18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

Thermodynamic Investigation of Raised-floor Air-cooled Data Centres

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Abstract

IT data centres of today consume significant amounts of power which makes thermal management of data centres an extremely challenging task. A detailed thermodynamic analysis of data centres using the first and second laws can be a useful tool in identifying the data centre efficiency. The work presented in this paper describes detailed thermodynamic analysis of an air cooled raised-floor data centre for exploring its optimised performance. Each component of the data centre has been considered as a control volume and thermodynamic laws are applied on each component in order to compute energy losses due to irreversibility. This provides the analytical framework required to design energy-efficient thermal management systems for data centres. Computational fluid dynamics (CFD) is used to build and simulate the flow and thermal fields in the data centre. CFD results have been used to evaluate the exergy destroyed in each of the components (using a purpose-built computer program).

Nomenclature

AE	airspace in the data centre environment
AR	airflow through the racks
C_p	specific heat at constant pressure (J/kg K)
CV	control volume
$\dot{m}$	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
p	processor
r	rack
R	room
w	cooling water
$\dot{W}$	CRAC inlet work

Introduction

IT equipment 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. 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 computer room air conditioning (CRAC) units will have a significant impact on the energy efficiency of the cooling infrastructure. As a result, an efficient thermal management of high-powered electronic equipment is a significant challenge for cooling of data centres. In order to address the issues, various methods of cooling optimisation are being proposed by different researchers, leading to improved cooling efficiencies in the design of data centres [3,7]. Thermodynamic analysis of data centres can be a useful tool in predicting the data centre energy efficiencies [5,6]. In this regard, the concept of exergy was proposed by Shah et al. [8] to analyse irreversibility in data centres.

In previous work [4], exergy destruction of a small-size data centre room airspace was studied. Results show that the locations of irreversibility and losses may be more precisely located using the exergy destruction as compared to the temperature and velocity fields alone. An exergy-based performance metric (EPM) was proposed which leads to a better decision for the application of the rectification design implemented for the data centre layout.

Thermodynamic analysis of the medium-sized data centres needs to be investigated in further detail in order to analyse the effect of hot air recirculation and infiltration as well as the evaluation of the data centre exergetic efficiency. In this paper, thermodynamic analysis of a medium-sized data centre is conducted for the airspace, racks, CRAC units and plenum. From CFD simulation, thermodynamic quantities required for the modelling are estimated. As a result, irreversibility of the main components in the room is obtained. Furthermore, the map of exergy destruction is presented at different heights of the room in order to identify the main locations of irreversibility.

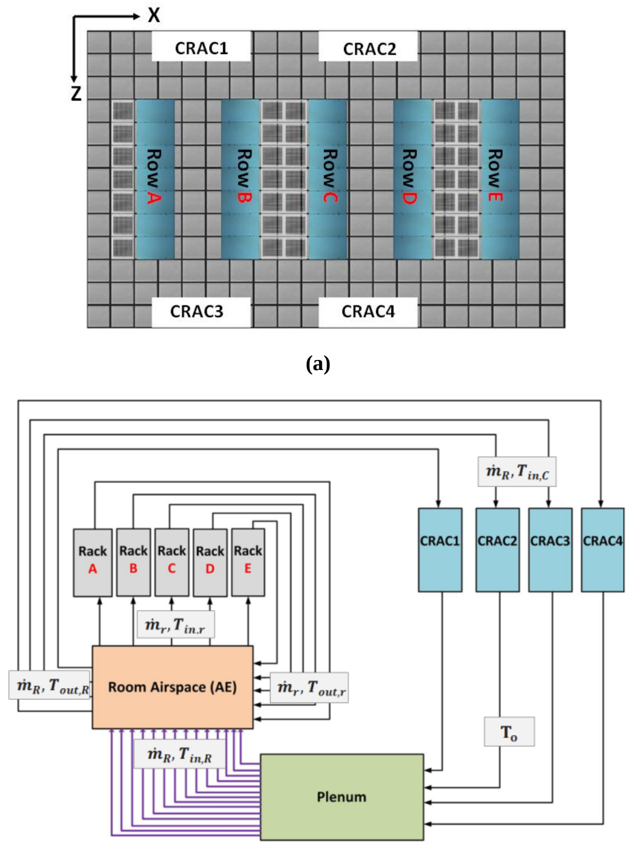
Thermodynamic Analysis

A Typical raised-floor data centre is studied as shown in figure 1(a). The cold air supplied by CRAC units enters the room through perforated tiles. After cooling the server racks, the resultant hot air returns back to the CRAC units and this loop continues. The data centre is assumed as a thermodynamic cycle consisting of four main components, namely the server racks, CRAC units, data centre room and under-floor plenum as shown in figure 1(b). Each component of the data centre has been considered as a control volume and thermodynamic laws are applied on each component in order to compute energy losses due to irreversibility. 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.

