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Second Law Analysis of Small Data Centre Airspace

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Abstract

The energy required for data centre cooling is a key fraction of total energy consumption in data centres. From a Second Law analysis point of view, the mixing of hot and cold streams in the room airspace caused by hot air recirculation is an irreversible process leading to wasted work potential in data centres. Therefore, a Second Law assessment allows one to quantify the irreversibilities leading to inefficiencies in data centre airspace. In this paper, numerical analyses of flow and temperature fields are conducted in order to evaluate the thermal performance of the data centre. Subsequently, from flow patterns and temperature profiles, First Law and Second Law of thermodynamic analysis of air cooled raised-floor data centres have been performed to reach a better thermal manageability, which will lead to more cost-effective optimum designs. The effectiveness of the exergy-based metric has been studied by analysing the impact of CRAC flow rates. It is shown that using both First Law and Second Law based metrics can be effective tool in evaluating the data centre performance.

Nomenclature

AE	airspace in the data centre environment
AR	airflow through the racks
C_p	specific heat at constant pressure (J/kg K)
$\dot{m}$	mass flow rate, (kg/s)
$\dot{Q}$	heat generation rate inside the rack, W

Greek symbols

$\dot{\psi}$	rate of exergy transfer, W
$\dot{\psi}_d$	rate of exergy destruction, W

Subscripts

0	reference or ground state
c	CRAC
in	inlet
out	outlet
r	rack
R	room

Introduction

The demand for computing resources and network infrastructure over the past decade has resulted in the evolution of high power density data centres. IT systems, housed in data centres, consume a considerable amount of energy. 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 [1]. 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 shown in Figure 1. 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 (see Figure 1). Therefore, an efficient thermal management of high-powered electronic equipment is a significant challenge for cooling of data centres.

Computational fluid dynamics (CFD) is an excellent tool to study the cooling issues in data centres. Since 2001, extensive research has been conducted to investigate cooling issues in data centres using CFD [2-8].

The concept of exergy can be used to address the cooling inefficiencies in data centres, proposed by Shah et al. [9]. They proposed an exergy-based model to study the effect of recirculation patterns in air-cooled data centres on the exergy destruction by presenting exergy loss maps in data centre airspace. 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. [10] studied the effect of room flow rate, supply temperature and rack heat loads on the data centre room exergy destruction with varying grid sizes. They modelled a small fictitious data centre consisting of a row of eight rack, two CRACs and eight perforated tiles. It was concluded that the data centre operating conditions dictate the largest justifiable grid size and consequently the fastest run times.

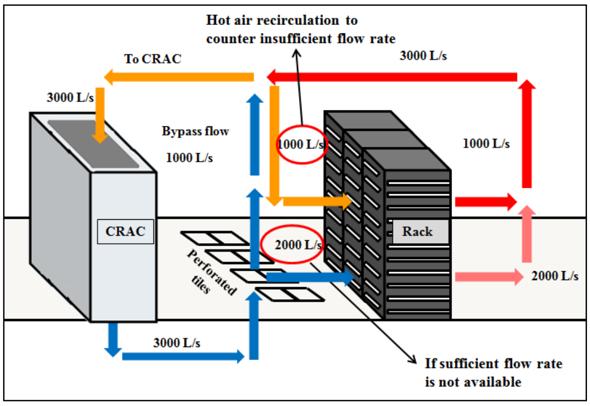


Figure 1. A typical data centre with hot air recirculation and cold air short-circuiting (total cold air supply of 3000 l/sec).

In previous work [11], the map of the exergy destruction for a prototype data centre was presented, showing critical points of irreversibility in the data centre environment. Moreover, an exergy-based performance metrics was introduced, and compared with First Law based performance metric. In this paper, CFD analysis of a typical data centre has been carried out. The effectiveness of the exergy-based metric has been studied by analysing the impact of CRAC flow rate.

Thermodynamic First Law and Second Law Based Performance Metrics

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 airspace 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 or increasing exergy destruction.

Data centre airspace can be divided into two main zones: data centre environment airspace excluding racks (AE), and airflow inside the racks (AR). The control volumes for these regions are depicted in Figure 2. 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 considered. Therefore, AE covers the airspace from the floor to the ceiling excluding the racks.

