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Exergy-based Performance Metrics to Evaluate Irreversibility in Data Centre Environment Airspace

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Abstract: IT equipment and systems, housed in data centres, consume a considerable amount of electricity. Most of the electrical energy consumed by the data centre IT equipment is released in the form of heat. From a second law of thermodynamics analysis point of view, the mixing of hot and cold air streams in the room caused by hot air recirculation is an irreversible process, leading to wasted work potential in data centres.
The work presented here, proposes an exergy based performance metric to identify inefficiencies in the data centre. Towards this, a numerical analysis of flow and temperature distribution of a raised-floor data centre is conducted in order to evaluate the thermal performance of the data centre. Subsequently, from flow patterns and temperature profiles, a detailed exergy analysis of the data centre is performed to get a better understanding of the room airspace irreversibility. The amount of exergy destroyed in the airspace is evaluated in order to cast a light on the nature of the irreversibility. Finally, a new performance metrics based on the second law of thermodynamics are proposed and used to assess the performance of a data centre. The effectiveness of the metric is evaluated for a typical data centre. A comparison between the performance metrics based on the first and second law of thermodynamics as well as the limitations of the newly derived performance metrics are discussed. It is shown that applying exergy analysis in data centres leads to optimum parametric design conditions.

Keywords: Data Centre Thermal Management, Exergy, Irreversibility, Performance Metric

Nomenclature

AE	airspace in the data centre environment
AR	airflow through racks
CV	control volume
C_p	specific heat at constant pressure (J/kg K)
EPM	exergetic performance metric
RHI	room heat index
SHI	supply heat index
$\dot{m}$	mass flow rate, (kg/s)
$\dot{Q}$	heat generation rate inside the rack, W
$\dot{q}$	volumetric flow rate, m^3/s

Greek symbols

α	dimensionless rack inlet temperature
β	dimensionless rack outlet temperature
$\dot{\psi}$	rate of exergy transfer, W
$\dot{\psi}_d$	rate of exergy destruction, W

Subscripts

0	reference or ground state
b	boundary
c	CRAC
CA	cold aisle
in	Inlet
out	Outlet
p	processor
r	Rack
R	Room
VR	volume region

1 Introduction

Electricity used by data centres worldwide increased by about 56% from 2005 to 2010 [1]. Electricity used in global data centres is 2010 accounted between 1.1% and 1.5% of total electricity use. For the US that number was between 1.7 and 2.2% [1]. In the face of rapidly escalating energy costs and the fact that data centres are contributing to global greenhouse gas emissions at a similar rate as the airlines, organisations are realising that increased data centre efficiency can simultaneously reduce costs and increase business agility [2]. On the other hand, cooling accounts for approximately 37% of electricity usage within a well-designed data centre and, in many cases, represents a significant opportunity to reduce IT energy costs [3].

A typical data centre consists of racks containing servers and IT systems, computer room air conditioning (CRAC) units, and air distribution systems to supply the cold air to the server racks and take the hot exhaust air from the racks back to the CRACs. As heat dissipation in data centres rises, inefficiencies such as hot air recirculation causing hot-spots and cold air bypass leading to short-circuiting of CRACs will have a significant impact on the thermal manageability and energy efficiency of the cooling infrastructure. Therefore, an efficient thermal management and cooling of high-powered electronic equipment is a significant challenge in data centres. Computational fluid dynamics (CFD) is an excellent tool to study the cooling issues in data centres. In the last decade, extensive research has been conducted to study thermal management in data centres using CFD [4-10]. These studies can be generally classified into the following categories:

- Investigation of the various cooling approaches.
- Identification of cooling issues in the data centre, and the impact on the thermal performance.
- Analysis of the air flow distribution systems proposed for data centres.
- Development of some performance metrics to evaluate the data centre cooling efficiency.

Few performance metrics have been proposed by previous researchers to evaluate the thermal behaviour of data centres. Rack cooling index (RCI) [11], supply heat index (SHI) and room heat index (RHI) [12] are some of these metrics which are mostly based on local temperatures, such as rack inlet and outlet temperatures, to investigate how effectively equipment racks are cooled and how significant is the impact of hot and cold air mixing on data centre performance.

The concept of exergy is another tool that maybe used to address the cooling inefficiencies in data centres, proposed by Shah et al. [13-16]. They proposed a formulation to analyse the multi-component data centre thermal management by introducing some non-dimensional parameters. A multi-CRAC system is decomposed into single-CRAC subsystems, and the effect of each CRAC unit is analysed on the zone of influence of each cold aisle [13, 14]. In addition, they proposed an exergy-based model to study the effect of recirculation patterns in air-cooled data centres by presenting exergy loss maps in data centre airspace. The relative magnitude of exergy loss in different components of data centres was also highlighted [15].Their work has demonstrated the viability of using exergy-based metrics for the concurrent assessment of the thermal manageability and energy efficiency of data centres. McAllister et al. [17] studied computational strategies to enhance the usefulness of the aforementioned exergy-based approach.

