Thermal Metrics for Data Centers: A Critical Review

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Thermal metrics for data centers: a critical review

Alfonso Capozzoli[a]*, Gianluca Serale[a], Lucia Liuzzo[a], Marta Chinnici[b]

[a]*Politecnico di Torino, , corso Duca degli Abruzzi, 24, Turin – 10129, Italy*
[b]*ENEA C.R. Casaccia, via Anguillarese, 301, Rome – 00123, Italy*

Abstract

Thermal management and air distribution performance are assuming a key role for achieving the energy saving and the IT equipment reliability for data centers (DCs). In recent years, to monitor and to control their variation several thermal performance metrics were introduced. This work presents a critical review on the most important thermal indices for DCs currently used. The main formulas and physical models on which they are based were discussed. Moreover, a critical analysis on the main advantages and drawbacks of each metric is carried out.

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Keywords: Data centers management; Energy efficiency; Metrics; Temperature in data centers, Data center thermal performance; Review

1. Main text

Modern DCs contain a large amount of IT equipment, which are used for achieving the different tasks (i.e. databases organization, telecommunication, email correspondences) and support a lot of users. The large amount of IT equipment causes high heat power densities in DCs, which are continuously increasing. To dissipate the heat power generation and ensure a good reliability – the ability for the servers to properly work and not lose data - of IT equipment, the DC must be adequately cooled. Indeed, IT equipment are less susceptible to failure and faults when work at certain environmental conditions [1]. In general, the reliability is the primary objective of a DC.

In recent years, information-based economy is growing both in public and in private sectors [2]. At the same time, the IT equipment computing improving is causing a further power density increase. In this scenario the HVAC system become a central element in the DC facility. About the 30% of the total power of a data center is due to the conditioning system [3]. For this reason the efficiency of the HVAC system become very important not only for IT equipment reliability, but also for energy saving. Moreover, it is necessary to evaluate how well cool air is distribut-

* Corresponding author. Tel.: +39-011-090-4413; fax: 39-011-090-4499.
E-mail address: alfonso.capozzoli@polito.it.

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ed in the DC rooms. The most common design structure in a DC is characterized by a raised floor with the racks arranged in Hot/Cold Aisle layout. A bad air distribution and thermal management cause different phenomena, such as recirculation of warm air inside the cold aisle and the short-circuiting (or by-pass) of the cold air back into the CRAC. The effect of these phenomena are hotspots and coldspots, which cause energy inefficiency and IT reliability problems.

In order to detect these phenomena indices or metrics - that qualitatively or quantitatively evaluate the thermal management or the air distribution performance in a DC – are necessary. Through the thermal metrics a real time thermal diagnostic analysis can be performed. Several different thermal performance metrics were proposed during the last few years [4]. This paper focused on the most important metrics currently used. Firstly, the variables and the physical models on which they are based were introduced. Afterwards, a critical analysis of the main advantages and drawbacks of each metric is carried out.

2. Scenario of thermal metrics for data centers

Thermal metrics are used to evaluate the DC airflow performance and thermal management both in design and operational stage. The common air distribution system is based on hot aisle and cold aisle [5]. Cool air is supplied from Computer Room Air Conditioning units (CRACs) into an underfloor plenum and, thus, it is supplied into cold aisles through vent tiles, where it reaches IT equipment. The heat power produced by equipment (about 98% of their energy consumption) is dissipated by convective heat transfer. At the final stage of cooling path, the airflow exhaust from equipment returns to the CRAC, where it is treated to be supplied again.