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 [2].

Irreversibility in Environment Airspace

Data centre airspace can be divided into two main regions: Data centre environment airspace excluding racks (AE), and airflow inside the rack (AR). AE covers the airspace from the floor to the ceiling excluding the racks.



(a)

(b)

Figure 1. Schematic of the analysed data centre, (a) Top view, (b) Thermodynamic cycle

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

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

Here, the ground state, T_0, is defined in the under-floor plenum adjacent to the perforated tiles.

Irreversibility in Rack Units

Exergy destruction in a rack can be considered as the irreversibility in the airflow through the rack (AR) plus the irreversibility due to conversion of electricity to heat as indicated in figure 2, where the cold air is supplied through the perforated tile to the rack inlet and the hot exhaust air exiting the rack outlet.

The exergy destruction in the airflow through the rack (AR) is calculated from equation (2), which shows the amount of irreversibility in the air layers because of the high temperature gradients in AR. Exergy destruction in the servers, indicated by CV2, is estimated from equation (3) assuming that the heat load is uniformly distributed across the servers.

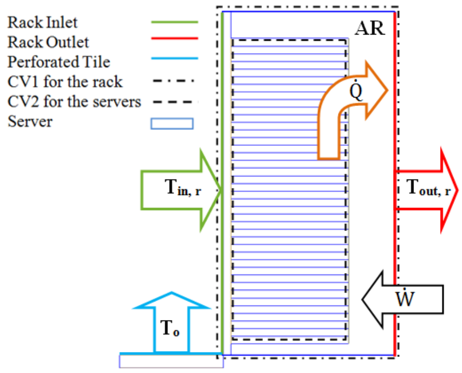


Figure 2. The schematic of the rack unit

$$\dot{\psi}_{d,AR} = T_0 \dot{m}_r C_p \left(ln \left(\frac{T_{out,r}}{T_{in,r}} \right) \right) - \dot{Q} \frac{T_o}{T_p} \tag{2}$$

$$\dot{\psi}_{d,P} = \dot{Q} \frac{T_o}{T_p} \tag{3}$$

Finally, from exergy balance on CV1, total exergy destruction in the rack unit can be estimated from equation (4).

$$\dot{\psi}_{d,r} = T_0 \dot{m}_r C_p \left(ln \left(\frac{T_{out,r}}{T_{in,r}} \right) \right) \tag{4}$$

Irreversibility in CRAC Units

In this study, the STULZ G-type direct expansion CRAC unit is considered for the modelling [9]. In this system heat from DX-circuit is transferred to chilled water by a condenser integrated into A/C unit. The chilled water circulates in closed circuit and emits that heat to outside air by an external dry cooler as shown in figure 3. Irreversibility in CRAC unit can be obtained using following equation:

$$\dot{\psi}_{d,C} = (\dot{\psi}_{in,C} - \dot{\psi}_{out,C}) + (\dot{\psi}_{in,w} - \dot{\psi}_{out,w}) + \dot{W}_{fan} + \dot{W}_{com} \tag{5}$$

The exergy flow for the air stream and the chilled water employed in the CRAC unit is calculated from equation (6). Pressure loss in the system is ignored here. Therefore, the exergy associated with the pressure is zero. The corresponding air inlet temperature ($T_{in,C}$) to the CRAC unit which is the room hot air temperature extracted by the CRAC unit, is obtained from CFD results. Since the air temperature exiting the CRAC unit is same as the temperature of the ground state, the resultant exergy of the cold supplied air ($\dot{\psi}_{out,C}$) would be zero. Temperature of the chilled water entering the CRAC unit is assumed to be 20 ^oC with 5 ^oC temperature increase after gaining heat from the condenser of the CRAC unit as shown in figure 3.

$$\dot{\psi} = \dot{m} \left[C_p (T - T_o) - T_o C_p \, ln \left(\frac{T}{T_o} \right) \right] \tag{6}$$

In order to calculate the exergy associated with the work of the CRAC unit, technical specification data of CRAC units from STULZ manufacturer company [9], has been used. The compressor work is obtained from equation (7), where the coefficient of performance (COP) of the CRAC unit is the function of the CRAC cooling load. Based on the results given by

