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Performance assessment of cooling systems in data centers; Methodology and application of a new thermal metric

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A B S T R A C T

This paper introduces a comprehensive cooling index to assess performance of cooling systems in data centers and demonstrates its application on a real case by using CFD (computational fluid mechanics) method. The proposed methodology provides a metric for comparing and ranking of the cooling efficiency of the air distribution configurations among available designs alternatives.

1. Introduction

Data center is a facility containing computer equipment and related devices such as storage systems of a telecommunication system. These devices consist of power supply, air conditioner, fire-fighting devices and security systems [1]. Air conditioner of data centers should work full time all over the year to remove the heat added to the system by operation of different devices. Development of telecommunication industry, therefore, made data center a common element for either general or dedicated usage [2]. Heat propagation increases the temperature and causes damage to rack servers; therefore protection of system and prolonging their life by cooling the inherent devices is of crucial importance. In other words, it's very significant to design an appropriate air conditioner to protect data center from destruction caused by heating. For proper operation of devices, they should be held on a certain and proper temperature. Each IT server should receive certain amount of cool air enough for the removal of the produced heating [3]. Appropriate operation of equipment depends on proper distribution of cool air on data center and the response of supply air to the demand of components.

Computational fluid dynamics is an assisting tool to configure the hall of devices. Some indexes are used for quantitative assessment of efficient performance of cooling systems. In practice, influence of the design factors is quantified using cooling indexes such as SHI, RHI, RCI and RTI (described in detail later in Section 2) for different models where each index indicates specific aspect of operation in the cooling systems; however in some cases the mismatch among existing approaches might end up with irrelevant results which makes decision making process a challenge. To overcome the

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deficiencies of this area, this article proposes a new framework for the quantification and ranking of the performance of cooling systems in data centers by using the results of CFD analysis.

In the sequel, first we will review the existing cooling indexes and the theory behind them. Then a new cooling index is proposed for more efficient estimation of the cooling performance of the data center and finally, its application will be elaborated on a real case in Iran considering different configurations for the design of cooling system.

2. Indexes for assessing data center cooling

Shrivastava et al. [4] introduced a dimensionless parameter that is a norm of cooling performance in rack level. Noh et al. [5] used three different methods to design data center with 5–6 KW racks. In communication equipment centers three states 'horizontal air supply and return flow system model', 'underfloor air supply and overhead return flow system model', and 'overhead air supply and underfloor return flow system model' were investigated and results showed that 'underfloor air supply and overhead return flow system model' state has better performance. Cho et al. [6] assessed the performance of air distribution system to reduce energy consumption in high-density data centers. 46 models for air distribution were studied and results showed that temperature of output air of package has the most pronounced effect on flow efficiency. In addition, it stated that closing the chamber of aisle can increase the temperature of output air of package up to 22 °C (without decreasing the efficiency).

2.1. Return heat index (RHI) and supply heat index (SHI)

Sharma et al. [7] introduced two dimensionless parameters called supply heat index (SHI), and return heat index (RHI) which are used to assess the temperature performance of data center. These indexes can be used for investigation of convective air flow in equipment room with raised-floor. Energy efficiency depends not only on the type of cooling system but also on the configuration of equipment room that influences the mixing of cold and hot air. Herrlin [8] studied the return heat index (RHI) that is a measure of net level of by-pass air or net level of recirculation air in data center. Both of them have deficient effects on total energy and temperature efficiency of air in that area.

RHI and SHI indicate the mixing of input cool air flow to the rack and output hot air flow from the rack. These indexes are formulated as follows:

$$SHI = \left(\frac{\delta Q}{Q + \delta Q}\right) \tag{1}$$

$$RHI = \left(\frac{Q}{Q + \delta Q}\right) \tag{2}$$

where Q is the total heat propagation of racks and indicates the amount of cool air enthalpy increase before its entering to the rack, i.e.:

$$Q = \sum_j \sum_i m_{i,j}^r C_p\left(\left(T_{out}^r\right)_{i,j} - \left(T_{in}^r\right)_{i,j}\right) \tag{3}$$

where $m_{i,j}^r$ is the entrance flow to the ith rack in the jth row. The relation between RHI and SHI is shown below:

$$SHI + RHI = 1 \tag{4}$$

As much RHI increases, SHI will decrease and the design will approach to the ideal design of cooling system for data center. This condition shows less mixing of cool air with the output hot air from the rack. Usually RHI ≥ 0.8 (80%) is acceptable.

2.2. Rack cooling index (RCI)

Rack cooling index has been introduced by Herrlin [9]. RCI is a measure of rack cooling and consists of two equations; one indicates allowable area for low rack temperature (RCI_{LO}) and the other for high rack temperature (RCI_{HI}) [5]. As Table 1 implies, RCI_{HI} more than 95% is desirable.