In this paper, exergy analysis of a data centre airspace is investigated in further detail in order to analyse the effect of hot air recirculation and infiltration in the data centre environment as well as the evaluation of the data centre exergetic efficiency. Data centre airspace is divided into two main regions: data centre environment airspace excluding racks (AE), and airflow inside the rack (AR). The control volumes for these regions are depicted in Figure 1. It is assumed that the CRAC unit is outside the room control volume. In all the analyses presented here, the exergy destruction in the under-floor plenum is not investigated. Therefore, AE covers the airspace from the floor to the ceiling excluding the racks. In previous work [18] detailed analyses of the exergy destruction for the data centre room airspace comprising the environment airspace (AE), and airflow inside the rack (AR) was estimated.

In this work, investigation on irreversibility in AE region is provided at different CRAC flow rates. The effectiveness of the previously proposed exergy-based metric [18] is discussed. Furthermore, detailed comparison of the first-law and second-law-based metrics is also provided. From the results, an optimum design condition for the CRAC unit is proposed.

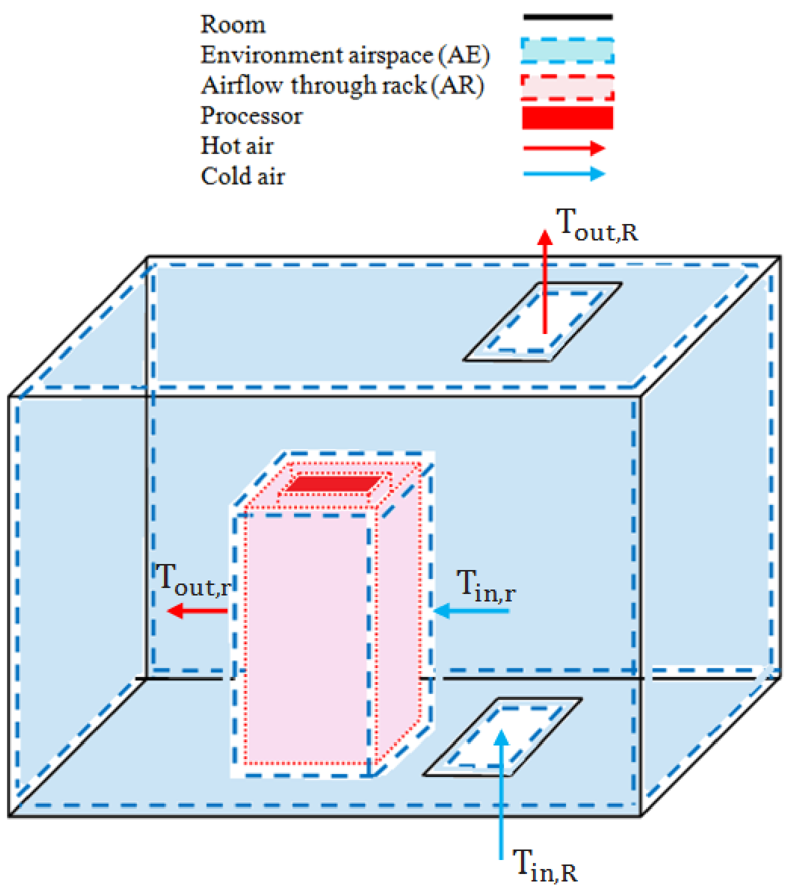


Figure 1: Airspace control volumes in the data centre

2 Analysis of Exergy Destruction

Exergy represents the maximum amount of useful work that can be theoretically obtained from a system. The property exergy serves as a valuable tool in determining the quality of energy and comparing the work potentials of different energy sources or systems [19].

In particular, exergy analysis gives efficiencies which provide a true measure of how close the actual performance is to ideal, and identifies more clearly the causes and locations of thermodynamic losses as compared to energy analysis. Consequently, exergy analysis can assist in improving and optimising system designs. Exergy losses, in addition, provide quantitative measures of deviations from the ideal scenario. Exergy losses also allow the location, type and cause of a loss, or inefficiency, to be clearly identified. This information is critical to increase exergy efficiency [20]. In addition, exergy measures how far the system is from the specified ground state. Thus, if a particular point in the room has a high exergy loss, the cooling system is particularly inefficient at that point. Whether due to a local hotspot or mixing of hot and cold air streams, the destruction of exergy at any point in the room provides a primary indication of the existence of unwanted phenomena [21].

2.1 Exergy Destruction in Data Centre Environment Airspace

Cooling power requirements in data centres can be significantly increased by inappropriate installation of air handling systems and rack layouts that allow the hot and cold air streams to mix. The main sources of exergy losses for data centre environment are associated with irreversibilities and are described qualitatively for the mixing of hot and cold streams in the room air-space caused by hot air recirculation leading to wasted work potential. Any irreversibility in the data centre environment results in a decline in the quality of the energy.

