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Energy Saving Strategies in Green Data Center Designing Based on Aerosol Corrosion Prevention

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Data centers (DC) are responsible for a large global electricity usage mainly due to their cooling systems. Air conditioning (AC) costs could be reduced using a Direct Free Cooling (DFC) system which uses outside air to directly cool the information technology (IT). However this approach involves the risk to introduce outdoor aerosol which can become electrically conductive if the surrounding air reaches the aerosol Deliquescence Relative Humidity (DRH), thus damaging electronic equipment.
In this work we present a study aimed to increase DC energy efficiency, whilst at the same time preventing aerosol corrosion. The study was conducted in Italy at Sannazzaro de' Burgondi (SdB, Po Valley), to specifically optimize the operating conditions of a DC designed for the Italian National Hydrocarbon Institution (ENI) (5,200 m^2 of IT installed, 30 MW).
Aerosol number size distribution was monitored and allowed to estimate the aerosol level entering the DC; moreover aerosol chemical composition was investigated and allowed to estimate the aerosol free acidity and the aerosol DRH using the thermodynamic Aerosol Inorganic Model (E-AIM). E-AIM output were validated through laboratory tests, using an Aerosol Exposure Chamber, and through a comparison among "wet" and "dry" aerosol size distribution measured at SdB. From these data it was possible to design the filtering system of the DC and to estimate the outdoor air supply time, by DFC, and thus to estimate the energy consumption of the DC. A potential energy savings of 60% was estimated compared to a traditional AC cooling system with a potential energy saving of 7358 kWh and 2.67 t of CO_2 (for 1 kW of installed IT).

1. Introduction

Data centers (DC) alone are responsible for ~18% of electricity use in Western Europe. The global DC electricity demand rose from 0.5 % in 2000 to 2 % in 2010 (Shehabi, 2009).
In a DC, a high density of IT (computers for data storage, global networks, etc.) is present, thus, the power density demand is ~1 kW/m^2, which is higher than other buildings, resulting in substantial room and IT heating (Greenberg et al., 2006). A traditional data center's cooling system is based on AC units that cool the hot air produced by the IT and then make it available again through a closed-loop air cycle (Shehabi, 2009). Thus, the high energy consumption of DC is due, for a significant fraction (~35-50 %), to the cooling process of the IT; other energy sinks are IT (~50-60%), energy losses (~5%) and lighting (~1 %) (Greenberg et al., 2006). Thus, these kind of AC-DC are characterized by high values of the Power Usage Effectiveness (PUE: the ratio of total data center electricity load to IT electricity load); a PUE ratio of 1.0 indicates that all the energy consumption is due to IT equipment alone while, a PUE equal to 2.0 indicates that cooling, lighting and energy losses are responsible for an equivalent energy consumption of IT. Traditional AC-DC have PUE close to 2.0 (Shehabi, 2009).
As a consequence, solutions able to offset their financial and environmental costs (greenhouse gas emissions) are required. In this respect, the need to reduce CO_2 emissions has led the EU to define environmental policies, which for Italy turns in a requested decrease of 27.90 Mtep by 2020. The need to reduce both energy consumption, in order to comply with the new regulations (i.e. EU/27/2012), and economic and environmental costs, push to towards innovative technologies. Moreover, the reduction of

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cooling process costs is a widely shared target (Raei, 2011; Ikka et al., 2009). DFC systems could be use for this purpose: outside air is used to directly cool the IT (Shehabi et al., 2008).

However, this approach involves the risk to introduce outdoor aerosol which can become electrically conductive if the surrounding air reaches the aerosol Deliquescence Relative Humidity (DRH); this process can cause bridging and corrosion that can damage the IT (Shields and Weschler, 1998; Lobnig et al., 1994).

Even the risks associated with changes in aerosol concentrations within DC has not been examined, recent studies quantified the increase in particle concentrations caused by using DFC systems rather than AC (Shehabi, 2009). No studies have been conducted to design a DC by starting from the knowledge of the aerosol properties measured directly in situ.

In this study we illustrate the design of a DC created for the Italian National Hydrocarbon Institution (ENI) (5200 m^2 of IT installed) which is currently under construction and will become operational in December 2013 (Eni web site).

The study was based on measured aerosol properties, in order to reach the energy-saving target by means of a DFC system. DFC operating cycle was adapted both to comply with the aerosol guidelines (ASHRAE, 2011a and 2009) and to prevent aerosol corrosion.