Table 1
Rack cooling rate (RCIHI and RCILO) [6].

100%	Ideal
≥ 96%	Good
91–95%	Acceptable
≤ 90%	weak

Current index deals with temperature of cool air, in other words, the condition that cooled racks need to keep up their operation. When the inlet temperature of racks becomes more than maximum allowable temperature, the over temperature of the devices will occur. Summation of over temperature of each rack is called total over temperature. Under temperature appears on the other hand when the inlet temperature of racks becomes less than minimum recommended temperature. The limitation of recommended temperatures depends on the instruction that is used, usually provided by the standards and regulations.

An efficient measurement of rack cooling can be depicted using graphical presentation. RCI indexes should be shown by understandable numbers which alter between 0% and 100%. The 100% value shows that all racks have cooled by a specific guide or standard. The criterion of a harmful condition should be defined. These indexes must be independent of measurement units and also be matched with each standard which recommended minimum and maximum temperature. In this case the indexes can be used in conjunction with standards.

RCI consists of two parts which illustrates the safety of server room in both sides of temperature limitation. RCI_{HI} is defined by Eq. (5) [10].

$$RCI_{HIGH}=\left[1-\frac{Total\ Overtemperature}{Max\ Allowable\ Overtemperature}\right]\times 100\%=\left[1-\frac{\sum(T_i-T_{max-rec})_{T_i>T_{max-rec}}}{n\times(T_{max-all}-T_{max-rec})}\right]\times 100\% \quad (5)$$

RCI_{HI} is a scale of over temperature absence. 100% value represents that over temperature does not occur. As much as it decreases, the probability of over temperature increases. The interpretation of this index is shown in Table 1. Similar index can be defined considering low temperatures. RCI_{LO} is the complement of RCI_{HI}, especially when the temperature of supply is lower than what is recommended. In this situation the indexes can be used as alternate of each other. As the low temperature is less harmful for the system, the concentration should be on RCI_{HI}. RCI_{LO} is defined by Eq. (6) as below.

$$RCI_{LOW}=\left[1-\frac{Total\ Undertemperature}{Max\ Allowable\ Undertemperature}\right]\times 100\%=\left[1-\frac{\sum(T_{min-rec}-T_i)_{T_i<T_{min-rec}}}{n\times(T_{min-rec}-T_{min-all})}\right]\times 100\% \quad (6)$$

RCI_{HI} is the most significant index in designing the plant of data center and other indexes would not be studied if this index is not in the appropriate range. Increasing the rate of input air to the racks improves this index and raises the energy consumption as is inferred from Eq. (5).

2.3. Return temperature index (RTI)

RTI indicates the output air flow rate from the cooling package to the equipment such as racks. Also return temperature index shows the existence of re-circulation or by-passed air. RTI is defined by Eq. (7):

$$RTI=\left[1-\frac{T_{Return}-T_{supply}}{\Delta T_{equipment}}\right]\times 100 \quad (7)$$

If the return temperature index is more than 100%, it indicates re-circulation and if the RTI is less than 100% the flow is by-passed. Therefor the ideal percentage for this index is 100%. RCI never achieves 100% in practice; however the desired value would be feasible by enclosing the chamber of aisle.

3. Introducing a new index for assessment of data center cooling

CRAC devices are used in data center hall for transferring cool air to the racks and IT equipment by using duct or the perforated raised floor vent tiles. Main application of ADS (air distribution system) in data center is preventing the increase of temperature in IT equipment, therefore it's significant to ensure if the cool and hot air in the entrance and exit of the equipment are mixed or not. Most of the practical users of data centers do not pay enough attention to the by-passed air that is provided by the CRAC and returns to the device without use. By-passed air makes a distance between produced air temperature in CRACs and entrance air to the servers. CRACs are designed to provide low temperature and prevent the return of hot air from servers back to the inlet of them. Also by-passed air causes lack of supply air to the servers and increases re-circulation of hot air (Fig. 1). Management of air is to prevent the hot air re-circulation and cool air by-passing in the data centers that not only improves the energy consumption but also makes better temperature condition. If the air flow in the server room is managed optimally, the efficiency of system will be improved. But because of lack of information, most of the data centers can not increase cooling performance and energy efficiency. Therefore to overcome heating problem, adding more cooling equipment is preferred instead of improving the cooling operation. Air management of server room consist of all steps of transferring cool air provided by CRAC to the IT servers and returning hot air to the CRAC after neutralizing the heat production. The factors which inhibit the air flow such as re-circulation and by-pass (as shown in Fig. 2) decrease the cooling efficiency and produce defective cycle of local temperature raise.