Therefore, a second law assessment allows one to quantify the irreversibilities causing cooling inefficiencies in data centre airspace. Shah et al. [22] suggested equation (1) to calculate exergy destroyed in the airspace by performing an exergy balance on the data centre, for a fixed control volume taken along the inside walls of a data centre. In this equation, the first and second terms represent the net exergy transfer through the room by mass transfer (enthalpy and entropy terms respectively), and the third term indicates the exergy transfer by heat transfer from the rack to the room,

$$\dot{\psi}_{d,airspace} = \dot{m}_R \left[c_p \left(T_{in,R} - T_{out,R} \right) - T_0 \left(c_p \, ln \left(\frac{T_{in,R}}{T_{out,R}} \right) \right) \right] + \dot{Q} \left(1 - \frac{T_o}{T_p} \right) \tag{1}$$

where T_p is the temperature at which heat production occurs in the servers. This calculation is then based only on supply air temperatures from CRAC units to the room, the average return air temperature from room to CRAC units calculated from the CFD results, and the heat dissipated from server racks in the data centre room. Equation (1) takes into account the total volume of the data centre airspace (AE+AR), and gives total destroyed exergy in the room airspace, and does not provide any information regarding the magnitude of the destroyed exergy in the environment airspace resulting specifically from hot air recirculation. Moreover, it is not useful to employ the exergy destruction calculated this way to compare the effect of the rectification designs (applying different geometry configurations with the same CRAC airflow and supply temperatures [23]) on data centre performance, since $\dot{Q}$, T_{in}, T_{out} and $\dot{m}$ for all modifications are equal.

Therefore, to investigate the effect of recirculation pattern on exergy destruction in AE, and in order to validate the irreversibility maps, a control volume is taken in such a way that it excludes volumes occupied by server racks and only includes the data centre environment airspace as shown in Figure 1.

Based on this control volume, the equation for exergy destruction in the airspace environment (AE) is obtained as following:

$$\dot{\psi}_{d,AE} = \sum \dot{m}_r \left[c_p(T_{out,r} - T_{in,r}) - T_0 \left(c_p ln \left(\frac{T_{out,r}}{T_{in,r}} \right) \right) \right] + \sum \dot{m}_R \left[c_p(T_{in,R} - T_{out,R}) - T_0 \left(c_p ln \left(\frac{T_{in,R}}{T_{out,R}} \right) \right) \right] \quad (2)$$

The equation is a function of the inlet and outlet temperatures to and from the racks and the data centre room. Therefore, it can provide the amount of exergy destruction in AE caused by hot and cold air mixing without considering destroyed exergy in the server racks. T_0 is the temperature of the reference or ground state which here is taken as the average temperature of the air entering the room via the perforated tiles.

2.2 Map of Exergy Destruction in AE

From a second law analysis point of view, the mixing of hot and cold air streams in the room caused by hot air recirculation is an irreversible process, leading to wasted work potential in data centres. Any irreversibility in the data centre environment results in a decline in the quality of the energy. Mapping of the exergy destruction in AE can result in better understanding of the causes and locations of the mixing, and leads to qualitative information for the mixing in the airspace. In data centre airspace, the pressure gradients and the change in potential energy can be assumed to be negligible. For mapping exergy destruction in AE, equation (3) has been applied, using the thermodynamic quantities (temperature and velocity) obtained from the CFD analysis. For the i^{th} cell in the room, the exergy destruction is obtained by summing up the exergy flows on the corresponding j^{th} faces of the cell [15].

$$\dot{\psi}_{d,i} = \sum_j \dot{m}_j \left[C_p(T_j - T_o) - T_o C_p \, ln \left(\frac{T_j}{T_o} \right) + \frac{V_j{}^2}{2} \right] \quad (3)$$

In this equation, T_j on the face of the i^{th} cell is calculated using an upwind scheme applying the temperatures in the neighbouring cells, and V_j is estimated as the average velocity of the i^{th} cell and the neighbouring cell. It is inferred that the exergy destruction for each cell is mesh dependent. However, by mapping the exergy destruction for the mesh size obtained from the grid dependency study, the value of the exergy destruction in each cell effectively presents the local probable mixing in that location. The exergy map of Shah et al. [15] appears to be the summation of the corresponding values in the individual cells over an arbitrary air volume region. Although the overall recirculation pattern can be identified, it does not provide the information of the location at which the higher amount of mixing occurs. For the validation of the exergy destruction, the summation of the relevant quantities in each cell of AE is compared with equation (2).

2.3 First-law and Second-law Based Performance Metrics

Supply heat index (SHI) and room heat index (RHI) are first-law based non-dimensional parameters suggested by Sharma et al. [12] and are given by equations (4) and (5), respectively. They can be used to evaluate the infiltration of hot air to the cold aisle and mixing of hot return air from server racks with cold air streams, prior to returning to the CRAC units.

$$SHI = \frac{\sum_j \sum_i \left((T_{in.r})_{i,j} - T_0\right)}{\sum_j \sum_i \left((T_{out.r})_{i,j} - T_0\right)} \tag{4}$$

$$RHI = \frac{\sum_k (\dot{m}_C)_k C_p ((T_{in.C})_k - T_0)}{\sum_j \sum_i (\dot{m}_r)_{i,j} C_p \left((T_{out.r})_{i,j} - T_0\right)} \tag{5}$$

In SHI, the numerator denotes the sensible heat gained by the air in the cold aisle before entering the racks while the denominator represents the total sensible heat gained by the air leaving the rack exhausts.