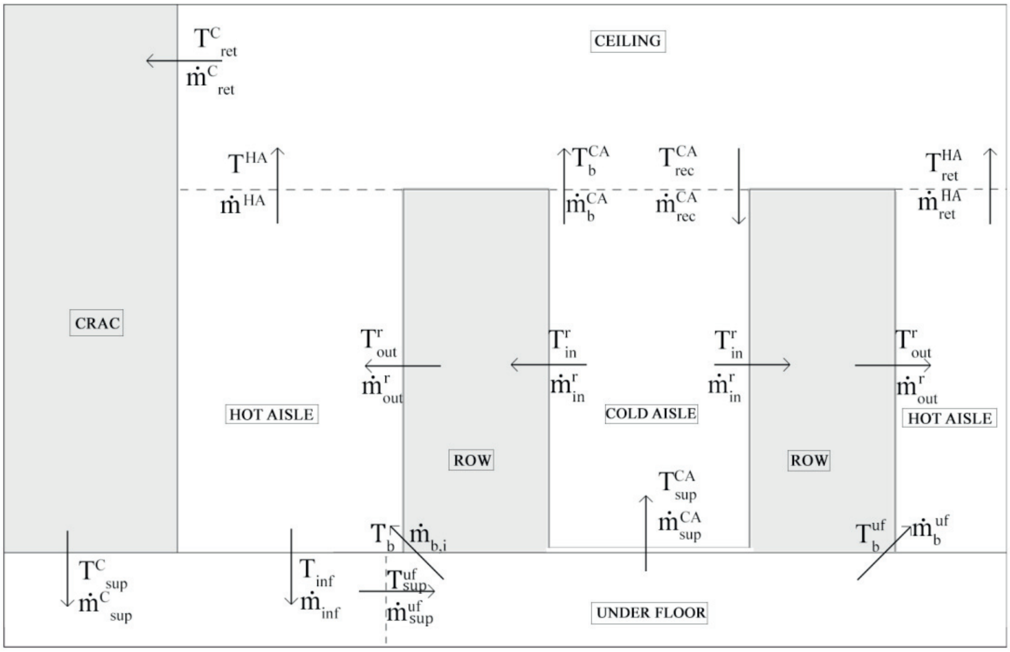

Fig. 1. Typical airflow within a general DC (Hot and Cold Aisle layout)

In a real DC recirculation, bypass or infiltration phenomena may occur. It has been estimated that only about 40% of airflow supplied by CRAC reaches IT equipment because of leakages throughout the environment [6]. In this way airflow ingested by a rack is a mix of cold and hot airflow coming from surrounding. In figure 1 typical DC airflows are shown. In general, thermal metrics are based on relationship between temperature and mass flow rate and they could be affected by geometric or physical parameters.

In recent years, because of high performance computing equipment, energy saving is straight related to thermal behavior: improving thermal performance allow to minimize energy cost of a data center [7]. Especially for large-scale data centers, whose load density can reach 10 kW/rack, the analysis of thermal behavior is not only necessary for equipment reliability but also for a reduction of energy consumption. In particular the most of the following thermal indices were proposed for these large-scale DCs. Furthermore, since racks and vent tiles are standardized, the thermal indices can be applied regardless on different data centers, at server, rack, row or room level. Moreover, in literature some energy saving strategies were developed with the aim to minimize heat recirculation, taking into account the optimization of airflow supply temperature [8], [9].

2.1. Supply Heat Index and Return Heat Index

Sharma et al. have proposed dimensionless parameters to evaluate thermal design and large-scale DCs performance [5]. These indices allow to evaluate the extent of cold and hot air mixing, related to racks and to the CRAC unit. They are scalable metrics and potentially applicable at racks, rows or at wide data center level. Considering $\dot{Q}^r$ the total heat power produced by IT equipment allocated into a rack, and $\Delta\dot{Q}^{CA}$ the airflow supply heat power (enthalpy) increase caused by hot air recirculation, Supply Heat Index (SHI) is given by the ratio between the enthalpy rise and the total heat power rise from supply to exhaust from the rack ($\dot{Q}^r+\Delta\dot{Q}^{CA}$)

$$\mathrm{SHI} = \frac{\Delta\dot{Q}^{CA}}{\dot{Q}^r+\Delta\dot{Q}^{CA}} = \frac{\sum_i\sum_j\left(T^r_{in_{i,j}}-T^C_{sup}\right)}{\sum_i\sum_j\left(T^r_{out_{i,j}}-T^C_{sup}\right)} \tag{1}$$

Where T^r_{in} is the rack intake airflow temperature, T^C_{sup} is the airflow supply temperature from CRAC unit and T^r_{out} is the airflow temperature exhaust from rack. The subscript i represents ith rack, while j the jth row within a data center. Under the hypothesis of equality of airflow rate across the rack ($\dot{m}^r_{in}$ is the same of $\dot{m}^r_{out}$) and absence of infiltration of hot air into the under floor plenum ($T^{CA}_{sup} = T^C_{sup}$), SHI depends only on the air temperature at the rack inlet, the rack outlet and the CRAC outlet. This index can be also calculated in a single rack to identify local hot spot. An increase of T^r_{in} means also an entropy rise caused by air mixing and, then, SHI could be considered even a metrics for energy efficiency measure.