2. Experimental

2.1 Data Center and Indoor Aerosol Pollution

The object of investigation is the *ENI Green Data Center* (GDC-ENI; 30 MW, 5.8 kW/m^2). The GDC-ENI is located in the middle of the Po Valley (Italy) at Sannazzaro de' Burgondi (SdB, 45°05'59"N, 8°51'40"E). Four rooms for Standard Computing (SC, 800 m^2 each of IT installed) and two rooms for High Performance Computing (HPC, 1000 m^2 each of IT installed) were designed. A total area of 5,200 m^2 of IT is planned. A DFC for the GDC-ENI is planned: outside air enters the building at floor level, passes through the IT to maintain a temperature set-point of 25°C, and exits through the roof by means of a chimney effect. This system allows to remove the expected rise in air temperature: 12°C in the SC rooms and 20°C in the HPC rooms. The expected DFC flows are $1.25 \cdot 10^6$ m^3 h^{-1} and $1.26 \cdot 10^6$ m^3 h^{-1}, in the SC and HPC rooms respectively.

To solve the potential problem of aerosol contamination within a DC together with energy saving the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Technical Committee 9.9 published guidelines concerning the thermodynamic limits and the aerosol contamination in DC (ASHRAE, 2011a, 2011b and 2009). Briefly, aerosol concentration must not exceed the ISO-8 class threshold (ISO14644-1), which are as follows: 1) $3.52 \cdot 10^6$ m^{-3} for d_p>0.5 µm: Class 1 (C_1); $8.32 \cdot 10^5$ m^{-3} for d_p>1.0 µm: Class 2 (C_2); $2.93 \cdot 10^4$ m^{-3} for d_p>5.0 µm: Class 3 (C_3). At the same time ASHRAE suggests "allowable" and "recommended" thermodynamic range are: 15°C-32°C (20%-80% of RH) and 18 °C-27 °C (5.5 °C of dew point - 60% of RH and 15 °C of dew point), respectively. If the GDC-ENI set-point indoor temperature (25 °C) is considered, the moisture ASHRAE's "recommended" thermodynamic range becomes 29-54% of RH.

However these guidelines are general and do not take account of the aerosol chemical and deliquescence properties at the investigated site.

Thus we developed an experimental procedure with the aim of supporting the design of a DC working with a DFC system.

The aerosol number size distribution was monitored over time (1 min time res) through an Optical Particle Counter Tandem system ($TOPC_s$: 2 Grimm *1.107 "Environcheck"*; 31 size classes, from 0.25 µm up to 32 µm). This system allowed measuring the "dry" and "wet" aerosol number size distribution. The "dry" size distribution allowed to assess the aerosol pollution level at the location of the GDC-ENI and to simulate the expected indoor concentration under DFC application following the method reported by Nazaroff et al. (2004) and Shehabi et al. (2008):

$$C_{i,in} = \frac{C_{i,out}\left[Q_S\left(1-\eta_{i,S}\right)+Q_N+Q_L P_i\right]+E_i}{Q_{rec}\eta_{i,rec}+(Q_S+Q_N+Q_L)+\beta_i V} \tag{1}$$

where i is the i-th OPC size class, $C_{i,in}$ and $C_{i,out}$ are the indoor and outdoor aerosol concentrations Q_S, Q_N and Q_L are the mechanical supply, natural ventilation and leakage flow pathways. $\eta_{i,S}$ is the size-dependent efficiency of the filtering system while P_i is the size-dependent penetration efficiency. E_i is the indoor aerosol emissions (size-dependent). Q_{rec} represents the re-circulated air flow within the DC, through a filter characterized by a size-dependent efficiency $\eta_{i,rec}$ equivalent to $\eta_{i,S}$. β_i and V are the size-dependent deposition loss rate (Riley et al., 2002) and the volume of the DC rooms.

The model described in eq. 1 was used to simulate the indoor aerosol concentration with the following semplifications: 1) Q_N and Q_L occurred only occasionally and their contribution was neglected; 2) the GDC-ENI was at the design, thus any estimation of the indoor sources was neglected; 3) β_i was neglected in order to simulate the worst indoor pollution scenario

$TOPC_s$ allowed also to compare “wet” and “dry” OPC data (Schumann et al., 1990). For this purpose, ΔV_1 and $\Delta V_{2.5}$ were calculated as the difference between the volumetric “wet” and “dry” size distributions below 1 µm and 2.5 µm, allowing to measure the instantaneous (1 min time res) degree of aerosol hydration (at ambient T and RH). Thus, instantaneous ΔV_1 and $\Delta V_{2.5}$ were averaged along the whole measurement campaign allowing the reconstruction of the hygroscopicity curve of each campaign to be subsequently compared with results estimated from aerosol chemistry via thermodynamic model (section 2.2 and section 3).