As discussed in [18], equation (2) for the exergy destruction in AE region can be rearranged in terms of the SHI and RHI as follows:

$$\dot{\psi}_{d,AE} = T_0 c_p ln \frac{\left[\frac{\dot{m}_r}{\dot{m}_R}(\alpha - 1)\frac{RHI}{SHI} + 1\right]^{\dot{m}_R}}{\left[\left(1 - \frac{1}{\alpha}\right)\frac{RHI}{SHI} + 1\right]^{\dot{m}_r}}$$

$$\alpha = \frac{T_{in,r}}{T_0} \tag{6}$$

where α is defined as the ratio of the rack inlet temperature to the reference temperature. This dimensionless parameter can be treated as a metric for the behaviour of the rack inlet temperatures with respect to the reference temperature.

As the rack inlet temperature reaches the reference temperature ($\alpha = 1$), SHI becomes zero. This shows that the performance of the data centre is ideal and there is no hot air infiltration to the rack inlet and no mixing occurs in the cold aisle. However, depending on the ratio of the mass flow rates entering the rack and the room, the exergy destruction in AE may be ever increasing while $\alpha = 1$. In this case ($\alpha = 1$), still there is irreversibility in AE, but the critical location of the mixing shifts from the cold aisle to the ceiling region. Equation (7), shows the resultant correlation for the exergy destruction when $\alpha = 1$.

$$\dot{\psi}_{d,AE} = T_0 c_p ln \frac{\left[\frac{\dot{m}_r}{\dot{m}_R}(\beta - 1) + 1\right]^{\dot{m}_R}}{[(\beta - 1) + 1]^{\dot{m}_r}}$$

$$\beta = \frac{T_{out,r}}{T_0} \tag{7}$$

where β is defined as the dimensionless rack outlet temperature. According to equation (7), the ideal scenario occurs when the entire mass flow rate entering the room enters the racks and the temperature of the cold air entering the room is equal to the rack inlet temperature. Therefore, second-law based optimal scenarios (at specific room flow rates and temperatures of the data centre) can be estimated in which the minimum exergy destruction is reached. However, the results based on the first-law based metrics may indicate otherwise.

2.4 Exergy-based Performance Metric

AE can be divided into four main volume regions; cold aisle and hot aisle (from the floor to the rack height), ceiling region (from the top of the rack to the ceiling) and the region between the rack and the wall of the CRAC unit. In a data centre room, depending on the room layout, the supplied cold air and the rack heat load, the main percentage of the irreversibility occurs in the ceiling region (because of the hot air recirculation), cold aisle (due to the hot air infiltration) or hot aisle (due to the mixing of the exhaust hot air with the neighbouring cold air).

An exergetic performance metric (EPM) given by equation (8) is proposed [18] to evaluate the performance of any of the aforementioned volume regions in AE with respect to the total exergy destruction in AE.

$$EPM = \frac{\dot{\psi}_{d,VR}}{\dot{\psi}_{d,AE}} \tag{8}$$

A proper volume taken in AE can be the volume region with the base of the standard "floor" tile dimensions as a standard metric for data centres with the height taken from the floor to ceiling. By estimating the irreversibility quantities in the airspace volumes with the tile-based area, exergy destruction can provide valuable information for data centre thermal management in order to identify in which tile of the room there is considerable amount of mixing, allowing these regions to be targeted and improved in the design of the system, which is not possible through thermal-flow maps or the first-law based performance metrics. SHI and RHI provide details on which region adjacent to the racks (or which isle by applying SHI for the cluster of the racks in the desired aisle) there is mixing. On the other hand, EPM provides the amount of the mixing in any space in AE. The lower is the EPM, the better is the performance of the volume region under consideration.

3 CFD Analysis

For investigating the irreversibility in AE, the prototype data centre (as a subsystem) studied here is modelled as a 3.4× 3.2×6m enclosure located over a 60cm deep under-floor plenum, as shown in Figure 2. There is one CRAC unit with a nominal cooling load of 80kW, which supplies cold air at 15^{o}C with a fixed flow rate of 3m^3/s. The cold air is delivered to the front of the racks located in the cold aisle, and the resultant hot exhaust air from the racks is returned back to the CRAC unit. Regions in front and back of the racks, cold aisle and hot aisle are shown by red boundaries in Figure 2 (a). There are seven perforated tiles in the data centre placed in front of each rack, of 0.6m × 0.6m size, in the cold aisle. There is one row of seven racks, as shown in Figure 2 (b). Each rack is modelled as 0.6×2×1m cabinet consisting of five 1kW heat sources resulting in a heat load of 5kW per rack, with a 10^{o}C temperature difference across the rack. Steady state numerical solutions for the velocity and temperature have been obtained using FloVENT v9.2 by Mentor Graphics Mechanical Analysis [24], employing a Cartesian grid and the standard κ–ε turbulence model. For the model, grid dependency tests were conducted with the monitoring parameter being the maximum temperature in the room and the grid dependent model had 216,000 cells.