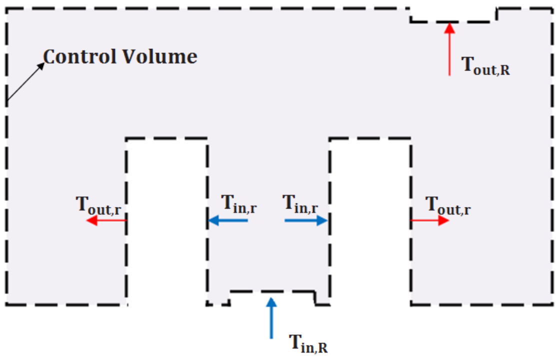


Figure 2. Control volume taken inside the room excluding server racks.

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

$$\dot{\psi}_{d,AE} = \sum \dot{m}_r \left[C_p (T_{out,r} - T_{in,r}) - T_0 \left(C_p ln \left(\frac{T_{out,r}}{T_{in,r}} \right) \right) \right] + \sum \dot{m}_R \left[C_p (T_{in,R} - T_{out,R}) - T_0 \left(C_p ln \left(\frac{T_{in,R}}{T_{out,R}} \right) \right) \right] \quad (1)$$

Supply heat index (SHI) is a First Law based non-dimensional parameter suggested by Sharma et al. [12] and given by equation (2). It 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.

$$SHI = \frac{\sum_j \sum_i \left((T_{in.r})_{i,j} - T_0 \right)}{\sum_j \sum_i \left((T_{out.r})_{i,j} - T_0 \right)} \quad (2)$$

A detailed description of these metrics is discussed by Fakhim et al. [11].

CFD Simulation

A prototype data centre is modelled as an 8×3.2×6 m^3 enclosure located over a 60 cm deep under-floor plenum. There are two CRAC units with a nominal cooling load of 80 kW. The cold air from these CRAC units is supplied to the perforated tiles at 16°C with a flow rate of 4 m^3/sec. This 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 as shown in Figure 3. There are seven perforated tiles in the data centre placed in the cold aisle in front of each rack. The perforated tiles are of 0.6 m × 0.6 m size with 56 % opening. There are three rows of racks with 1 kW, 3 kW and 7 kW heat load respectively. Each row consists of 7 racks with the same heat load, as shown in Figure 3. The temperature difference across each rack is set as 10 °C.

Steady state numerical solutions for the velocity and temperature have been obtained using FloVENT v9.2 by Mentor Graphics Mechanical Analysis [13], 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 501,120 cells were found to be adequate.

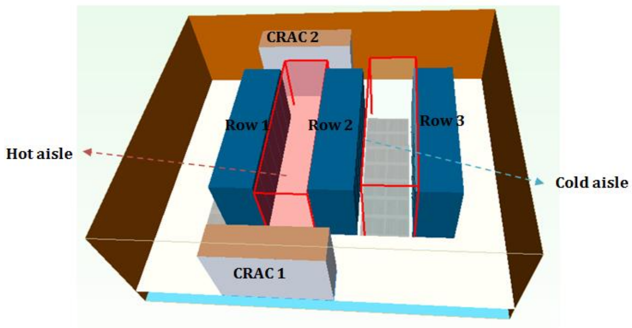


Figure 3. Schematic of the modelled data centre.

Results

The temperature distribution in the room environment for this case is shown in Figure 4. The exergy destruction is 0.55 kW with SHI of 0.09.

