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A multi-zone building energy simulation of a data center model with hot and cold aisles

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ABSTRACT

In this paper, a building energy simulation code, EnergyPlus, was used to study the effects of wall boundary conditions, climatic locations, supply air temperatures, and volumetric flow rates, on the energy consumption and thermal performance of a popular data center model. The data center model having 1120 servers distributed in four rows of rack was investigated under two major climatic conditions–hot and humid (Miami, FL), and cool and humid (Chicago, IL). A multi-zone modeling approach was proposed to resolve the hot and cold aisles in the data center, and was compared to existing well-mixed single-zone model. Using the multi-zone approach that is believed more reasonable, both monthly and annual overall energy consumptions as well as cooling load were analyzed under various boundary conditions. In addition, monthly thermal behavior in the zones for hot and cold aisles within the data center was analyzed. The simulation results show that thermal performance of the data center is significantly affected by locations or climatic conditions. The effects of location and wall boundary conditions are particularly appreciable during the summer and winter seasons. An optimal supply temperature of 11.8 °C, and air flow rate of 2.5 m^3/s were found to be most preferred selections for the data center model.

1. Introduction

Within the last two decades, the size and load density of data centers have been steadily increasing [1]. As a result of this development, data center energy consumption has become a significant issue. A data center is a facility where the server racks or computer systems are hosted to be used for telecommunications or other purposes. Its infrastructure includes many components, such as uninterruptible power supply (UPS) system, and environment control system (e.g., chiller plant, hot and cold lines, computer room air conditioner, fire suppression). Data centers are constantly powered by redundant or backup power supply. Therefore, its energy consumption is typically huge compared to other building types. It is reported that data centers can consume up to 100 times more energy than a standard office building [2].

According to the US Congress [3], the Environment Protection Agency (EPA) has estimated that over 100 billion kWh at a cost of $7.4 billion would be consumed by 2011 by the data centers. Beside the demanding electricity to power up IT equipment (e.g. server hardware, storage, UPS, etc.), the major factor that accounts for these costs is the cooling electrical energy consumption in the data centers. Nowadays, power usage effectiveness (PUE) is a common method to calculate a data center's energy usage. It is defined as a ratio: (total electric power)/(server power). The total electric power consists of server power, cooling power, and power distribution losses. Typically, the value for PUE is close to 2, which also means that the cooling power takes up to 50% of the total electric energy consumption in a modern data center [4].

Energy and thermal management in data centers is still an underlying problem in terms of both effectiveness and efficiency, although many techniques were proposed for performance improvement [5–7]. In the past, IT equipment is organized with great levels of randomness in most data centers, resulting in low energy efficiency [8–10]. In modern data centers, hot and cold aisles are the common practice for isolating hot and cold air plumes to prevent the air mixing, which results in effective thermal management and high energy efficiency [5,7,11]. With the popularity of computational tools, data center performance improvements are more and more reliant on computer-based modeling and simulations, due to their cost effectiveness and quick turnaround time as compared to physical experiments or data collection.

Among the modeling and simulation approaches, computational fluid dynamics (CFD) programs can be used as analytical tools to obtain detailed thermal/fluid transport information inside

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the data center, such as air velocity and temperature distributions, thermal comfort, as well as indoor air quality [5,7,11]. Building energy simulation (BES) programs, on the other hand, can be used to obtain information on the overall performance of the whole building. BES can also provide information on the sizing of the heating, ventilating and air conditioning (HVAC) system and the consumption of electrical energy on an hourly or sub-hourly basis. Although CFD programs are able to provide three-dimensional thermal fields, their limitations in practical applications are still present in terms of meshing, running time, and computational resources, particularly for transient problems. The BES programs, though giving less detailed results inside the building, can provide quick insights into the overall building energy behavior with change of time [12–16].

A literature survey shows that although building energy simulation can be used to estimate annual energy consumption of any building, its application in data centers has been very limited in the open literatures. Hong et al. [17] compared the HVAC simulations between EnergyPlus and DOE-2.2 for a data center. They found that annual cooling electricity consumptions calculated from both programs were reasonably matched within a range of −0.4% to 8.6%. In another study, Pan et al. [18] utilized EnergyPlus to compare the energy saving options of two office buildings housing IT equipment in Shanghai, China. They have found that the proposed design options can save energy up to 27% from China Code buildings and 21% from AHSRAE budget buildings. These existing studies demonstrated the feasibility of using BES code in data center analysis. However, all of the previous studies have adopted the well mixed single-zone approach, without considering the existence of hot and cold aisles in the data center. Considering the importance of the hot and cold isles in thermal management, the authors believe a modeling approach that resolves the existence of the isles could be more reasonable in the energy simulation. Also to our knowledge, data center thermal and energy performance under different boundary conditions have not been investigated systematically. Recognizing the importance of modern data centers, it is obvious that more studies on data center's performance are required using an improved data center modeling approach.