Finally a meteorological station (LSI-Lastem) allowed recording the basic meteorological parameters (1 min time res).

2.2 Aerosol Chemistry and Deliquescence Relative Humidity

PM_1 and $PM_{2.5}$ were sampled every 4 hours and 8 hours, respectively using a FAI-Hydra dual channel low-volume sampler (2.3 m^3 h^{-1}, PTFE filters, Ø=47 mm). PM samples were chemically analyzed by means of ion chromatography (IC, Dionex ICS-90 and ICS-2000 copuled system) (Ferrero et al. 2011). PM samples were extracted in an ultrasonic bath (20 minutes; SOLTEC SONICA®) with ultrapure water (Milli-Q). The following ions were analyzed: Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^- and SO_4^{2-} together with mono and dicarboxylic acids (formiate, acetate, propionate, oxalate, malonate, succinate, glutarate).

The aerosol chemistry was used as an input parameter to calculate the aerosol DRH.

Aerosol DRH was estimated using the thermodynamic Aerosol Inorganic Model (E-AIM Model-II) by Clegg et al. (1998): a state-of-the-art thermodynamic model for the H^+-NH_4^+-SO_4^{2-}-NO_3^--carboxylic acids-H_2O aerosol system (Hueglin et al., 2005; Pathak et al., 2004).

The outdoor aerosol chemical composition (and the related atmospheric thermodynamic conditions) (section 2.1), were used as inputs for the model to determine the most restrictive thermodynamic limits within which the worst DRH occur to optimize the DFC operating cycle for the GDC-ENI.

In order to validate the E-AIM DRH estimation, the E-AIM hydration curve was compared with that of $TOPC_s$ (section 1).

Moreover an Aerosol Exposure Chamber (AEC) had been specifically designed at the University of Milano-Bicocca for studying the aerosol hygroscopicity. It is a 1 m^3 chamber in which is possible to control the thermodynamic conditions. Within the AEC, it is possible to house up to six PM filters over special PTFE supports provided with a pair of electrodes each. The aerosol hygroscopicity is studied by means of conductivity measurements carried out on each filter as a function of the relative humidity (1% RH step). Humidity in the AEC was increased by means of evaporation unit filled with ultrapure water (Milli-Q).

Conductivity measurements were carried out using the Hewlett-Packard 3421A acquisition module, while a T and RH were monitored using LSI-Lastem sensors. Measurements were conducted at 25°C, the temperature set-point of IT within the GCD-ENI, on $PM_{2.5}$ samples. The aim was to verify if the E-AIM model rightly estimated the aerosol DRH.

3. Results

Spring (24/03/2010-19/04/2010) and summer (10/06/2010-10/07/2010) campaigns were conducted at SdB to measure aerosol properties (number size distribution, chemical composition) and meteorological parameters (all averaged data are reported here as mean ± mean standard deviations).

Atmospheric stability conditions (i.e. low mixing height), common for the Po Valley (Ferrero et al., 2012), promoted high aerosol concentrations and C_1, C_2 and C_3 averaged values were: 1) $1.1 \cdot 10^7 \pm 4.8 \cdot 10^5$ m^{-3}, $6.2 \cdot 10^5 \pm 4.1 \cdot 10^4$ m^{-3} and $4.0 \cdot 10^4 \pm 1.9 \cdot 10^4$ m^{-3} during spring; 2) $5.3 \cdot 10^6 \pm 1.7 \cdot 10^5$ m^{-3}, $5.9 \cdot 10^5 \pm 1.2 \cdot 10^4$ m^{-3} and $2.5 \cdot 10^4 \pm 3.0 \cdot 10^3$ m^{-3} during summer.

As a consequence the outdoor ISO equivalent aerosol classes overreached the ISO-8 standards, for 74% and 55% of the time, and were 8.3±0.4 during spring and of 8.1±0.4 during summer;

Thus the GDC-ENI needed a filtering system to maintain the ISO-8 standard levels. Particularly, the filtering systems was designed composed of 456 MERV13 (Minimum Efficiency Reporting Value) filters (total filtering surface of 165 m^2 with a maximum flow rate of 2763 m^3 h^{-1} for each filter). The global MERV13 filter efficiency is lower than 100 % and increase with particle size, up to 100 % at 3 µm. (Nazaroff 2004).