STULZ company [9], COP of 5 is taken here for all the CRACs. The work associated with the fan as a function of the CRAC supply flow rate ($4m^3/s$), is estimated to be 2.5kW.

$$\dot{W}_{com} = \frac{\dot{Q}}{COP_C} \quad (7)$$

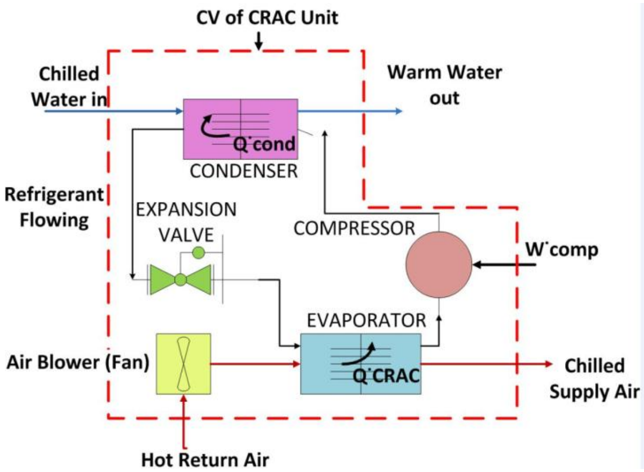


Figure 3. Thermodynamic cycle of the CRAC unit

Irreversibility in Plenum

The exergy destruction in the plenum can be assumed to be zero providing that the following assumptions are met:

- There is no back flow of hot air to the perforate tiles.
- The temperature of the cold air supplied by the CRAC unit is approximately equal to the cold air entering the room through perforated tiles.
- Changes in kinetic energy are negligible.

In the data centre studied here, the obstructions in the plenum are not modelled and the irreversibility is negligible.

Map of Exergy Destruction

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. 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. For mapping exergy destruction in AE, equation (8) 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.

$$\dot{\psi}_{d,i} = \sum_j \dot{m}_j \left[C_p(T_j - T_o) - T_o C_p \ln\left(\frac{T_j}{T_o}\right) + \frac{{V_j}^2}{2} \right] \quad (8)$$

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.

CFD Simulation

The prototype data centre studied here for investigating the irreversibility is shown in figure 4 (also figure 1(a)). The infrastructure is modelled as a 12.6×3.2×7.8m enclosure located over a 60cm deep under-floor plenum. There are four CRAC units with a nominal cooling load of 80kW, which supply cold-air at 16^oC with a fixed flow rate of $4m^3/s$. 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 units. Regions in front and back of the racks, cold aisles and hot aisles, are shown by blue and red boundaries, respectively in figure 4. There are 35 perforated tiles (seven perforated tiles in five rows) , of 0.61m × 0.61m size, in the data centre placed in front of each rack in the cold aisle. There are five rows of seven racks. Each rack is modelled as a 0.6×2×1m cabinet consisting of 5kW heat load, with a 10^oC temperature difference across the rack. Steady state numerical solutions for the velocity and temperature have been obtained using FloVENT v9.2 [1] by Mentor Graphics Mechanical Analysis, 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 530,880 cells were found to be adequate.

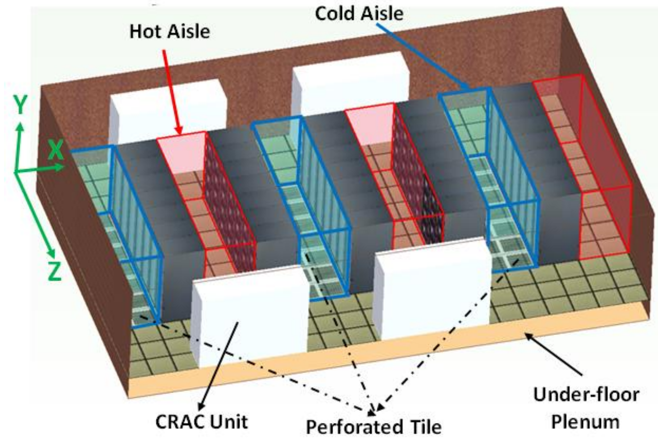


Figure 4. Orthographic view of the data centre

Results

From the CFD analysis, the temperature and velocity are obtained for each cell in AE. Thus, by applying equation (8), the map of exergy destruction is provided. Figure 5 shows exergy destruction fields at three different heights in the room.

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. It is observed that there is higher amount of irreversibility at the end of the rack row because of the hot air infiltration to the cold aisles. By comparing figures 5(a) and 5(b), the mixing of hot air and cold air at the end of the rack rows increases with distance from raised-floor. As seen in figure 5(c), the impact of the hot air recirculation on the exergy destruction is revealed over the top of the rack. 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.