Main goal of this paper is to offer the optimum state of investigated hall not only by comparing several parameters such

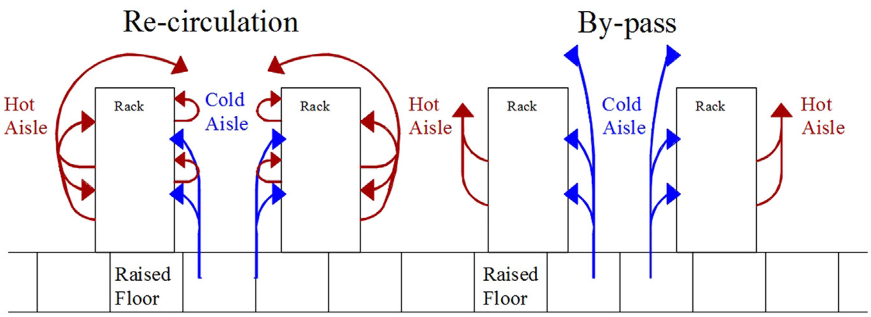

Fig. 1. Air re-circulation and by-pass in data center racks [2].

as thermal contour, outlet and inlet temperature of packages and racks but also by studying the coefficients of RCI, RTI, RHI, SHI and appropriate air flow. All these indexes assess only a limited aspect of cooling operation; therefore it is not possible to have a comprehensive study of the system. A new index should be introduced to indicate the results of whole indexes. In this paper a new index is presented which is called CCI (comprehensive cooling index). This index includes not only previous indexes but also average temperature of cool and hot aisles between racks. Eq. (8) is suggested for CCI index:

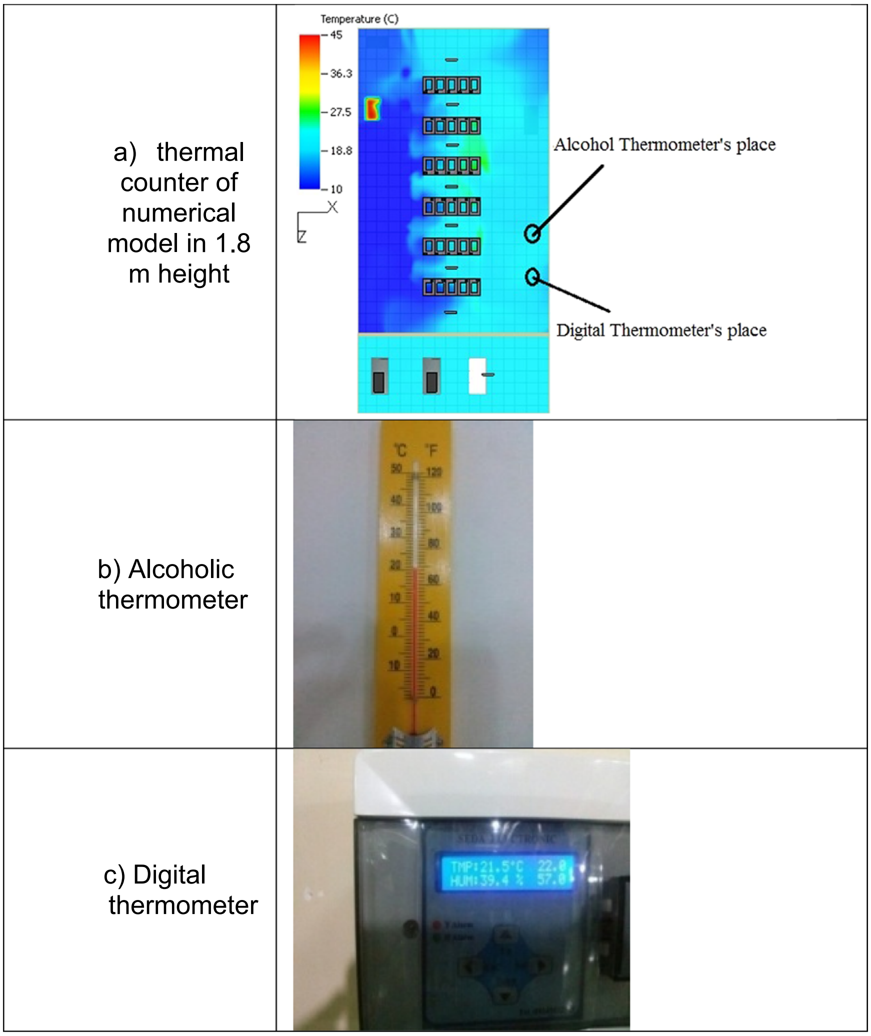

Fig. 2. Thermometer of Marand-PC data center; (a) thermal counter of numerical model, (b) Measured Temperature by Alcoholic thermometer, (c) Measured Temperature by Digital thermometer.

$$CCI = (2\times SHI) + \left(\frac{100 - RCI_{HI}}{100}\right) + \left(\frac{100 - RTI}{100}\right) + \left(\frac{ATA - T_{out}}{ATA}\right) \tag{8}$$

All the indexes should be dimensionless and not in percentage form to balance the indexes. As the summation of SHI and RHI is one, 2 times of SHI is used in Eq. (9). As much as RC_{HI} and RTI are close to 100 and also average temperature of aisles (ATA) is close to outlet temperature of package, ideal condition will be achieved. Therefore the lower the CCI values the better the design performance. Finally by calculating the number of CCI and comparing them, the models are sorted by operation and optimum state.