Thus, the chemical properties of PM_1 and $PM_{2.5}$ samples, smaller than the 100 % size-efficiency of the MERV13 filters were investigated.

PM chemical composition showed that the ionic fraction was on average the 32±3% of PM_x mass during both campaigns, and NO_3^-, SO_4^{2-} and NH_4^+ accounted for 90-95% of the whole ions while, other cations (i.e. Cl^-, K^+, Na^+, Mg^{2+}, Ca^{2+}) and carboxylic acids accounted ~ 2% of PM_x mass.
As previously mentioned (section 1) the ionic component can damage the electronic equipment after solubilisation at the DRH. Thus the E-AIM model (section 2.1) was applied to each PM_x sample to estimate the DRH values, which were found to fall within a broad range of 40-80% for both PM_x. Within this range, the most abundant DRH_s were to be found in the 60-65% range, with a frequency percentage of 39 % and 43% for PM_1 and $PM_{2.5}$ respectively. As a result, the average DRH for PM_1 was 61.2±1.1% (spring), and 68.4±1.4 % (summer), while in the case of $PM_{2.5}$ it was 60.8±0.7% (spring) and 62.4±0.9% (summer).
Lower DRH values during spring reflected the influence of aerosol chemistry: NO_3^- was predominant during spring (17-20% of PM_x mass), while SO_4^{2-} during summer (10-18% of PM_x mass); NH_4^+ remain fairly constant during both campaigns (4-7% in both cases). This PM_x chemical composition is close to that reported in literature for the Po Valley (Perrone et al., 2012, Daher et al., 2012) and turns into changes of the sulphate to nitrate ratio [SO_4^{2-}/(SO_4^{2-}+NO_3^-)] and the ammonium to hydrogen ratio [NH_4^+/(NH_4^++H^+_{tot})] along time. Potukuchi and Wexler (1995) showed that for a fixed ammonium to hydrogen ratio, an increase in the sulphate to nitrate ratio (i.e. summer conditions) leads to higher DRH_s. The measured PM chemical composition showed higher sulphate to nitrate ratio during summer (0.72±0.03 and 0.59±0.03 for PM_1 and $PM_{2.5}$) than in spring (0.33±0.03 and 0.20±0.02 for PM_1 and $PM_{2.5}$) while the ammonium to hydrogen ratio remained fairly constant (0.95±0.01 for PM_1 and 0.95±0.01 and 0.84±0.01 for $PM_{2.5}$ during both campaigns).
Due to the crucial role of estimated DRH values in optimizing the design of the GDC-ENI DC, the obtained E-AIM output were validated through the use of $TOPC_s$ data and from experiments conducted on $PM_{2.5}$ samples in AEC. For this purpose $TOPC_s$ ΔV_1 and $\Delta V_{2.5}$ were calculated as a function of RH (section 2.1), they were averaged along each campaign and they were compared with the averaged E-AIM output (moles of condensed H_2O on PM_x). E-AIM values agreed with those estimated using the $TOPC_s$; R^2 between $TOPC_s$ and E-AIM were 0.97 and 0.85 for PM_1, in spring and summer, and were 0.98 and 0.95, for $PM_{2.5}$.
Moreover, the AEC (specifically designed at the University of Milano-Bicocca) was used to measure, at 25 °C, the aerosol hygroscopicity on 15 $PM_{2.5}$ samples with the aim to validate if the E-AIM model rightly estimated the aerosol DRH. Figure 1 shows an experimental $PM_{2.5}$ hygroscopicity measurement (AEC data) compared with the E-AIM predicted moles of condensed water versus RH. Considering the whole $PM_{2.5}$ ensemble, the averaged DRH estimated via E-AIM was 62.8±2.0 % in keeping with the values measured using the AEC: 62.6±1.2 %.
These results show the reliability of using E-AIM to derive aerosol DRH_s, and also are comparable to that estimated at SdB during the sampling campaigns.

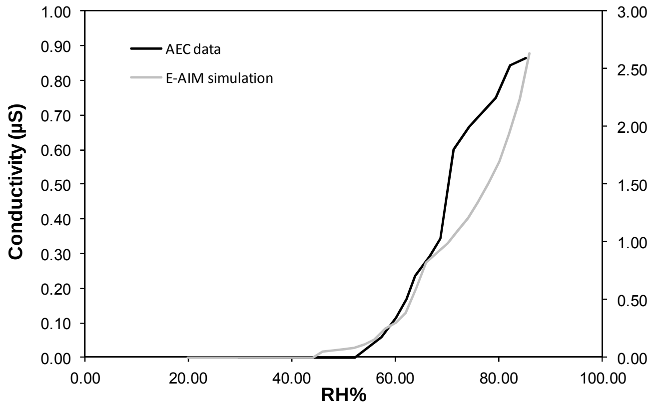

Figure 1: Aerosol hydration curve measured on a $PM_{2.5}$ sample and predicted by E-AIM (Model II) application.

