<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>Thermal analysis for underground data centres in the tropics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Jiao, Yanmei; Li, Yuanlong; Wen, Yonggang; Wah Wong, Yew; Chuan Toh, Kok; Cheng Chua, Chee; Ang, Wilson</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2017</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/46192">http://hdl.handle.net/10220/46192</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2017 The Authors. Published by Elsevier Ltd. Peer-review under responsibility of the scientific committee of the World Engineers Summit – Applied Energy Symposium &amp; Forum: Low Carbon Cities &amp; Urban Energy Joint Conference.</td>
</tr>
</tbody>
</table>
Thermal Analysis for Underground Data Centres in the Tropics

Yanmei Jiao\textsuperscript{a}, Yuanlong Li\textsuperscript{a}, Yonggang Wen\textsuperscript{a,}\textsuperscript{*}, Yew Wah Wong\textsuperscript{b}, Kok Chuan Toh\textsuperscript{c}, Chee Cheng Chua\textsuperscript{d}, Wilson Ang\textsuperscript{d}

\textsuperscript{a}School of Computer Science and Engineering, Nanyang Technological University, Nanyang Avenue, 639798, Singapore
\textsuperscript{b}Energy Research Institute @ NTU (ERI@N), X-Frontiers Block, Research Techno Plaza, 50 Nanyang Drive, 637553, Singapore
\textsuperscript{c}Temasek Laboratories @ NTU, BorderX Block, Research Techno Plaza, 50 Nanyang Drive, 637553, Singapore
\textsuperscript{d}Infocomm Media Development Authority, 3 Fusionopolis Way #16-22 Symbiosi, 138633, Singapore

Abstract

Different with traditional aboveground data centres, underground data centres have attracted increasing attention during recent years due to its inherent geographical advantages such as zero solar heat gain, low ambient temperature, natural geothermal cooling, and solid rock surrounded structures. The energy reduction in air-conditioning and mechanical ventilation (ACMV) system of the underground data centre is even more significant for the tropical regions where air is hot and humid all the year round. However, little study has been conducted to systematically analyse the relationship between the air-conditioning effectiveness and the corresponding energy efficiency. In this work, both energy simulations and computational fluid dynamics (CFD) simulations are conducted to the underground air-conditioning data centres in the tropics. The former one studies the energy consumption and energy efficiency of the whole ACMV system for a data centre. Meanwhile, the latter one studies the corresponding detailed airflow pattern within the data centre room. Optimizations in air management of the ACMV system are also proposed based on the energy and CFD simulation results.

© 2017 The Authors. Published by Elsevier Ltd.

Keywords: Underground Data Centre; ACMV System; Energy Analysis; CFD Analysis; Air Management
1. Introduction

The dramatically increasing demand for the storage, networking and computing of data centres has made the data centre industry becoming hotter and hotter, especially with the rapid growth in the computer and the electronic technologies (Capozzoli and Primiceri 2015). Therefore, the corresponding electricity consumption in data centre industry is also experiencing surging growth. In 2013, U.S. data centres consumed an estimated 91 billion kWh of electricity. The projected electricity consumption of data centre will increase to roughly 140 billion kWh annually by 2020 (Whitney and Delforge 2014). In Singapore, data centres consumed approximately 6.9% of Singapore’s total electricity usage in 2012. This figure is projected to reach 12% by 2030 with the increasing demand of data centres in Singapore. An average of 37% of the total energy consumption in the data centres is consumed by the ACMV system (Infocomm Media Development Authority Singapore 2014).

In tropical country like Singapore, high temperature and humidity is a major disadvantage which results in more energy consumption to cool the data centre than any other part of the world. To solve this problem, a potential solution is to build the data centre underground. The underground data centres can achieve higher energy efficient as the cooling system is not required to offset solar heat gain from the sun and also benefits from natural geothermal cooling (Miller 2013). Yet the benefits of the underground data centre have not been theoretically validated.

To validate an innovative concept such as the underground data centre here, a simulation analysis approach has become more and more popular due to its efficiency when compared to physical measurement in conducting experiments. With the increase in the capabilities and accuracy of simulation tools, various components in data centre such as ACMV system can be modelled and simulated to study their energy consumption and fluid dynamics. Energy simulations focus on energy consumption and efficiency of ACMV system while computational fluid dynamics (CFD) simulations focus on details of the thermal, velocity and pressure fields of the data centre, i.e., the energy effectiveness.

