-1,l)} + t_{p1}^{(k,l)}}{2} - t_1^{(k-1,l)}\right) \tag{12}$$

5.6 Adiabatic pads

Adiabatic pads efficiency is modelled by interpolation of constructor data taking into consideration external air temperature and relative humidity, and air flow speed through the pads. Also additional pressure drops has been considered as a function of air speed.

6. Main energy analysis calculation routine

The code related to the modelling of each component has been inserted into a higher level calculation routine that allows to evaluate the seasonal behaviour of the various IT cooling technologies considered. A data upload section by the user allows to enter data relating to the load and the thermo-hygrometric conditions of the room. The user also enters the model and the number of cooling units to simulate, thus recalling the components relating to the selected unit from a specific database. By selecting the desired location, the data relating to temperature, relative humidity and hourly distribution for seasonal simulation are obtained from the database. As the ventilation in the room is a closed loop, the first step of the calculation is always regarding the solution of the aeraulics, to account for additional load related to user fans dissipations. After this stage, in accordance with external climatic conditions, an evaluation of the available amount of free cooling is made, givin as a result the call for a full free cooling regulation, a mechanical top up cooling request, or a full mechanical cooling request if free cooling is not available or not advantageous. While the convergence cycle for the mechanical cooling and it's regulation requires lot of iterations and involve subroutines dedicated to condensation control, compressor's envelope limits control and so on, only a simplified flow chart valid for all the cooling units is reported in Fig. (11).

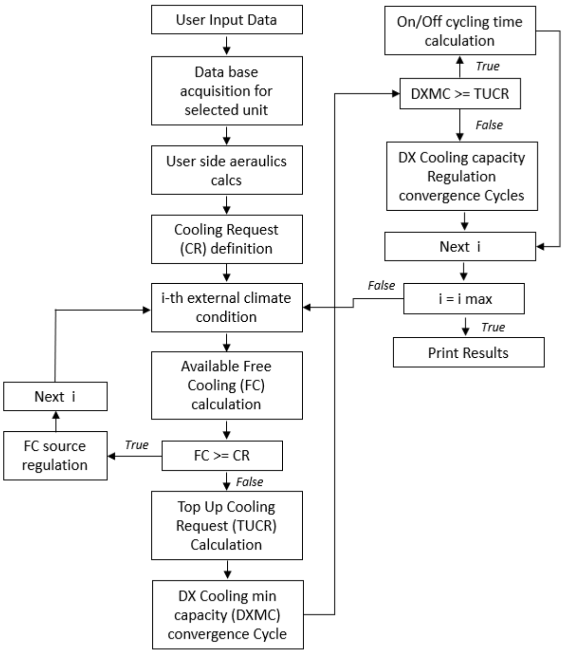

Fig. 11 – Seasonal energy analysis calculation flow chart

7. Climatic conditions for the considered data center locations

The Cities of Palermo, Milan and Frankfurt has been considered for the camparison of seasonal performances of the different cooling technologies. The distribution of seasonal hourly temperature and the annual average relative humidity for each temperature are shown in the graphs in Fig. 12 for each of the three cities considered.