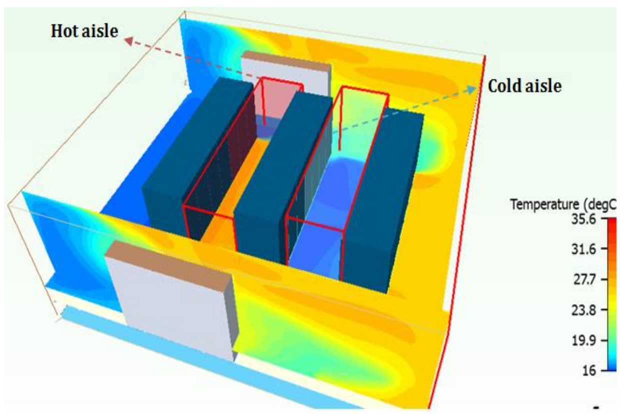
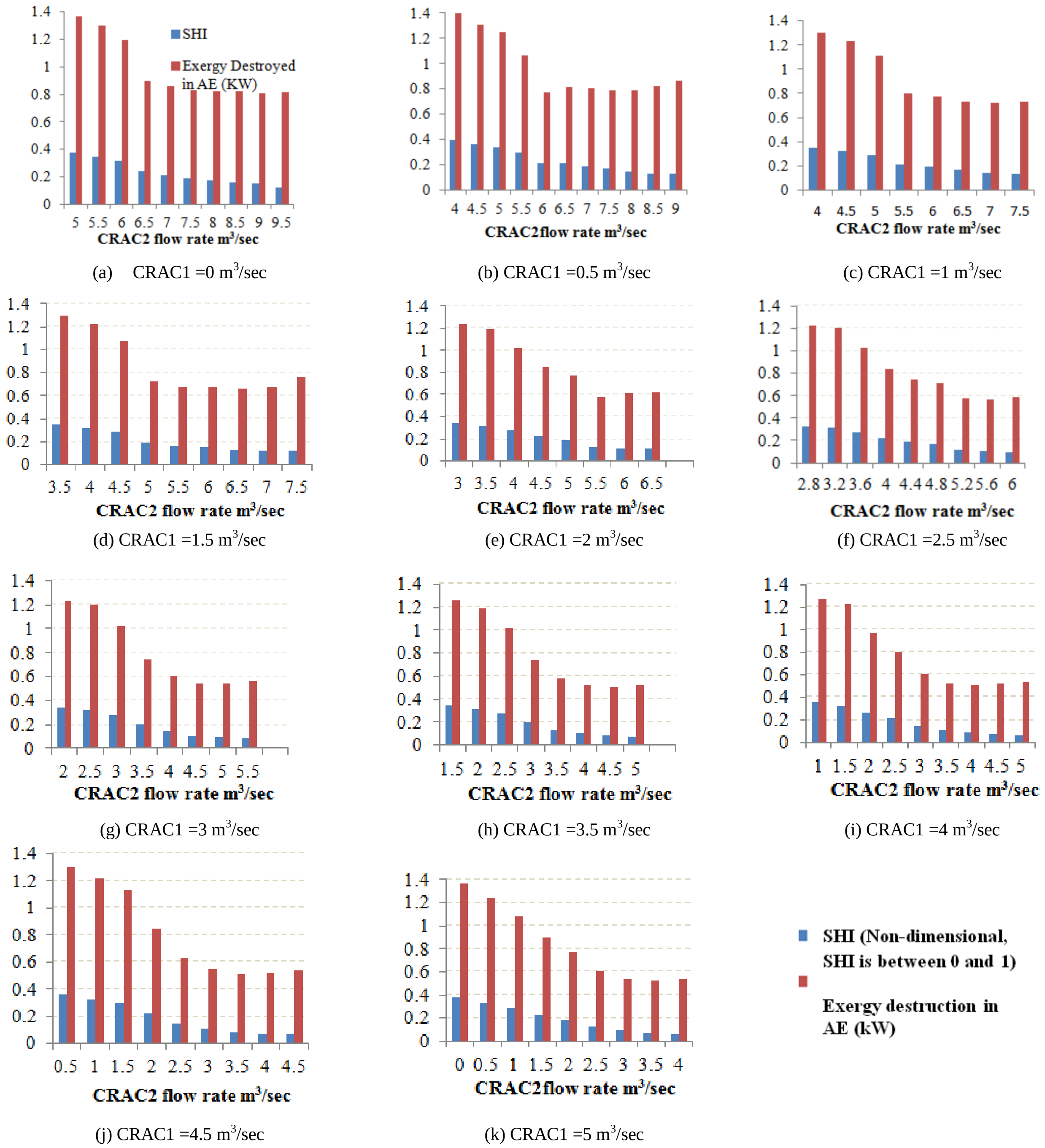


Figure 4. Temperature distribution in a room space.

Impact of CRAC Flow Rate

To study the effect of the CRAC flow rate on the data centre performance different models are investigated. In all these models, CRAC1 is specified with a fixed flow rate and the flow rate of CRAC2 varies. The results are shown in
Figure 5. It can be observed from the results that although SHI drops with increasing the flow rate of CRAC2, in all models, the minimum exergy destruction occurs when the total flow rate of the CRAC units is in the range of 8 to 8.5 m^3/sec. Also the value of minimum exergy destruction decreases as the flow rate of CRAC1 increases. The reason is that by increasing CRAC1 flow rate, the racks receive air at uniform temperature. This causes a decrease in the exergy destruction associated with the racks (first term of equation (1)) leading to decrease in exergy destruction.