Considering, instead, the return path to the CRAC unit, for energy balance, the heat power rise in the cold aisle $\Delta\dot{Q}^{CA}$ implies a decrease in the ceiling one $\Delta\dot{Q}^{Ce}$. In other terms, which is lost in the cold aisle it is regained in the CRAC unit and the heat powers magnitude is the same. Likewise, due to energy balance, the load on the CRAC $\dot{Q}^C$ is the same of the total heat power produced by the rack $\dot{Q}^r$. The ratio between the heat power on CRAC $\dot{Q}^C$ and the total power rise from supply to exhaust from the rack represent the mathematical expression of the Return Heat Index, which is the complementary number of SHI.

$$\mathrm{RHI} = \frac{\dot{Q}^C}{\dot{Q}^r+\Delta\dot{Q}^{Ce}} = \frac{\sum_k \dot{m}^C_{sup_k}\cdot c_p\cdot(T^C_{ret_k}-T^C_{sup})}{\sum_i\sum_j \dot{m}^r_{out_{i,j}}\cdot c_p\cdot\left(T^r_{out_{i,j}}-T^C_{sup}\right)} = 1-\mathrm{SHI} \tag{2}$$

Where $\dot{m}^C_{sup}$ is the mass flow rate supply from CRAC unit, $\dot{m}^r_{out}$ the mass flow rate across equipment and T^C_{ret} the airflow return temperature at CRAC. Even though these dimensionless parameters are easy enough to calculate and measure, they present limits to describe or predict local condition, as hot spot phenomena. The temperature values considered on these indices are only average values: a single rack could be affected by a rapidly increase in temperature, that could comport a local hot spot that SHI could not identify. Several researchers [11], [12], [13], [14] claim that these indices give a macro evaluation of the recirculation phenomena, but they fail especially when the rack intake temperatures have to be evaluated in respect of IT equipment reliability. They also give information about recirculation but do not take into account the effect of bypass on recirculation.

2.2. Rack Cooling Index

Herrlin proposed the Rack Cooling Index (RCI) [15], [16]. The aim of this metric is to provide a tool to evaluate rack intake temperatures comparing them with the allowable and recommended ones in DCs, telecom central offices and mission-critical facilities in general. The threshold values can be suggested into guidelines (as T.C. 9.9 [1]) or imposed by the thermal manager. RCI assumes two expressions in relation to high and low limits: RCI_{Hi} and RCI_{Lo}. In particular, the metrics are based on temperature distribution along the rack height:

$$RCI_{Lo} = \left[1 - \frac{\sum_{i=1}^{n}\left(T_{LO-rec} - T_{in_i}^{r}\right)}{n \cdot (T_{LO-rec} - T_{LO-allow})}\right] \cdot 100\ [\%] \text{ if } T_{in_i}^{r} < T_{LO-rec} \tag{3a}$$

$$RCI_{Hi} = \left[1 - \frac{\sum_{i=1}^{n}\left(T_{in_i}^{r} - T_{HI-rec}\right)}{n \cdot (T_{HI-allow} - T_{HI-rec})}\right] \cdot 100\ [\%] \text{ if } T_{in_i}^{r} > T_{HI-rec} \tag{3b}$$

$T_{LO-allow}$ and $T_{HI-allow}$ are allowable values, while T_{LO-rec} and T_{HI-rec} recommended ones, low and high respectively. If no one rake intake temperature exceed both recommended and allowable values, RCI is equal to 100%, while it is lower if one or more temperatures exceed the recommended range. Although the effect of temperature variation could be analyzed with the standard deviation of the rack intake temperatures [7]. Since the aim of cooling is to guarantee the IT equipment health condition, RCI is the main important metric to evaluate thermal behavior of equipment allocated into the racks. In addition, several guidelines consider the evaluation of this metrics for thermal effectiveness [1], [17], [18], [19]. In general, RCIs do not provide information about the source but only on IT equipment effects. The evaluation of other global metrics is necessary to this purpose [20].