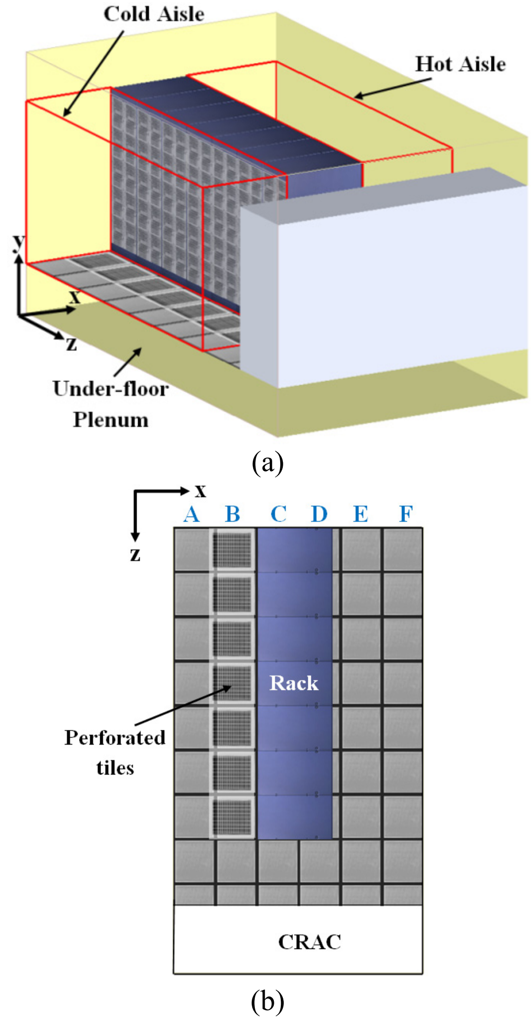


Figure 2: The Schematic of the room layout (a) orthographic view, (b) top view

4 Results

4.1 Maps of the Thermodynamic Properties

From the CFD analysis, temperature and velocity are obtained for each cell of the AE. Thus, by applying equation (3), the map of exergy destruction is provided at the middle and end of the rack row (z=2.1m and z=4.2m). Figure 3 shows thermal, velocity and exergy destruction fields in the room.

The temperature and velocity fields show regions of high gradient where significant mixing and losses may be expected. However, the exergy destruction field shows the precise locations where the temperature and velocity combine to give high exergy destruction, allowing these regions to be targeted in the design of the system. As seen in Figure 3 (c), the impact of the hot air recirculation on the exergy destruction is revealed over the top of the rack. In addition, there is considerable amount of mixing of the supply air flow before entering the rack, because of the intense temperature gradient and irreversibility due to the kinetic energy. It is observed that there is higher amount of irreversibility at the end of the rack row. Although the quantities of the exergy destruction for the current grid size is of a small order of magnitude, the trend of the exergy destruction gives qualitative information regarding the nature of the irreversibility in AE.