4. Development of numerical model and calculation of CCI for different configuration of data center

In this paper, CFD method is used for analyzing and modeling of data center. Primary data center of Marand is selected and simulated as a sample of telecommunication data centers in Iran. The design factors affect the efficiency of data center air flow, therefore several physical conditions based on standard modulus of design and architecture variables are investigated. Air flow in data center is turbulent and an appropriate turbulent model should be selected for simulation. Previous investigations indicated that k-ε turbulent model has better performance and produce results in good agreement with experimental data in comparison to the k-ω, SST, RSM and RNG k-ε models [11–13].

4.1. Governing equations

Data center is simulated by SIGMA DC 6 package software where basic equations are solved in a steady-state, turbulence and incompressible 3D field [12,14]. Considering the turbulence air flow on data center, for numerical modeling of incompressible flow on aisle of it, not only the equation of state of gas and equations of conservation of mass, momentum and energy but also a turbulence model must be used. The 3D equations of flow field for conservation of mass, momentum and energy is provided in the following:

$$\frac{\partial}{\partial x_i}\left(\rho u_j\right) = 0 \tag{9}$$

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)\right] + \frac{\delta}{\delta x_j}\left(-\bar{\rho}\,\bar{u}_i'\bar{u}_i'\right) \tag{10}$$

$$\frac{\partial}{\partial x_i}\left[u_i\rho\left(h + \frac{1}{2}u_j u_j\right)\right] = \frac{\partial}{\partial x_j}\left[k_{eff}\frac{\partial T}{\partial x_j} + u_i(\tau_{ij})_{eff}\right] \tag{11}$$

$$k_{eff} = K + \frac{c_p\mu_t}{Pr_t} \tag{12}$$

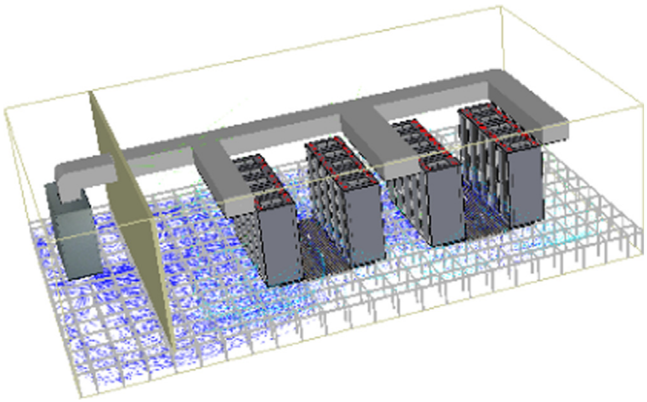

Fig. 3. A sample of modeled data center.

Table 2
Numerical results of Marand-PC data center.

		CFD Results
Alcoholic thermometer of model	21.1 °C	21.0
Digital thermometer of model	21.8 °C	21.5

And also the ideal gas model is used for simulation since air is used as working fluid.

$$p = \rho RT \tag{13}$$

Data center has low temperature air flow and small value of Mach number; therefore incompressible, non-viscous and irrotational air flow is expected. This assumption is becoming less accurate around the racks and walls because of thick boundary layer but a precise model is achieved [14,15].

Finite volume method is employed to solve above equations. For accurate calculation, discretization of the continuity, momentum and energy equations is done by second order method [14]. In addition because of incompressible working fluid, SIMPLE algorithm is employed to make the velocity and pressure dependent. Segregated Solver algorithm is employed to solve the equations.

4.2. Boundary condition and inlet

According to the thermal architecture of data center are presented hall, following assumptions for definition of the systems:

1. Location and amount of inlet flow is known and measurable. According to the catalog of blower fan of CRAC, flow rate is about 7000 CFM, outlet section of blower is 8 ft^2 and the velocity of outlet air in blower is about 875 $\frac{ft}{min}$ (4.4 $\frac{m}{s}$).
2. Velocity boundary condition for each rack in data center is to consider the velocity of air flow in cool and hot aisle as inlet and outlet velocity respectively (Fig. 3).
3. Location and amount of return flow to each CRAC is following the steady state condition.
4. Location and amount of cooling load in the room is known and measurable.
5. Walls of data center hall are isolated, therefore it is assumed to be adiabatic and the effect of radiation is not considered.

Table 3
dimensions of hall and thermal load of equipment.