2.3. Beta Index

The β Index was proposed to evaluate local rack increase temperature [11]. This index is defined as:

$$\beta = \frac{T_{in}^{r}(z) - T_{sup}^{C}}{T_{out}^{r} - T_{in}^{r}} \tag{4}$$

Where $T_{in}^{r}(z)$ is the airflow inlet temperature at position z from the floor. The numerator in (4) represents a local value, while the denominator is an average one. The common values range is between 0 and 1. The value 0 means absence of recirculation, while a value above 1 indicates the presence of self-heating. The main aim of this index is to fill the gap introduced since SHI was formulated. Indeed, the authors in [11] claimed that SHI and RHI are largely global metrics and they could not provide a good evaluation of a design that at local level could bring a dangerous cooling condition in IT equipment.

2.4. Negative Pressure, Bypass, Recirculation, Balance, Thermal Performance, Flow Performance

In [21], [22] and [23] a group of metrics to evaluate different phenomena that could occur in DCs were proposed. In particular, the effect of air ambient infiltration into the under floor plenum caused by negative pressure was introduced in addition to bypass and recirculation phenomena. Negative pressure can occur in proximity of the CRAC unit, where the airflow speed is high.

The proposed indices are based on the mass flow rate and energy balance into the DC:

$$NP = \frac{\dot{m}_{inf}}{\dot{m}_{sup}^{C}} = \frac{T_{sup}^{uf} - T_{sup}^{C}}{T_{ret}^{C} - T_{sup}^{uf}} \tag{5}$$

$$BP = \frac{\dot{m}_{b}^{uf} + \dot{m}_{b}^{CA}}{\dot{m}_{sup}^{uf}} = \frac{T_{out}^{s} - T_{ret}^{C}}{T_{out}^{s} - T_{sup}^{uf}} \tag{6}$$

$$R = \frac{\dot{m}_{rec}^{CA}}{\dot{m}_{in}^{s}} = \frac{T_{in}^{s} - T_{sup}^{uf}}{T_{out}^{s} - T_{sup}^{uf}} \tag{7}$$

$$BAL = \frac{\dot{m}_{sup}^{C}}{\dot{m}_{in}^{s}} = \frac{T_{out}^{s} - T_{in}^{s}}{T_{ret}^{C} - T_{sup}^{C}} = \frac{1-R}{(1-BP)\cdot(1+NP)} \tag{8}$$

Where $\dot{m}_{inf}$ is the mass flow rate referred to the infiltration air into the under floor plenum, $\dot{m}_{sup}^{uf}$ to the air supplied into the plenum from the CRAC, $\dot{m}_{b}^{uf}$ to the bypass air into the plenum, $\dot{m}_{b}^{CA}$ to the bypass air in the cold aisle and $\dot{m}_{rec}^{CA}$ to the recirculated air inside cold aisle.

Negative Pressure Ratio (NP), eq. (5), is given from the ratio between the infiltration mass airflow rate $\dot{m}_{inf}$ and the supply air from the CRAC unit $\dot{m}_{sup}^{c}$. ByPass Ratio (BP), eq. (6), is defined as the ratio of the airflow mass rate which does not enter to IT equipment $\dot{m}_{b}^{uf} + \dot{m}_{b}^{CA}$ before returns to the cooling plant on the total airflow rate into the under floor plenum $\dot{m}_{sup}^{uf}$. Recirculation Ratio (R), eq. (7), is defined as the ratio of the recirculated airflow rate $\dot{m}_{rec}^{c}$ that enters into the IT equipment on the total mass airflow rate through the equipment $\dot{m}_{in}^{s}$. If only the sensible load is considered, R coincides with SHI, eq. (1). BAL, eq. (8), represent the balance among the airflow rate produced by the CRAC and the server request [24] and it could be expressed as a function of both Bypass BP and Recirculation ratio R.

Moreover, it is claimed that the considered temperature values are calculated as the average on airflow rate. Considering different case studies, it has been noticed that average temperature are good enough, reaching results with acceptable errors. In this way, measures are very easy to be taken, except for infiltration related to the negative pressure that should be calculated by means CFD model. Anyway, the group of metrics give information about bypass and recirculation phenomena, which can occur simultaneously: a large rate of bypass could cause the recirculation effect because of less airflow availability. These metrics can be applied to rack, row or wide data center level [25].