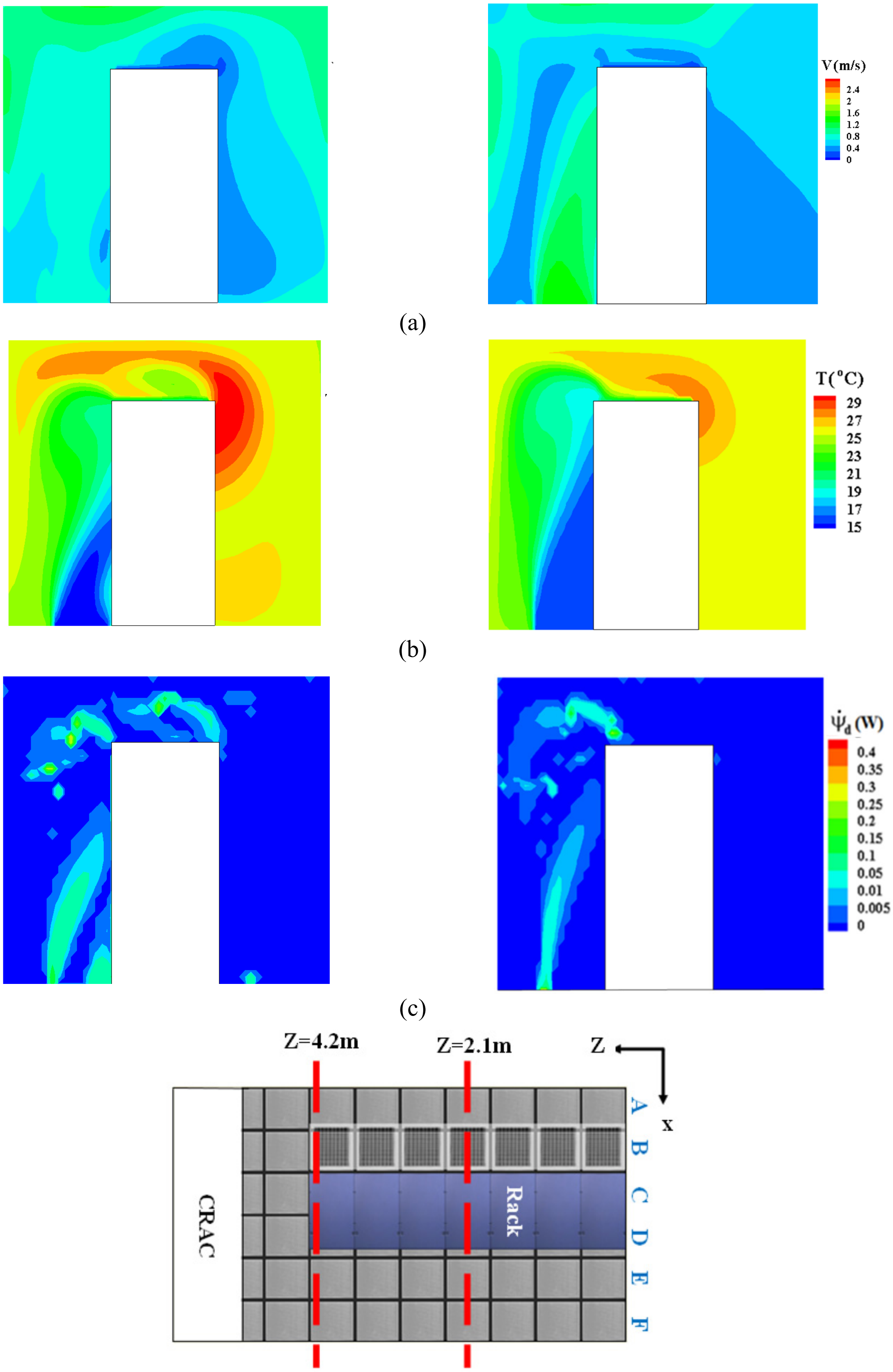


Figure 3: Contours of (a) velocity magnitude (velocity vectors are shown as well), (b) temperature and (c) exergy destruction, at z=2.1m (right side) and z=4.2m (left side)

4.2 Evaluation of the Exergy Destruction in the Room

For the configuration studied here (Figure 2) EPM is illustrated for four main regions constituting AE with three different CRAC flow rates in Figure 4. For the case study ($\dot{q}$=3m^3/s), a substantial portion of the exergy is destroyed in the cold aisle and the ceiling region because of the higher amount of mixing. However, the exergy destruction in the hot aisle is a very small portion of the exergy destruction. This will provide valuable information regarding the distribution of the exergy destruction in the main regions of the environment airspace. By increasing CRAC flow rate, exergy destruction in cold aisle decreases and shifts to the ceiling region as a result of uniform flow rate in cold aisle corresponding to reduction in hot air infiltration leading to decrease in irreversibility in cold aisle. On the other hand, there is increased mixing of hot and cold air in the ceiling region leading to higher EPM with increasing CRAC flow rates.

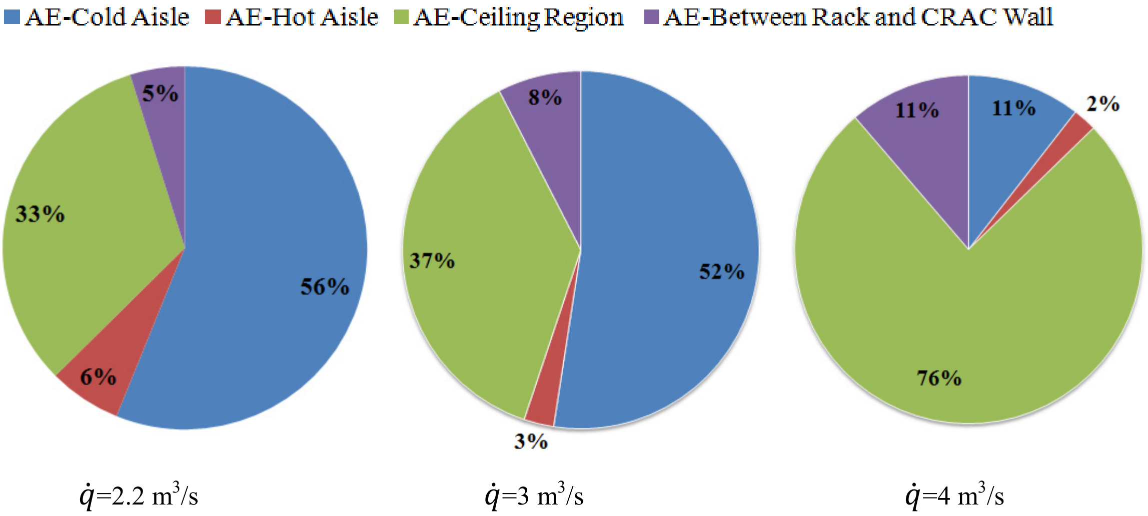
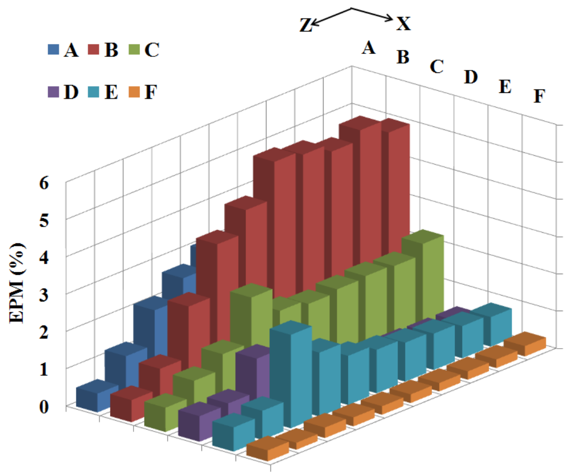