Total exergy destruction in AE is calculated to be 0.96kW by summing up the exergy destruction of all grid cells from equation (8). This is validated by applying equation (1).

The results for the exergy destruction in the rack rows and the CRAC units are given in table 1. Regarding the rack unit, considerable amount of irreversibility occurs in the processors.

Rack Row	Power Input (kW)	$\dot{\psi}_d$ (kW)		
		$\dot{\psi}_{d,r}$	$\dot{\psi}_{d,p}$	$\dot{\psi}_{d,AR}$
A	1	7.2	6.1	1.1
B	3	21.6	18.2	3.4
C	7	50.4	42.5	7.9
D	1	7.2	6.1	1.1
E	5	36.1	30.4	5.7
CRAC No	**CRAC Cooling Load (kW)**	$\dot{\psi}_d$ (kW)		
1	25.5		7.2	
2	35		9	
3	25.5		7.2	
4	35		9	

Table 1. Exergy destruction for the rack rows and CRAC units

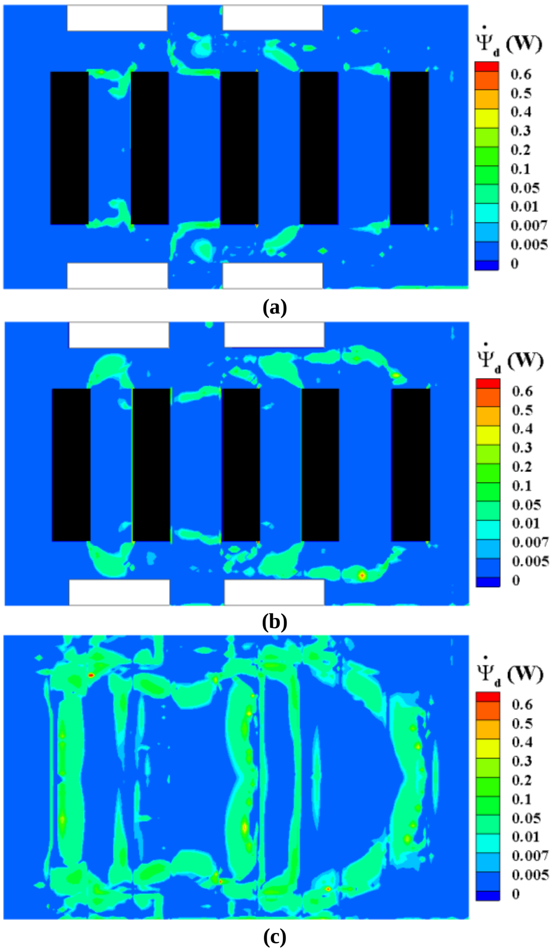


Figure 5. Maps of exergy destruction at (a) y=0.8m, (b) y=2m and (c) y=2.5m

For these calculations, the processor temperature of the servers is taken to be 60°C, and as the processor temperature increases, the portion of the exergy destroyed in AR increases. Exergy destruction in AR shows the amount of irreversibility in the air layers because of the high temperature gradients in AR. The main portion of the exergy destroyed in CRAC units is from the total work input (compressor & fan) to the CRAC unit. In this respect, as the cooling load rises, the corresponding exergy destruction increases as shown in figure 6 for CRAC units 2 and 4 which are placed in the hot region.

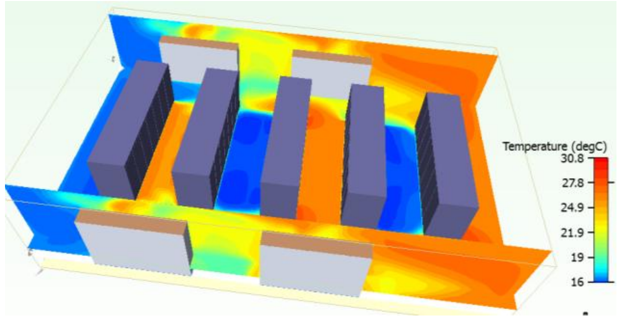


Figure 6. Maps of temperature at different locations in the room

Conclusions

A detailed thermodynamic analysis in the data centre is performed to develop a better understanding of the room irreversibility. A typical data centre is studied as a thermodynamic cycle consisting of four main components. In order to obtain thermodynamic quantities, CFD analysis is performed, and from the resultant thermal and temperature field, the map of exergy destruction is obtained. Results show that areas of irreversibility and loss may be more precisely located using the exergy destruction.

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