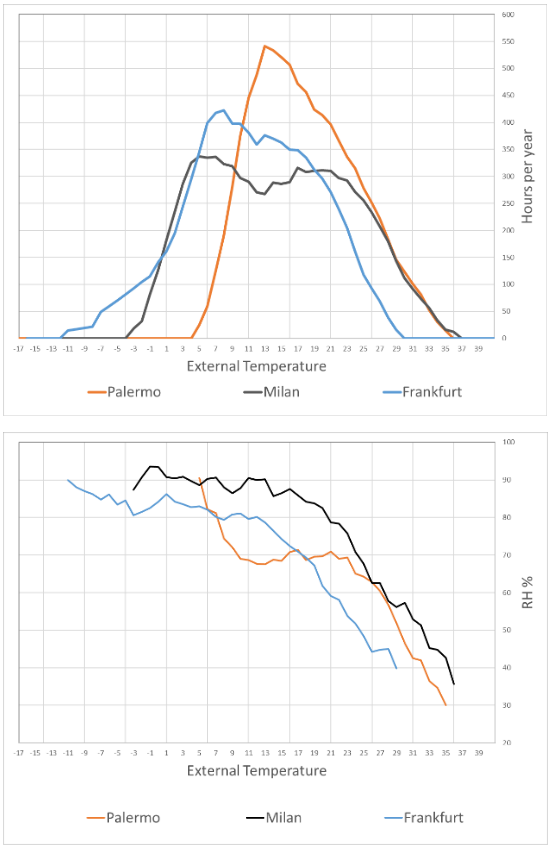

Fig. 12 – Seasonal temperatures and humidity distributions for three considered locations

8. Results comparison

In Tab. 1 all the results in terms of PUE and also in terms of WUE for units that are equipped with evaporative cooling modules are listed. An indication of the footprint split in indoor and outdoor is also reported.

8.1 Energy analysis

Depending on temperature distribution, on annual basis, the absorbed energy and the cooling energy delivered by the systems are calculated and synthesized in Figure 13 (Frankfurt), 14 (Milan) and 15 (Palermo). This helps highlight the extent of each cooling method and each component consumption contribution (fans, compressors, pumps).

Tab. 1 – Results comparison of seasonal energy analysis of each cooling technology for all the considered locations

	PUE			WUE			Footprint Indoor	Footprint Outdoor
	Palermo	Milan	Frankfurt	Palermo	Milan	Frankfurt	m² per 1MW data hall	m² per 1MW data hall
Case 1 (Direc Free Cooling CRAC)	1,073	1,068	1,056	0	0	0	22,3	29,7
Case 2 (Indirect Evaporative Cooler)	1,089	1,083	1,062	0,93	0,64	0,59	0,0	83,5
Case 3 (Adiabatic Free Coolig Chiller + CW CRAC)	1,142	1,122	1,093	0,49	0,26	0,25	15,7	44,2
Case 4 (Free Coolig Chiller + CW CRAC)	1,159	1,126	1,102	0	0	0	15,7	44,2
Case 5 (Indirec Free Cooling CRAC)	1,156	1,130	1,112	0	0	0	22,3	47,0

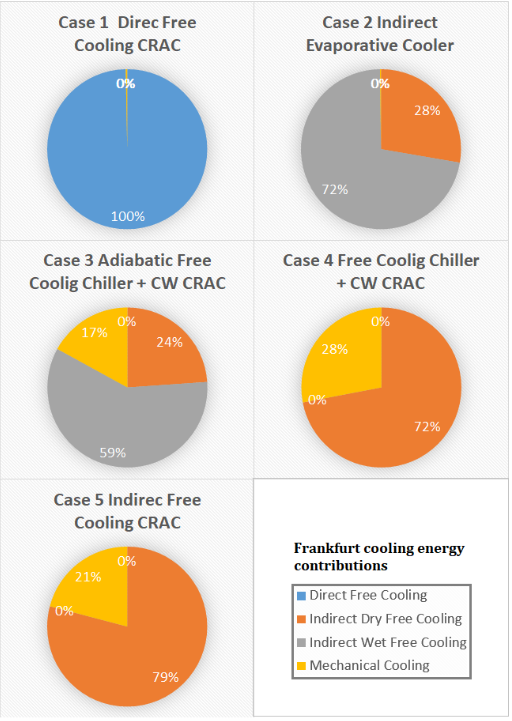

Fig. 13 – Cooling energy contributions from each cooling technology with Frankfurt climate data