96 m^2	Area of hall
4 m	Height of hall
0.64 m	Height of under floor
20	Number of racks
3 KW	Thermal load of each rack
5.59 KW	Thermal load of cooling system
65.59 KW	Total thermal load
87.92 KW	Cooling capacity of package

Table 4
Models description.

Model 1	Downward flooded package blowing from the front of aisle and recirculate the air to the front of package
Model 2	Downward flooded package blowing from the front of aisle and recirculate the air to the top of the package using local duct to the hot aisles
Model 3	Upward package blowing from the front of aisle using local duct to the cool aisles and recirculate the air to the top of the package using local duct to the hot aisles
Model 4	Upward package blowing from the front of aisle using local duct to the cool aisles and recirculate the air to the front of the package
Model 5	Downward flooded package from package room and recirculate the air to the front of package by recirculation chamber of package room (2.5 m height)
Model 6	Downward flooded package from package room and recirculate the air to the top of the package using local duct to the hot aisles
Model 7	Upward flooded package blowing from the exit chamber of package room and recirculate the air to the front of package by recirculation chamber of package room (1 m height)
Model 8	Upward flooded package blowing from the exit chamber of package room and recirculate the air using recirculation chamber of package room (2.5 m height) by local duct to the hot aisles
Model 9	Upward blowing package with local duct to the cool aisle and recirculate the air to the front of package by recirculation chamber of package room (1 m height)
Model 10	Upward blowing package with local duct to the cool aisle and recirculate the air using recirculation chamber of package room (2.5 m height) by local duct to the hot aisles
Model 11	Downward flooded package blowing from the front of aisle (cool aisle with enclosed chamber) and recirculate the air to the front of package
Model 12	Downward flooded package blowing from the front of aisle (cool aisle with enclosed chamber) and recirculate the air to the top of the package using local duct to the hot aisles
Model 13	Downward flooded package from package room (cool aisle with enclosed chamber) and recirculate the air to the front of package by recirculation chamber of package room (2.5 m height)
Model 14	Downward flooded package from package room (cool aisle with enclosed chamber) and recirculate the air to the top of the package using local duct to the hot aisles
Model 15	Downward flooded package blowing from the front of aisle (with partitioning underfloor) and recirculate the air to the front of package

4.3. Validation of the model

Numerical results of temperature are validated by comparing them to the measured values of 2 diverse thermometers located in data center, depicted schematically by two circles in the graphs of Fig. 2. Measured values of the PC data center are compared with the computational results obtained by CFD calculations. The result shows a very good agreement between calculated and measured values as reported in Table 2.

4.4. Modeling and problem description

Channeling, downward or upward blowing of packages, closing the chamber of cool aisle and partitioning underfloor are some design alternatives for the architecture of data center hall. Number of meshes in the current models is about $3*10^6$. This is achieved through a number of sensitivity analyses to show the independence of the results form the number of nodes.

First of all, geometry of model is simulated according to the location and dimension of racks, dimension of saloon, location and power of electrical equipment (Table 3). The heat load is calculated by the software and suitable package is