As for the energy simulations of data centres, Phan and Lin proposed a multi-zone modeling approach to deal with hot and cold aisles in the data centre, which studies the effects of locations and boundary conditions on the data centre energy and thermal performance (Phan and Lin 2014). Ham et al. proposed to use a server model to account for thermal characteristics according to the CPU utilization, which can be applied to the hourly cooling energy consumption simulation of a data centre. Their study simulated modular data centres with high ambient temperature and predicted the corresponding impact on annual cooling energy consumption (Ham et al. 2015). EnergyPlus and DOE-2 have been widely used by the data centre industry to estimate energy consumption and energy efficiency. Hong et al. compared those two software and indicated that both simulation tools are reasonably matched within a range of -0.4% to 8.6% for annual cooling electric consumption. But the study also presented the advantages of EnergyPlus over DOE-2 in the simulation of energy performance of data centres (Hong et al. 2009). In this study, EnergyPlus is utilized to build up the energy model and predict the energy consumption and energy efficiency of the whole ACMV system for both aboveground and underground data centres.

As for the CFD simulations, Sharma et al. conducted a study on the performance optimization of a data centre in aspects including cold and hot aisles, ceiling space, and IT rack loads (Sharma et al. 2002). VanGilder and Schmidt studied on the impact of perforated tile airflow uniformity through CFD models with inputs from the real data centre. (VanGilder and Schmidt 2005). Nada et al. investigated different arrangements of racks and different computer room air conditioning units (CRAC) layouts, as well as different configurations of side and roof top cold aisle containment (Nada et al. 2016, Nada and Said 2017). In this study, 6SigmaDCX is used to create the CFD models and simulate different air management scenarios of a data centre.

In this paper, the thermal analysis of a data centre is to be studied through both energy and CFD simulations. Different data centre configurations and air management scenarios are to be investigated. The energy models are firstly built up to compare the effects of both aboveground and underground environments on energy consumption. The CFD models are subsequently developed to investigate two different air management approaches. Finally, the optimization in air management for the ACMV system of a data centre based on the results from the CFD and energy simulation are summarized and presented.
2. Methodology

The building energy simulation of EnergyPlus are essentially developed based on the energy balance of a control volume such as a room or a thermal zone where the heat generated inside equals the heat removed by the air going through the control volume. The general form of the energy balance in EnergyPlus is given as:

\[
\dot{Q}_\text{load} = \sum_{i=1}^{N_z} \dot{Q}_i + \sum_{i=1}^{N_{\text{surface}}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{\text{mix}}} \dot{m}_i c_p A_i (T_{zl} - T_z) + \dot{m}_\text{inf} c_p (T_\infty - T_z)
\]

where \(\dot{Q}_\text{load}\) is the zone conditioning requirements, \(\sum \dot{Q}_i\) is the sum of the convective internal loads, \(\sum_{i=1}^{N_{\text{surface}}} h_i A_i (T_{si} - T_z)\) is the convective heat transfer from the zone surfaces, \(\sum_{i=1}^{N_{\text{mix}}} \dot{m}_i c_p A_i (T_{zl} - T_z)\) is the heat transfer due to interzone air mixing, \(\dot{m}_\text{inf} c_p (T_\infty - T_z)\) is the heat transfer due to infiltration of outside air, and \(T_z\) is the desired zone temperature as defined by the control system setpoints that must be specified for each zone. As validated in the multi-zone data centre modeling study by Phan and Lin (Phan and Lin 2014), the infrared transparent (IRT) model and the ‘ZoneRefrigerationDoorMixing’ (ZRDM) object are to be used in this study too.

The CFD software, 6SigmaDCX, generates a virtual facility model that can be used to assess and compare new designs, to model and troubleshoot existing facilities, and to provide the basis for ongoing change management. The \(k-\varepsilon\) turbulence model is utilized in the CFD model, which is composed of continuity equation, momentum equation, and energy equation. With applying this solution procedure, a hierarchy of Cartesian grids (i.e., multi-level unstructured grids) and a face to cell connectivity graph to discretize the differential equations (Semin et al. 2015).