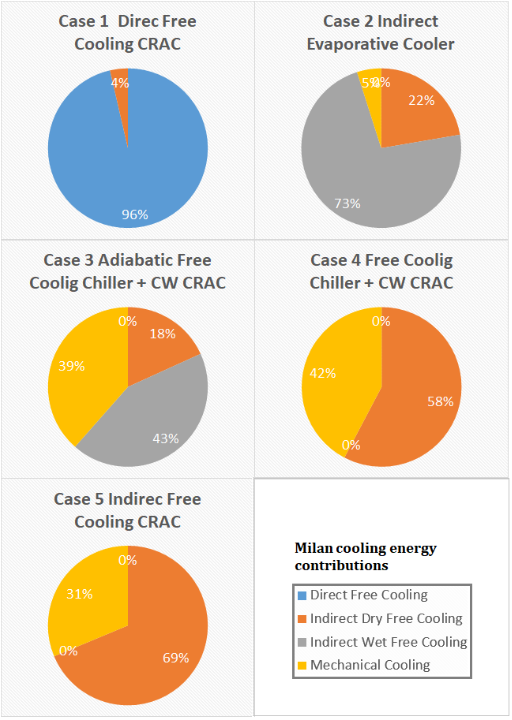

Fig. 14 – Cooling energy contributions from each cooling technology with Milan climate data

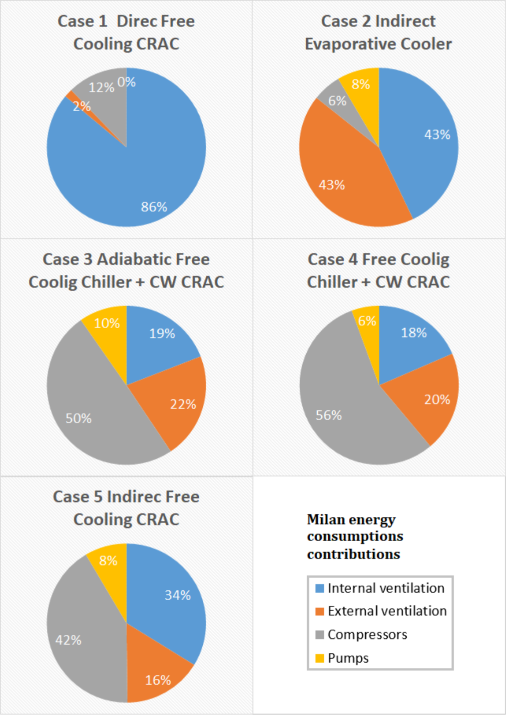

Fig. 15 – Energy consumptions contributions from each cooling technology with Palermo climate data

9. Conclusions

By comparing different values obtained by simulations, it is clear that from a strictly thermodynamic point of view the direct free cooling technology is extremely convenient, even more due to the adopted conditions of return air from the data center with high temperatures that allow full free cooling to be pushed beyond 90% of the annual hours even in a Mediterranean climate like the one of Palermo. The negative aspect of this technology concerns the limitations in terms of quality and pollution of the outdoor air in large cities where data centers are currently built up.

The only units with indirect free cooling capable to obtain results close to direct free cooling in terms of seasonal PUE are the IECs (Indirect evaporative coolers), which take advantage of large heat exchange surfaces and the use of large quantities of water to feed the evaporative cooling system of the outdoor air.

Following the efficiency classification in terms of seasonal PUE visible in Tab. (1) it is evident that from case 3 onwards the technologies are penalized by the fact that free cooling is based on the use of a carrier fluid that acts as a medium between external air and indoor air, introducing an extra step in the heat exchange process and reducing its efficiency. In chillers with adiabatic free cooling this problem is mitigated by the effect of lowering the external temperature through adiabatic pads, which have lower water consumption than indirect evaporative systems with cross flow heat exchanger (see WUE values in Tab. (1)).

Hence the most efficient solution is not the one usually adopted, since other factors should be considered such as the impact on costs of ordinary and extraordinary maintenance (filter replacement, water treatment, nozzle replacement, etc.) as well as the variability of cooling loads on a daily and/or seasonal basis (data traffic fluctuations) and environmental, space and noise requirements for each specific application. A financial analysis should also be carried out to estimate the initial investment rate of return, which may also differ significantly from one solution to another. In this context, the developed calculation tool fits perfectly to produce the data necessary for a technical-economic analysis, allowing to evaluate the best choice for the cooling system starting from the early design stages of the data center in the climatic context of interest.

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Data statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.