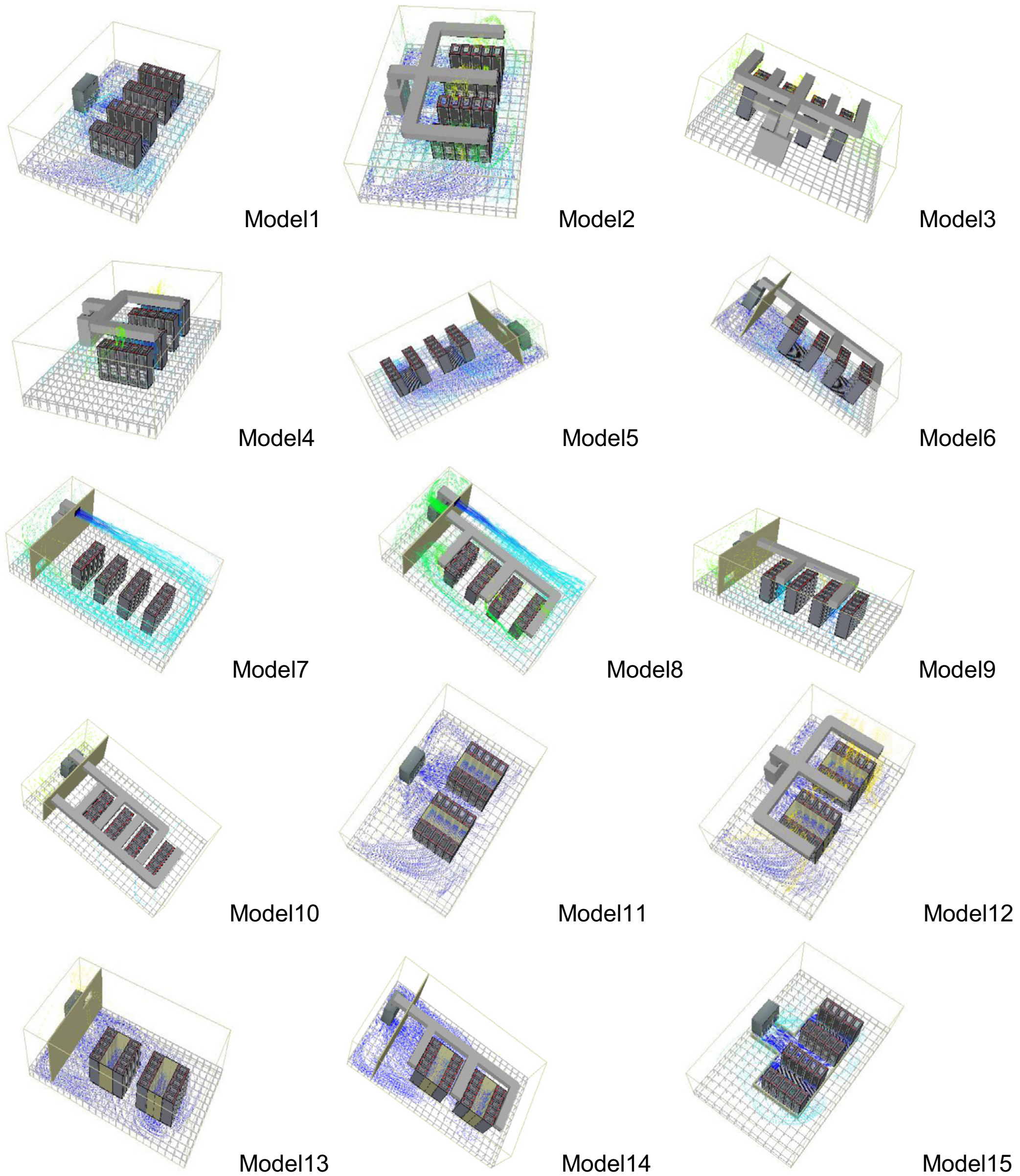

Fig. 4. Investigated models.

selected. The type of package (upward or downward blower) is selected considering the saloon and the location of racks. Finally the momentum, energy and conservation equations are solved and the outlets of equations are obtained including velocity, temperature, pressure, humidity and operation indexes (RCI, RTI, SHI and RHI).

Values of indexes (such as RTI and SHI) for different mesh dimensions and maximum size of 5 cm, 10 cm, 15 cm, and 25 cm that makes mesh numbers more than 2,900,000, is approximately constant; therefor the results are independent of mesh numbers.

4.5. Detailed room summary of Marand PC data center and introducing alternative models

One of the modeled data centers is shown in Fig. 3. Dimension, thermal load of used equipment in the hall is presented in Table 4.

A general method for specifying the CRAC capacity is to sum the 1.3 times of cooling load of data center and every other extra load [11]. In current data center the whole load is 85.27 Kw; therefore a CRAC package by the capacity of 87.92 KW (from catalog) is selected. In the practical data center an 80 KW CRAC is used and in investigated model the same capacity is simulated. Optimum rack layout and cooling distribution are studied. Different configuration of channeling and also putting the cool aisles in closed chamber is shown on Fig. 4 with their detailed explanation provided in Table 4.

5. Results

5.1. Investigated temperature points

For better thermal analyses of cool and hot aisles, a number of points (at the beginning, middle and end of aisle) are selected in 3 different heights (0, 1 and 2 m from floor) and their associated temperatures were calculated by the simulated sensors (Fig. 5). The inlet and outlet temperature of package are sensed as well as selected points.

5.2. Assessing the performance and cooling efficiency

Among all the models some of them have the same configuration and they can be classified in same groups, so that these groups can be investigated separately. We categorized them in 3 groups as described in the following.

5.2.1. Group 1: models 11–14

Current models have cool aisle with closed chamber and downward blowing packages (cooling from the floor). Model 12 and 14 which contain local channeling to return to the hot aisles have better conditions in comparison to the other models of this group. Also number 14 that has a separated package room and cool air blowing is perpendicular to the aisle direction has better results in average temperature of corridors and separation of hot and cools air in comparison to the model 12. But in re-circulation of hot air, number 12 is better than 14. Same RTI is obtained for number 11 and 13 that have no local channeling. And also model 11 has better results for SHI and average temperature of aisle in comparison with model 13. It's noticeable that all the models do not have overheating (RCI_{HI}) and also RTI is almost the same (Table 5).