Figure 4: Variation of EPM in individual volume regions for different CRAC flow rates

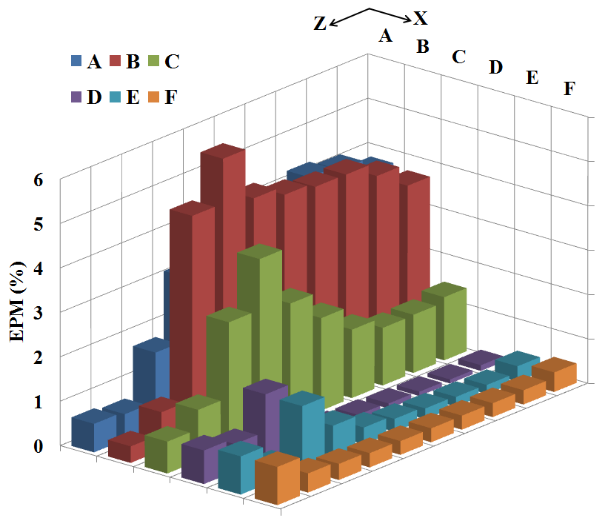
4.3 Distribution of the Exergy Destruction in Tile-based Volumes

EPM for the tile-based volume regions in AE of the room at different CRAC flow rates is shown in Figure 5. It is apparent in which tile-based region of the room there is a considerable amount of mixing, allowing these regions to be targeted and improved in the design of the system which is not possible through thermal-flow maps or the first-law based performance metrics. The distribution of EPM throughout the data centre environment gives valuable information on how irreversibility varies on each tile-based volume by changing the CRAC flow rates.

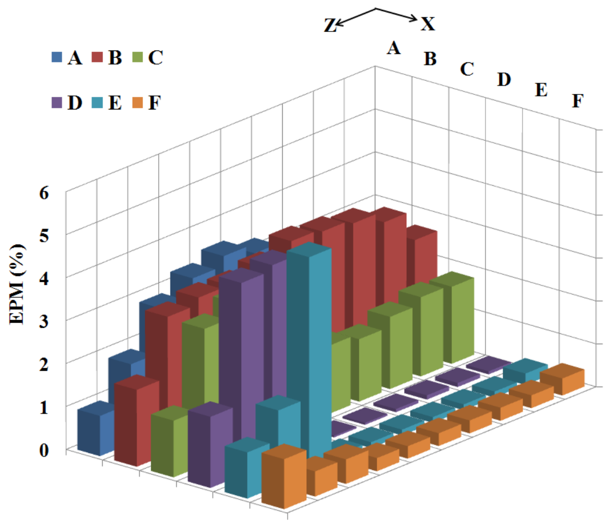
Knowing EPM in each region of the data centre leads to a better decision on the application of the rectification design implemented for the layout of the data centre room, such as for applying ceiling ducts, the places where the ducts should be used can be selected, which cannot be readily achieved by locating the regions with hot spots or using the first-law based metrics in the room.



$\dot{\boldsymbol{q}}$=2.2 m^3/s



$\dot{\boldsymbol{q}}$=3 m^3/s



$\dot{\boldsymbol{q}}$=4 m^3/s

Figure 5: EPM in tile-based volume regions

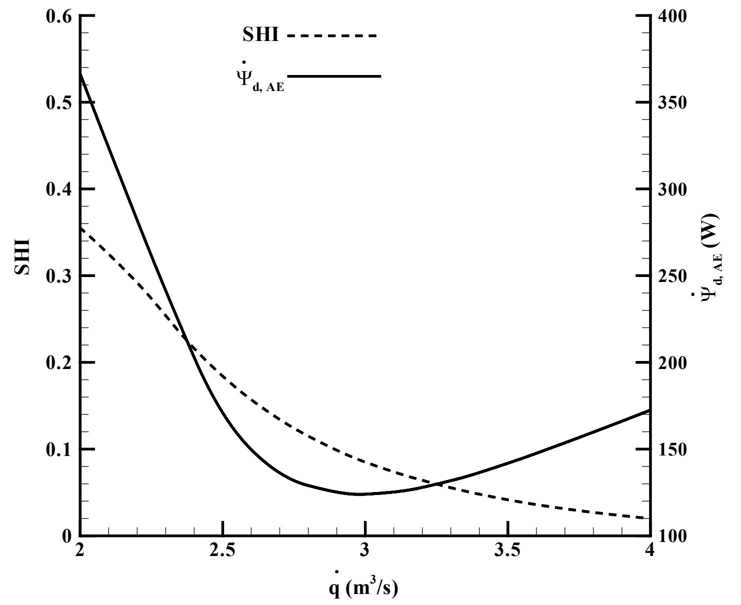
4.4 Comparison of first-law and second-law based metrics