2.5. Return Temperature Index

Return Temperature Index was introduced in literature by Herrlin, in 2007 [26]. The index is based on the percentage ratio of the total airflow mass rate at rack inlet on the one produced by CRAC unit, eq. (9). It gives information about recirculation or bypass in a DC. RTI can be also defined as the percentage ratio of return and supply temperature difference at the CRAC unit on the temperature difference across the IT equipment. The two possible RTI formulations are the following:

$$RTI = \frac{\sum_i \dot{m}_{in_i}^{r}}{\sum_k \dot{m}_{sup_k}^{C}} \cdot 100 = \frac{T_{ret}^{C} - T_{sup}^{C}}{T_{out}^{r} - T_{in}^{r}} \cdot 100\ [\%] \tag{9}$$

If RTI assumes values below 100%, it means that the airflow has bypassed IT equipment. In this case the airflow produced by the CRAC is higher than the IT equipment request. A value above 100% means that recirculation occurs and the IT equipment have ingested hot air from surrounding environment. A value of 100% means the perfect balance between the airflow request by the rack and supplied by the CRAC. The index could be coupled with RCI for giving information about thermal behavior in a DC. RCI provides the rack health cooling conditions and RTI becomes a tool to investigate airflow efficiency [27]. Even though RCI is one of the most applied in literature, it is not completely able to discriminate a phenomena rather than other ones. Indeed, the approximation of considering bypass in spite of recirculation, or vice versa, could comport the underestimation of the mutual influence. For this reason BAL metric, eq.(8), could be employed instead of RTI. Furthermore, RTI is the percentage of the inverse of BAL while R and BP metrics can be viewed as a decomposition of RTI [25].

2.6. Cross Interference Coefficients

A fast thermal evaluation for high performance DCs, based on abstract heat flow model, was proposed by Tang et al [12]. The heat power algorithm is modeled within the DC environment considering the thermal interference among IT equipment, or nodes, caused by recirculation. For this purpose Cross Interference Coefficients α_{ij} are introduced: they can provide information about self-interference of a node on its own, or cross interference between a node on another ones. Each Cross Interference Coefficient α_{ij} is obtained as the percentage of heat power exiting from i^{th} node and entering into j^{th} node. Into a DC with n nodes, **A**, eq. (10), is defined as the Cross Interference Coefficients Matrix and it represents the total interference between nodes. Considering the influence stable for different IT equipment power consumption, wide DC can be represented with a system based on matrix **A** and some column vectors (such as the outlet temperature $\vec{\mathbf{T}}^{\mathbf{s}}_{\mathbf{out}}$, server power consumption $\vec{\mathbf{P}}$, air supply temperature $\vec{\mathbf{T}}^{\mathbf{C}}_{\mathbf{sup}}$), eq. (11).

$$\mathbf{A} = \begin{vmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \ddots & \\ \alpha_{n1} & & \alpha_{nn} \end{vmatrix} \tag{10}$$

$$\mathbf{K} \cdot \vec{\mathbf{T}}^{\mathbf{s}}_{\mathbf{out}} = \mathbf{K} \cdot \vec{\mathbf{T}}^{\mathbf{C}}_{\mathbf{sup}} - \mathbf{A}' \cdot \mathbf{K} \cdot \vec{\mathbf{T}}^{\mathbf{C}}_{\mathbf{sup}} + \mathbf{A}' \cdot \mathbf{K} \cdot \vec{\mathbf{T}}^{\mathbf{s}}_{\mathbf{out}} + \vec{\mathbf{P}} \tag{11}$$

The terms of the diagonal matrix **K** are the product between airflow mass rate $\dot{m}^{s}_{in_i}$ and specific heat c_p. From local behaviors to global DC, this system provides information enough good for analyzing both IT equipment cooling condition and global effect of recirculation. Since Cross Interference Coefficients have to be calculated by means CFD, this model is not quickly applicable like other indices based only on air temperatures. On the other hand, after several CFD analyses, the obtained heat power model could represent the structure of a task scheduling algorithm with thermal awareness [7], [8], [9], that links the problem of server functioning with thermal environment.