5.2.2. Group 2: models 5–10

Models number 5 and 6 have downward blowing packages, other ones have upward blowing and in whole models the blowing is perpendicular to the aisles direction. Number 10 has local channeling and results are close to the ideal condition while re-circulation is more than others (Table 6). Number 9 is the second model that has acceptable operation whereas it performs weakly at re-circulation of hot air in aisles. The other model that has desirable operation is number 6. It includes only local returning channel that has the most RTI. Number 5 that is the real sample of problem comes after number 6. Both 7 and 8 configurations have the worst results in RCI_{HI} ($\leq 100\%$) that indicates the overheating of racks. It's noticeable that number 7 is in the first rank of hot air re-circulation (RTI) because of distance of return air chamber from air supply channel.

5.2.3. Group 3: models 1–4 and 15

Number 3 and 4 have upward blowing packages, other ones have downward blowing and in whole models the blowing is across to the aisles direction. Number 3 contains local channeling for supplying and returning to the aisles and is in the first rank. Second rank is number 4 that only have return local channel to the hot aisle. Number 2 comes after number 4 that only has return local channeling and gets the most re-circulation. In number 15 cool air flow is limited by partitioning the aisles that avoids the wasting in the floor. The worst operation is for number 1 that has not any channeling or partitioning where all the data centers of Iran has this configuration (Table 7).

5.2.4. Numerical calculation of CCI

As mentioned before, among the entire indexes high temperature rack cooling index (RCI_{HI}) should be studied first. RCI_{HI} shows that whether the temperature of racks is less than the universal maximum standard temperature or not. If the RCI is

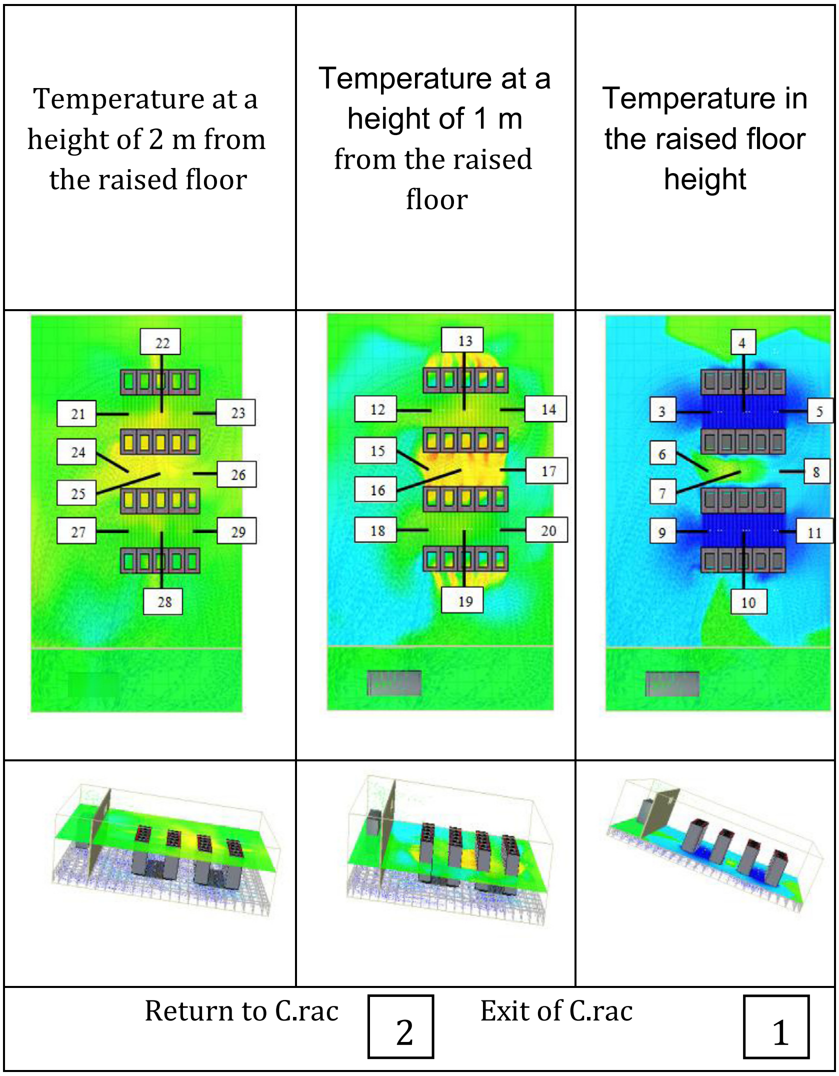

Fig. 5. Thermal assessed points of model.

Table 5
Comparing 11, 12, 13 and 14 models.

Rank 4	Rank 3	Rank 2	Rank 1	
13	11	12	14	SHI
(0.1513)	(0.1444)	(0.1439)	(0.1428)	
-	-	-	11,12,13,14	RCI-hi
			(100)	
-	-	11,13,14	12	RTI
		(115.3)	(115.2)	
13	11	12	14	ATA
(17.477)	(17.296)	(17.180)	(17.014)	

Table 6
Comparing 5, 6, 7, 8, 9, 10 models.

