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A dynamic compact thermal model for data center analysis and control using the zonal method and artificial neural networks

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HIGHLIGHTS

- The developed compact zonal model accurately describes the data center temperature and airflow patterns.
- The zonal model is well-suited for feeding into thermal control system in real time.
- The ANN–GA based PID controller yields improved control accuracy and efficiency.

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ABSTRACT

Full-scale data center thermal modeling and optimization using computational fluid dynamics (CFD) is generally an extremely time-consuming process. This paper presents the development of a velocity propagation method (VPM) based dynamic compact zonal model to efficiently describe the airflow and temperature patterns in a data center with a contained cold aisle. Results from the zonal model are compared to those from full CFD simulations of the same configuration. A primary objective of developing the compact model is real-time predictive capability for control and optimization of operating conditions for energy utilization. A scheme is proposed that integrates zonal model results for temperature and air flow rates with a proportional–integral–derivative (PID) controller to predict and control rack inlet temperature more precisely. The approach also uses an Artificial Neural Network (ANN) in combination with a Genetic Algorithm (GA) optimization procedure. The results show that the combined approach, built on the VPM based zonal model, can yield an effective real-time design and control tool for energy efficient thermal management in data centers.

1. Introduction

Today, the energy consumption of data centers is driving considerable research to achieve better energy efficiency through optimal thermal management in a wide variety of data center configurations for a broad range of operating conditions. Efficient thermal management requires real-time prediction of airflow and temperature distributions and the results must be sufficiently accurate to build a reliable control system. Generally, fully three-dimensional, physics-based flow and temperature modeling using CFD cannot be conducted in real time. The CFD simulations require the use of turbulence models which significantly increase the number of unknowns. In order to incorporate CFD models into control strategies, time-dependent simulations will often be required.

At present, control systems for thermal management are often designed using relatively simple volume averaged compact models (e.g., well-mixed nodal approach). However, it is well-known that the temperature distribution in certain server inlet regions can be sensitively affected by hot air recirculation from the server outlets. The resulting inlet temperatures in the hotspot zones are significantly different from the temperature of the cooling air entering through the perforated floor tiles. This undesirable inlet temperature variation throughout the data center cold aisle space might be significant. This temperature variation is not typically sensed by the air conditioning control systems, and this results in incorrect control actions.

Ideally, an accurate control system requires a compact model to compute the airflow and control the temperature in a more precise way. Proper Orthogonal Decomposition (POD) has been used to optimize data center cooling [1–3]. POD is capable of providing predictive capability for thermal analysis. However, more generalizable compact models that are capable of extrapolation to a broad range of configurations and operating conditions are needed. Zonal

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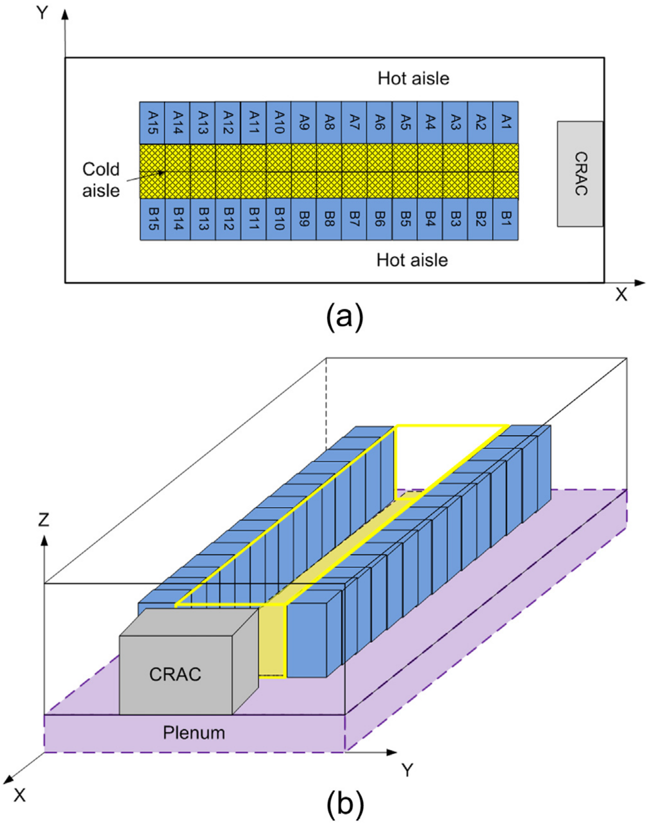