2.7. Capture Index

The evaluation of thermal behavior could be carried out by means Capture Index (CI) [29]. It is based on the mass rate balance introduced by VanGilder [30], which tried to model airflow recirculation with Recirculation Index (RI). CI allows to evaluate the airflow ingested by local component. It is measured into cold aisle or hot aisle, for rack or local extractor unit respectively. The mathematical formulations of CI, in both cold and hot aisle, are:

$$\mathrm{CI_i(cold\ aisle)} = \frac{\dot{m}^{sC}_{in\,i}}{\dot{m}^{C}_{sup_i}} \tag{12}$$

$$\mathrm{CI_i(hot\ aisle)} = \sum_{j=1}^{N} \frac{C^{C}_{ret_{ij}} \cdot \dot{m}^{C}_{ret_j}}{\dot{m}^{r}_{out_i}} \tag{13}$$

Where $\dot{m}^{sC}_{in}$ is the mass flow rate ingested by a rack, $\dot{m}^{C}_{sup}$ is the total mass flow rate coming from the CRAC, $C^{C}_{ret_i}$ is the concentration of the i^{th} mass flow rate $\dot{m}^{r}_{out}$, discharged by a rack, on the total mass flow rate $\dot{m}^{C}_{ret}$ at the j^{th} local extractor. The hot aisle CI is valid only in the case of local cooler or extractor. Anyway a CI value of 100% indicate good cooling performance, while the opposite case 0% indicate bad cooling condition. Although these indices give information only about mass flow rate, a value of 0% does not imply necessary that local air temperatures overcame threshold values [31].

Since both indices are values based on airflow rate, results good enough can be obtained only by means CFD analysis. Measurements in loco provide only rough results with errors not negligible. For this reason, CI is computed primary in design stage for improving design parameters and it is associated to a difference temperature between threshold value and airflow temperature ingested by a rack [32].

2.8. Thermal Influence Indices

The Thermal Influence Indices proposed in [33] and [34] are global metrics used to measure the casual relationship between heat sources and sinks. A component A is defined as “thermally influence on a component B” if it is a heat source for B. The IT equipment and the CRACs are equally considered thermally influencing components. The concept is the same of the Cross Interference Coefficient, in fact thermal influence indices are the ratio between the heat power at inlet component coming from a source $\dot{Q}_{in}^{A,B}$ and the total heat power at inlet component $\dot{Q}_{in}^{B}$, eq. (16).

$$\mathrm{Inf}(A,B)/B = \frac{\dot{Q}_{in}^{A,B}}{\dot{Q}_{in}^{B}} = \frac{\dot{m}_{in}^{A,B} \cdot c_p \cdot T_{out}^{A}}{\dot{m}_{in}^{B} \cdot c_p \cdot T_{in}^{B}} \quad (14)$$

The main difference between Thermal Influence Indices and Cross Interference Coefficient is the compenent on which they are focused. While the Cross Interference Coefficients consider only IT equipment, the Thermal Influence Indices involve also the CRAC unit. The field of knowledge became larger in comparison to other performance indices. Since they are based on mass fraction that exiting from a component enter into another one, good results are achieved by means CFD method only.

They are used both during the design stage and the operation time of a DC. Once the casual relationship between components are defined, the indices are used to maximize the heat load (in design stage) or optimize airflow supply temperatures (in operation stage).

2.9. Overall Airflow Efficiency Evaluation Standard

Most of all the previously described indices introduced in literature consider different aspects of the thermal management. Cho et al. [27] proposed an Overall Airflow Efficiency Evaluation Standard, based on the metrics available in literature, which involves four evaluation steps for eight different cases.

Table 1. Overall efficiency evaluation standard. Indices evaluation in column with priority order, cases in row.