Rank 6	Rank 5	Rank 4	Rank 3	Rank 2	Rank 1	
8	7	5	6	9	10	SHI
(0.5414)	(0.5396)	(0.406)	(0.399)	(0.3759)	(0.3405)	
-	-	-	7	8	5,6,9,10	RCI-hi
			(98.82)	(99.63)	(100)	
6	10	9	5	8	7	RTI
(116)	(115.7)	(115.6)	(115.5)	(115.2)	(115.1)	
7	8	5	6	9	10	ATA
(25.521)	(24.392)	(22.178)	(19.774)	(17.873)	(15.525)	

Table 7
Comparing 1, 2, 3, 4 and 15 models.

Rank 5	Rank 4	Rank 3	Rank 2	Rank 1	
1	15	2	4	3	SHI
(0.4419)	(0.4156)	(0.398)	(0.3979)	(0.3845)	
-	-	1	15	2,3,4	RCI-hi
		(97.46)	(98.91)	(100)	

Table 8
Values of indexes.

ATA	RTI	RCIhi	RHI	SHI	Model
23.567	115.6	97.46	0.5583	0.4419	Model 1
20.174	115.6	100	0.6012	0.398	Model 2
15.809	115.2	100	0.614	0.3845	Model 3
17.506	115.3	100	0.6012	0.3979	Model 4
22.178	115.5	100	0.5942	0.406	Model 5
19.774	116	100	0.602	0.399	Model 6
25.521	115.1	98.82	0.4584	0.5396	Model 7
24.392	115.2	99.63	0.4566	0.5414	Model 8
17.873	115.6	100	0.6243	0.3759	Model 9
15.525	115.7	100	0.6591	0.3405	Model 10
17.296	115.3	100	0.8562	0.1444	Model 11
17.180	115.2	100	0.8566	0.1439	Model 12
17.477	115.3	100	0.8495	0.1513	Model 13
17.014	115.3	100	0.8579	0.1428	Model 14
21.632	115.9	98.91	0.5865	0.4156	Model 15

exactly equal to 100%, the racks are in an ideal temperature. As shown in Table 8, most of the models are in ideal situation however models number 1, 7, 8 and 15 have acceptable results that can be improved by either supplying more cool air or decreasing temperature of supply air. Except these 4 models, no overheating happened in the IT data center equipment.

Low temperature rack cooling index (RCI_{LO}) presents the difference between the temperatures of racks and equipment. This index is not a noticeable parameter because if the temperature becomes less than standard, it will be controlled by reducing flow rate.

Energy efficiency in air management system is presented by RTI. This index indicates the existence of re-circulation or

Table 9
Ranking of models according to the CCI index.

CCI	Model	Rank
1.027	Model (14)	**1**
1.032	Model (12)	**2**
1.037	Model (11)	**3**
1.055	Model (13)	**4**
1.387	Model (10)	**5**
1.478	Model (3)	**6**
1.516	Model (9)	**7**
1.549	Model (4)	**8**
1.604	Model (6)	**9**
1.605	Model (2)	**10**
1.651	Model (5)	**11**
1.678	Model (15)	**12**
1.768	Model (1)	**13**
1.952	Model (8)	**14**
1.968	Model (7)	**15**

by-pass air flow. As results show, in all the models RTI is more than 100%, therefore by-pass air flow does not exist and re-circulation happens. Model 7 has the least amount of RTI and re-circulation air flow that causes better cooling performance. In spite of this, model 6 has the biggest RTI and the least efficiency.

As mentioned before, RHI and SHI are the indexes for the separation rate of hot and cool air. According to the Table 8, only 11, 12, 13 and 14 models have suitable conditions regarding this index.

By using the results shown in Table 9 and Eq. (8) comprehensive cooling indexes are calculated and the models are ranked. As is apparent from this table, the calculated values for CCI fall between 1 and 2 where number 14 and 7 models are in the best and the worst state respectively.

6. Conclusion

A new index is introduced here as comprehensive cooling index (CCI) to identify the best design of data centers. The verification of the developed method is sought on meaningful case study in Iran where Marand data center is assessed in more detail. Different configurations of the data center (15 configurations) were analyzed to find out the most desirable design of the cooling system. Based on the obtained results, the following conclusion is derived:

1) Cooling systems by downward blowing have more cooling efficiency in comparison to upward blowing packages.
2) Not only closing the chamber of cool aisles but also local channeling of hot aisles improves the efficiency of cooling system.
3) Closed chamber cooling system has better performance than cooling system with normal under floor.
4) Conducting cool air to the IT equipment by either channeling or partitioning is useful for improving the efficiency of cooling system where channeling is more effective than partitioning.
5) If the cool air flow is across the aisle direction better results are obtained than perpendicular configuration.

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