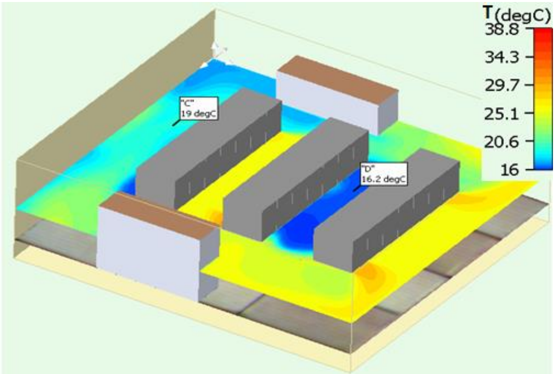


(a) CRAC1 =0 m^3/sec
(b) CRAC1 =0.5 m^3/sec
(c) CRAC1 =1 m^3/sec
(d) CRAC1 =1.5 m^3/sec
(e) CRAC1 =2 m^3/sec
(f) CRAC1 =2.5 m^3/sec
(g) CRAC1 =3 m^3/sec
(h) CRAC1 =3.5 m^3/sec
(i) CRAC1 =4 m^3/sec
(j) CRAC1 =4.5 m^3/sec
(k) CRAC1 =5 m^3/sec

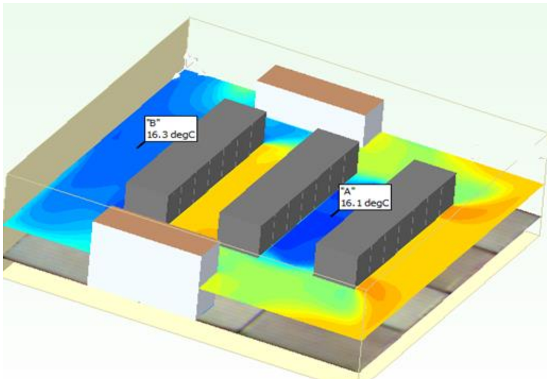
Figure 5. Variation of exergy destruction and SHI at different CRAC flow rates.

This can be observed by comparing two models (d) and (j). Model (d) with CRAC1=1.5 m3/sec and CRAC2=6.5 m3/sec results in minimum exergy destroyed in airspace (661.8 Watt), and model (j) with the combination of CRAC1=4.5 m3/sec and

CRAC2=3.5 m3/sec leads to minimum exergy destruction of 506.8 Watt. Temperature distribution at the height of 1.6 m is presented in Figure 6. It can be seen that for model (j) there is a uniform supply of cold air between the racks where as for model (d) there is certain hot air infiltration is present in the cold aisle leading to an increase in the inlet temperature of racks placed near that region which causes a rise in the exergy associated with these racks (first term in equation (1)) along with increase in their SHI value. It can also be noticed that the maximum temperature in the room for model (d) is higher as compared to model (j). Due to these reasons the exergy destroyed in the air space for model (d) is higher as compared to the exergy destroyed in model (j).



Model (d)



Model (j)

Figure 6. Temperature distribution at a height of 1.6m.

From sensitivity analysis for different CRAC flow rates it is observed that the optimum flow rates of two CRAC units for which we get minimum exergy destruction in the air space are CRAC1=4.5 m^3/sec and CRAC2=3.5 m^3/sec or CRAC1=3.5 m^3/sec and CRAC 2=4.5 m^3/sec. Both configurations give the similar results regarding exergy destruction=506 Watt and SHI=0.08 therefore it is recommended to use either of these combinations.

Conclusions

Application of Exergy analysis on a prototype data centre is presented. A detailed comparison of the First Law based and Second Law based metrics is presented. It is inferred that the optimum parametric design conditions for the data centre operation, can be detected efficiently from considering both Second Law of thermodynamics and the behaviour for the First Law based metric. Variation of the thermodynamics metrics as a function of the CRAC volumetric flow rate is studied. It is shown that applying exergy analysis in data centres can lead to determining an optimal design condition.

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