The objectives of this paper are to first develop a more reasonable simulation model for data center in order to resolve the hot and cold isles, and then apply the developed model to perform systematic studies of data center's thermal and energy performance under different conditions. Specifically, a new multi-zone modeling strategy was proposed for a popular data center model that has both hot and cold aisles. A parametric study using the BES code, EnergyPlus, was carried out to investigate the effects of five different surface boundary conditions (surface exposures) on the cooling electricity consumption and the zone mean air temperature in the data center. The studies were carried out for two typical U.S. climates: hot and humid (Miami, FL), and cool and humid (Chicago, IL). In addition, the effects of both supply temperature and volumetric flow rate of the supply side were investigated.

Nomenclature

C_p	Zone air specific heat (J/g K)
C_T	Sensible heat capacity multiplier
ρ_{air}	Zone air density (kg/m^3)
$\dot{Q}$	Total heat extraction rate (W)
$\dot{m}$	Mass flow rate (kg/s)
A	Area of surface (m^2)
C_z	Air capacitance(J/m^3 K)
h	Convective heat transfer coefficient (W/m^2 K)
N	Number of enclosure surfaces
q	Heat flux (W/m^2)
T	Zone temperature, surface temperature (K)

Greek Symbols

δ	Partial derivative
η	Fraction of the time step
σ	Stephan Boltzmann constant

Subscripts

1-2	Between surface 1 and 2
2-3	Between surface 2 and 3
3-4	Between surface 3 and 4
∞	Outside air
desired	Desired temperature
i	Index of enclosure surfaces
inf	Infiltration, surrounding air
load	Zone load
sup	Supply temperature
sys	System
z	Zone

2. Data center modeling

2.1. Data center description

In this paper, the data center model investigated was adopted from the one that has been used by several investigators in previous studies [19–22]. In those works, the model was used for the studies of other aspects of the data center, rather than energy simulation. The dimension of the data center is 40′ × 12′ × 30′ (12.2 m × 3.66 m × 9.14 m). The data center has a total of 1120 server blades which are distributed into four rows of rack unit. Each row consists of seven 40 U rack units (1 U equals 45 mm) as shown in Fig. 1. There are four CRAC (computer room air conditioner) units placed in the middle of four different walls. The CRAC units supply cooling air at 55 F (12.8 °C) from the pressurized 2-foot raised floor plenum. The data center was configured using the current best practice of hot and cold aisles. The server racks are placed in such a way that their back sides are facing each other to form hot aisles, while the front sides, which receive cooling air from the perforated floor tiles, form cold aisles.

In this study, the load density of the data center model consisting of IT equipment and lighting load was specified to be 100 W/ft^2 at all time (totally 8760 h a year) based on a previous study by Hong et al. [17]. The HVAC system used was a packaged single zone (PSZ) direct expansion (DX) system. It has air-cooled condenser, constant supply fan, but has no humidity control as well as air-side economizer. Similar to the load schedule, the fan schedule was also assumed to be on at all time. The current geometrical model was created using Google Sketchup tool, then transferred to EnergyPlus to perform building energy simulation.

The main focus of this paper is to use a multi-zone model (to be described in the next section) to divide the computer room into

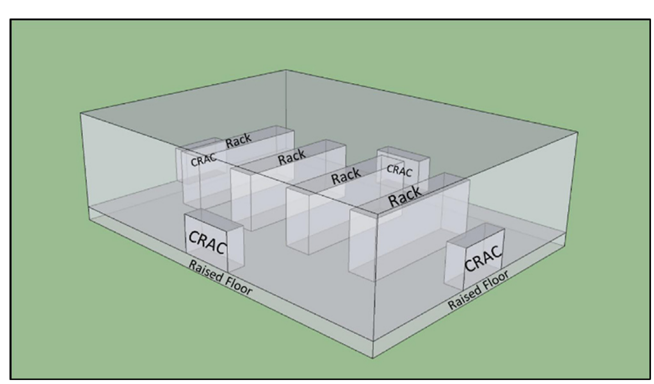

Fig. 1. 3D data center model.