	RCI_{Hi}	RCI_{Lo}	RTI	SHI/RHI	Overall Airflow Efficiency Evaluation Standard
	Ideal 100% Good ≥96% Acceptable 91÷95% Poor ≤90%	Ideal 100% Good ≥96% Acceptable 91÷95% Poor ≤90%	Target 100 % Good >100±5%> Poor <100 ±30%<	Good SHI<0.2 RHI>0.8	
1	Poor	-	-	-	No Good
2	-	Poor	-	-	No Good
3	-	-	Poor	-	No Good
4	Acceptable	-	-	-	Acceptable
5	Good/Ideal	Poor	Bypass or recirculation	-	Acceptable
6	Good/Ideal	Good/Ideal	Bypass or recirculation	-	Good
7	Good/Ideal	Good/Ideal	Good	-	Very Good
8	Ideal	Ideal	Target	Good	Ideal

Columns of table 1 represent the order of priority of the individual thermal metric assessment. Whereas IT equipment reliability is the main aim of air conditioning, RCI_{Hi} is the first metric to evaluate. Secondly, RCI_{Lo} is calculated to assess the absence of over-cooling, which could bring to wasted energy. Then, RTI provide information about the occurrence of bypass or recirculation and SHI and RHI about airflow energy efficiency.

The different cases are obtained from varying individual indices rating, as shown in table 1. Considering benchmark values for each metrics, an overall evaluation is proposed with a rating varying from Poor, Acceptable, Good, Very Good to Ideal. For example, since RCI_{Hi} is at least acceptable overall evaluation is acceptable too, regardless of other indices value. Remaining indices give information about thermal management, without bringing detrimental condition for IT equipment.

3. A summary of thermal indices

The main metrics discussed in this work are summarized in table 2, whose aim is to provide a tool reference for thermal performance assessments during the operating time of a DC. For this reason, metrics based on CFD method are not considered in the following table. The table provides for each metric information on the phenomena detected by the index, the input variables to be measured for their calculation and the benchmark values reported in literature (if these values were not find in literature, they were obtained from analogies among similar metrics).

Table 2. Summary of Thermal Indices

Index	Information provided	Input Measures	Formula	Benchmark	
SHI	Recirculation extent within cold aisles	Airflow supply, inlet and outlet temperatures	(1)	target	0
				good	< 0.2
RHI	Effectiveness utilization of cold airflow	Airflow return, supply and outlet temperatures	(2)	target	1
				good	> 0.8
RCI_{Lo}	Rack cooling condition in respect of cold threshold values	Rack intake air temperatures distribution	(3a)	ideal	100%
				good	$\geq 96\%$
				acceptable	$91 \div 95\%$
				poor	$\leq 90\%$
RCI_{Hi}	Rack cooling condition in respect of hot threshold values	Rack intake air temperatures distribution	(3b)	ideal	100%
				good	$\geq 96\%$
				acceptable	$91 \div 95\%$
				poor	$\leq 90\%$
β Index	Presence of recirculation and over heating	Local airflow inlet supply and outlet temperatures	(4)	target	0
NP	Airflow infiltration into underfloor plenum	Airflow plenum, supply and return temperatures	(5)	negligible	
BP	Bypass extent within data center	Plenum airflow, return and outlet temperatures	(6)	ideal	0
				good	$0 \div 0.05$
				acceptable	$0.05 \div 0.2$
R	Recirculation extent within cold aisles	Airflow supply, inlet and outlet temperatures	(7)	target	0
				good	< 0.2
RTI	Presence of recirculation or bypass phenomena	Airflow return, supply and outlet temperatures	(9)	target	100%
				good	$95 \div 105\%$
				poor	$<70\% \wedge >130\%$

4. Conclusions

In this paper, a critical review on the most important thermal metrics for DCs is presented. For each index, both usefulness and limits were discussed in order to evaluate the capability in detection thermal management and airflow efficiency problems. Detecting airflow performance can help to infer measures to improve cooling performance, both on cooling plant and in design space. Moreover, from these measure, it is possible not only improve thermal condition for IT equipment, but also to save about 35% of HVAC energy consumption, leading a reduced cost for owner in operational stage [17], [18], [25]. Nowadays, this aim is becoming more and more important for DCs stakeholders, due to the increasing DCs energy costs and consumption.

Furthermore, these metrics can be useful for a real time feed-back concerning the air management. Indeed the normalized non dimensional nature of these metrics enables scalability across the rack, row and room levels, considering different DC sizes. However, even if some metrics can be related to a single rack, they are not always able to predict in a comprehensive way local phenomena (such as the hot spots). For this reason it is important to underline that some thermal metrics are devoted to give information on local phenomena while through others only average thermal condition can be derived. Eventually, a complete scenario on the analyzed thermal metrics was provided in a summary table, as a reference tool to follow in assessment of operational DCs.

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