3. Results and Discussion

First, the underground boundary conditions for the energy simulation are identified. Institute of Meteorological Service Singapore statistically analyses the data from Changi Climate Station from the year 1982 to 2016, showing that the mean monthly temperature varies from 23.9 °C to 32.3 °C (Meteorological Service Singapore 2016). Since the underground environment is unexposed to the sun and wind, a series of constant temperatures of 20 °C, 24 °C, 28 °C, and 32 °C will be parametrically studied as the underground boundary conditions.

Second, the National Supercomputing Centre (NSCC) of Singapore is selected as our research target. As known that, the National Supercomputing Centre (NSCC) Singapore has been established as a national facility of petascale standard to support high performance scientific and engineering computing needs in Singapore. In order to achieve better cooling performances to this supercomputing data centre, a systematic simulation study on different air management scenarios is conducted to its ACMV system. Since the chilled water, used to cool the NSCC, is achieved from an independent chiller plant, the district cooling mechanism is utilized in this study. The NSCC mainly comprise two sections, the storage section and the supercomputing section. As the supercomputing section is the core part to deal with all the supercomputing tasks sent from all the end users, it is selected as the investigation domain in this study. Generally, there are two kinds of IT racks with dimensions of 2.2m × 0.7m × 1.33m and 2.2m × 0.735m × 1.157m. It is assumed that each IT rack has a power limitation of 12 kW.

For the energy simulations, a multi-zone data centre simulation model is adopted, which has been proved to be able to precisely capture the hot and cold aisles heat transfer and the effects of boundary conditions to the energy usage of a data centre. The energy usages for aboveground data centre directly exposed to outdoor environment and underground data centre with different underground environment temperatures are simulated and compared. In addition, the energy consumed by the underground data centre at different room setpoint temperatures are also studied. As for the CFD simulations, different air management scenarios are investigated. The detailed thermodynamic analyses are conducted and optimization approaches are provided based on the achieved results.
3.1. Energy Efficiency

Within the NSCC data centre, the electricity is mainly consumed by IT racks, ACMV system (including fans, pumps, etc), lighting, and other related supporting facilities. The heat loads mainly come from the components mentioned above. But there is still one important aspect immediately affecting the operation of a data centre, which is the weather, particularly the solar. In this study, the solar effects on the energy consumptions of the aboveground and underground data centres are comparatively conducted. The energy simulation model is shown in Fig. 1. The electricity consumed by the IT load, lighting and other supporting facilities except the ACMV system are summarized as Fig. 2, which is the same for both aboveground and underground data centres.

![Energy simulation model of NSCC.](image)

However, the cooling loads, as shown in Fig. 3, vary with different outdoor conditions. The cooling load of the aboveground data centre fluctuates throughout the year. On the contrast, the cooling loads of the underground data centre are relatively consistent due to the much more stable surrounding boundary conditions. In addition, it is also found that the data centre with lower underground temperature requires less cooling load. According to energy analysis, the cooling loads for underground temperatures of 20 ºC, 24 ºC, 28 ºC, and 32 ºC are 88.83 RT, 89.05 RT, 89.32 RT, and 89.61 RT, respectively.

In addition to the studies on the different boundary conditions, research works are also conducted on the different temperature setpoints. As known that, the recommended dry-bulb temperature for general Class A1 to A4 of data centre is from 18 ºC to 27 ºC (ASHRAE TC 2011). Therefore, four different temperature setpoints, including 18 ºC, 21 ºC, 24 ºC, 27 ºC, are simulated and analyzed. The corresponding district cooling loads at a given supply air temperature of 15 ºC are summarized in Table 1, which shows that: the required district cooling load decreases with
rising the temperature setpoint. In addition, according to thermal balance equation, the cooling load is proportional
to the supply air flow rate and the temperature difference between the supply air from the CRAC units and return air
exhausted from the racks. Compared to low temperature setpoint, the high temperature setpoint induces large
temperature difference of the air stream. Therefore, a low volume flow rate of the supply air stream is required at the
same cooling load requirement, which ultimately reduces the fan energy consumption.