Figures 6(a) and 6(b) show the variation of the SHI and exergy destruction in the data centre as a function of the CRAC mass flow rate and rack heat load respectively. As shown in Figure 8(a), SHI decreases by increasing the CRAC flow rate. This is obvious because of the uniform cold air occurring with increased CRAC flow rate at the rack inlet. Therefore, the hot air infiltration to the cold aisle drops and the rack inlet temperature approaches the reference temperature (air temperature adjacent to the perforated tile) leading to reduced SHI. On the other hand, there exists minimum value for AE exergy destruction at 3 m^3/s and rises afterwards. In other words, the minimum exergy destruction for AE calculated from CFD results occurs when the entire room mass flow rate equal to the mass flow rate entering the rack ($\dot{m}_R = \dot{m}_r = 3m^3/s$). This is verified by equation (6) when $\dot{m}_R$ equals $\dot{m}_r$ as following:

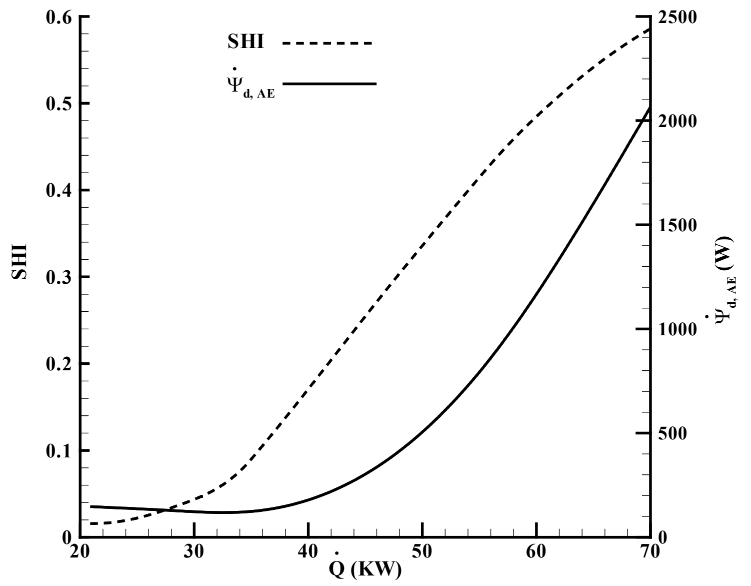
$$\dot{\psi}_{d,AE} = T_0 c_p \ln\left[\alpha \times \left(1 + \frac{1-\alpha}{\beta}\right)\right]^{\dot{m}_R} \quad (9)$$

Equation (9) gives the minimum exergy destruction in AE. Practically, there is some amount of hot air recirculation in any data centre environment, and it is not always possible to convey the entire room mass flow rate to the racks. Therefore, there should be a trade-off between the first law and second law based performance. In this regard, according to Figure 6(a), the flow rate in the range of the 2.4 and $3.2m^3/s$ can be taken as the CRAC design flow rate.

At the constant CRAC flow rate ($3m^3/s$); the behavior of SHI and AE exergy destruction is studied by increasing the rack heat load, as shown in Figure 6(b). As a result, the rise in rack inlet temperature results in increasing behavior of the SHI. The same trend is observed for AE exergy destruction except a minimum value occurring at the rack heat load of 35KW which is the corresponding heat load to the minimum exergy destruction obtained from equation (9).



(a)



(b)

Figure 6: Variation of SHI and exergy destruction with (a) CRAC mass flow rate, (b) data centre rack heat load

5 Concluding Remarks

A detailed analysis of the exergy destruction in the data centre is performed to develop a better understanding of the room airspace irreversibility. CFD analysis of a prototype data centre is performed and from the resultant thermodynamic quantities, the map exergy destruction is obtained. Results show that areas of irreversibility and loss may be more precisely located using the exergy destruction than by considering only the temperature and velocity fields. An exergy-based performance metric (EPM) is proposed and is compared with the metric on the basis of the first-law. By estimating the irreversibility quantities in the airspace volumes with the tile-based area, exergy destruction can provide valuable information for data centre thermal management in order to identify in which tile of the room, there is considerable amount of mixing, allowing these regions to be targeted and improved in the design of the system which is not possible through thermal-flow maps or the first-law based performance metrics. Knowing EPM in each region of the data centre leads to a better decision for the application of the rectification design implemented for data centre room. For example, by applying ceiling ducts, the places where the ducts should be used can be selected, which cannot be easily achieved by locating the regions with hot spots or using the first-law based metrics in the room. A detailed comparison of the first-law based and second-law based metrics is investigated. It is shown that applying exergy analysis in data centres leads to optimum parametric design conditions.

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