Given the validation of DRH calculation, the DRH_s values were used to optimize the DFC operating cycle. Estimated DRH_s values at SdB were higher than the RH limit "recommended" by ASHRAE (2011) (54 %: 15 °C dew point at 25 °C) and it was lower than the "allowable" limit (80 % of RH).
Moreover, all the averaged DRH_s were found to be slightly higher than 60 % allowing choosing 60% of RH as the upper limit for the DFC operating cycle to prevent a corrosive effects of the aerosol.

As a final step, eq. 1 was applied to the outdoor OPC "dry" data in order to prove if the designed DFC operating system (MERV13 filters plus 60% of maximum RH) allowed to attain the indoor ISO-8 standard (section 2.1). In this respect, the external air supply (Q_S) and the re-circulated one (Q_{rec}) were estimated along time as a function of the measured outdoor T and RH considering: the IT temperature set-point (section 2.1) and the above-mentioned thermodynamic limits optimized for the DFC in the GDC-ENI. (section 3.1.3).

Results evidenced that both during spring and summer, C_1 and C_2 attained the ISO-8 standard: $2.2*10^6 \pm 1.2*10^5$ m^{-3} and $2.7*10^4 \pm 1.2*10^3$ m^{-3} (ISO-equivalent class: 7.5±0.5) in spring and $4.3*10^5 \pm 2.3*10^4$ m^{-3} and $2.4*10^4 \pm 1.2*10^3$ m^{-3} (ISO-equivalent class: 4.0±3.6) in summer. C_3 equalled zero because MERV13 filter efficiency reach the 100% yet at 3 μm (re-suspension was also neglected in the model; section 2.1).

The balancing between the external air supply (Q_S) and the re-circulated one (Q_{rec}) along time allowed to estimate the energy consumption of the GDC-ENI and its PUE (section 1). A PUE equal to 1.2 was found, lower than traditional AC data centers (PUE=2.04; Sullivan, 2009), and of other DCs adopting DFC (PUE=1.42-1.46; Shehabi, 2009).

This PUE value turns into an annual energy saving of 81% compared to traditional AC data centers (PUE=2.04): 7.4 MWh for 1 kW of installed IT and 221 GWh for the entire GDC-ENI. The annual energy saving, compared to other DCs adopting DFC system (PUE=1.42-1.46), was also relevant: 55% (2.1 MWh for 1 kW of installed IT and 63 GWh for the entire GDC-ENI).

In terms of environment savings t of CO_2 not emitted were estimated considering a CO_2 emission factor of 362 gCO_2 kWh^{-1} (European Environment Agency, EEA. Results evidenced an emission savings for each kW of IT: 2.7 t of CO_2 (80 kt the entire GDC-ENI), compared to traditional AC data centers (PUE=2.04) and 0.8 t of CO_2 (23 kt for the entire GDC-ENI), and compared to other data centers adopting DFC systems (PUE=1.42-1.46).

4. Conclusions

This work reports results regarding a-priori study conducted on a DC, for the Italian National Hydrocarbon Institution (GDC-ENI at Sannazzaro de' Burgondi, Po Valley). The study aimed to optimize a DFC operating cycle to save the largest amount of energy and to prevent, at the same time, aerosol corrosion. This goal was reached through the determination of the most reliable thermodynamic limits (especially moisture) based on in-situ measured aerosol properties. The aerosol properties (number size distribution, chemical composition, DRH, acidity) and meteorological parameters were investigated using reliable and shared methods, characterized by reasonable costs: a situation able to promote this experimental design as a "standard protocol" applicable in similar situations for any DC to estimate its economic and environmental costs in feasibility studies.

The investigated aerosol properties determined the potential levels of aerosol entering the DC (equivalent ISO class) and its DRH allowing to choose both the appropriate filtering system (MERV13 filters) and the best thermal cycle (60% of maximum allowed RH) applicable to the DFC. Then, the GDC-ENI operating cycle was investigated showing that the aforementioned choices allowed to reach the indoor ISO-8 standard required by ASHRAE itself.

The energy consumption of the DC was investigated revealing an energy saving of 81% compared to traditional AC cooling systems.

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