![Fig. 3. District cooling consumptions of aboveground and underground data centres.](image)

Table 1. District cooling load at different temperature setpoints.

<table>
<thead>
<tr>
<th>Temperature setpoint</th>
<th>18 °C</th>
<th>21 °C</th>
<th>24 °C</th>
<th>27 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>District cooling load</td>
<td>89.32 RT</td>
<td>89.12 RT</td>
<td>88.93 RT</td>
<td>88.76 RT</td>
</tr>
</tbody>
</table>

3.2. Effectiveness of ACMV System

In this section, two different air management scenarios are studied, the CFD models of which are shown in Fig. 4.
Generally, all the settings are the same for both scenarios except the different structures of cold aisle containments.
The baseline case, Fig. 4 (a), has a semi-closed cold aisle containment with two slop partitions on the top of the
containment. While the what-if case, Fig. 4 (b), has a cold aisle containment with fully covered top ceiling. In order
to provide uniform supply air through the floor tile, a recommended pressure of 15 Pa is maintained within the
raised floor, which in turn controls the supply air flow rate from the precision cooling unit (PCU). Each row of floor
tiles has a uniform slot angle of 10º to tune and facilitate the supply air to flow into the IT racks.

![Fig. 4. CFD models of NSCC. (a) Baseline case, (b) What-if case.](image)

The simulation results are summarized in Fig. 5. It is seen from the figure that, IT racks of both cases are meet
the temperature requirement of the ASHRAE 2011 for data centres of Class A1, i.e., all the cabinets fall into
acceptable air inlet temperature range from 18 °C to 27 °C. However, the maximum room temperatures for both
cases are significantly different with each other, which are 34.1 °C and 31.1 °C for baseline case and what-if case, respectively. In addition, the two streamline figures at front view show that, the flow paths of the cold supply air for both cases are considerably different. As for the baseline case, although the floor tiles with angled slots give rise to large initial inlet momentum of the supply air through the rack and the slop partitions on the top of the containment intend to block the cold air within the containment, a certain portion of the cold air still escapes from the top opening because the fluid always chooses the less resistance way to go. On the contrast, since the containment of the what-if case is sealed by a flat ceiling, almost all the supplied cold air is forced passing through the IT racks with only limited portion of cold air leaking from the top crack. Therefore, compared to the baseline case, the amount of the cold air effectively passing though the IT racks are much higher for the what-if case. Simulation analysis shows that, the average air flow rates are 0.237 m³/s and 0.388 m³/s for baseline case and what-if case, respectively. Therefore, at the same IT load, the temperature of air exhausting from the IT racks is relatively lower for the what-if case and higher for the baseline case.

Fig. 5. CFD simulation results of NSCC. (a) Baseline case of top view, (b) Baseline case of front view, (c) What-if case of top view, (b) What-if case of front view.

The thermodynamic analysis above shows that, with a good air management strategy, the cold supply air can be effectively utilized at the maximum potential. At this situation, the volume flow rate of the cold air can be reasonably reduced and thus the fan energy can be reasonably reduced by 20% to 25%.

4. Conclusions

Firstly, this work studied the advantages of the innovative underground data centres through comparing the district cooling loads with that required by the traditional aboveground data centres. Results and analysis indicate that: the stable and consistant underground environment, with little effects from the solar and wind, requires relatively stable district cooling loads, which is beneficial to the stability of the ACMV system. Secondly, fan energy can be reasonably saved at high temperature setpoint due to the high temperature difference between the supply and the return air. Thirdly, the thermodynamic analysis on the air managements based on CFD simulations are conducted to study the effectiveness of the ACMV system. Within this section, one improved scenario is also
proposed and simulated for comparison and optimization. Analysis proves that performance of the fully-closed cold aisle containment is significantly superior to that of the semi-closed cold aisle containment due to the strict separation of the cold supply air from the hot exhaust air. Due to the well-organized cold-hot aisle layouts and properly-applied containment, the fan energy can be potentially saved by 20% to 25%.

Acknowledgements

This research work was supported by EIRP02 Grant from Singapore EMA, GDCR01 Grant from Singapore IMDA. The authors also thank National Supercomputing Centre (NSCC) of Singapore for their great support on this work.

References