Fig. 1. Data center configuration.

models are regarded as a physically based intermediate approach between CFD and a multi-node lumped model. They are capable of taking various transport phenomena into consideration, such as thermal advection, conduction and radiation in order to calculate energy transport and temperature distributions. The zonal approach applied in Ref. [4] gives reasonably accurate airflow and air temperature results for simple rectangular geometries in 2D and 3D. The model was easily incorporated into a modular simulation and control environment and requires very little computation time. A complex conduction problem was studied in Ref. [5], which demonstrates how the zonal technique can be used for both steady and transient problems. The zonal model in Ref. [6] was formulated to describe the cooling process of distribution transformers. Different generations of zonal models have been developed over the last two decades for applications in building energy usage and ventilation. A momentum zonal model based on the inviscid Euler equations was developed to improve building load and energy simulations by predicting indoor airflows and temperatures [7]. This approach was also employed recently to predict physical parameters in HVAC studies, such as the combination of a system employing both air conditioning and natural ventilation for large enclosures [8,9]. The study reported in Ref. [10] showed some advantages of zonal modeling over coarse-grid CFD and Fast Fluid Dynamics (FFD). A velocity propagating zonal method was developed and implemented using Modelica to characterize the airflow and temperature patterns in an isothermal room [11]. The broad range of applications indicates that zonal models may be used to predict the flow distribution and spatial temperature variation for the relatively complex room configurations seen in data centers. To the best of our knowledge, this work is the first attempt to utilize the VPM zonal method to develop a compact model for dynamic thermal analysis and control in data centers.

2. Data center computational model

In order to develop the zonal model, first a model for a basic raised floor data center configuration was built and analyzed using the commercial, finite-volume CFD software package FloTHERM. Different views of the data center model configuration are shown in Fig. 1. The room has a single computer room air conditioning (CRAC) unit located on the right end. The cooling air from the CRAC is delivered through the plenum (outlined in purple) into the cold aisle. The present study focuses on the use of cold aisle containment (outlined in yellow). Two rows of fifteen server racks are located on either side of the center cold aisle. The server racks are modeled as solid wall enclosures with inlets and exits using air resistances, uniform heat sources and internal fans with specified flow rates. Solid walls are used to model the cold aisle containment. The total airflow demanded by all of the racks is equal to the CRAC supply (100% provisioning). The height of the CRAC and the server racks is 2.1 m. The cold aisle consists of two rows of perforated tiles. Air resistance modeling was used to characterize the flow distribution through the perforated tiles. The room is 11 m long by 4.2 m wide and is 3.3 m high from the top of the raised floor to the ceiling. This single cold aisle room configuration is similar to one previously analyzed by Patankar [12] using a different CFD software package. In the model, the lower part of the CRAC is a source that provides a constant flow rate of air (4.71 m^3/s) at a specified temperature (13 °C) into the under floor plenum, while the same amount of air returns via the top of the CRAC from the room.

For the CFD calculations, a finite-volume approximation of the Reynolds-averaged Navier–Stokes and energy equations with the standard k–ε turbulence model is solved. Buoyancy effects are included, but otherwise constant properties for air are assumed. A mesh sensitivity study was performed using the tile flow rate and CRAC outlet temperature to assess the accuracy of the calculation. The optimum mesh (a good trade-off between accuracy and computation time) in the model consisted of 353,696 grid points in the 3D computational domain. Note that the grid spacing in the overall domain is non-uniform, with finer resolution near the boundaries. The minimum grid spacing was 0.013 m, and the maximum grid spacing was 0.026 m. This grid level was used to obtain all of the CFD data to the numerical comparison with zonal modeling.

3. Zonal method

Zonal models are able to predict pressure, temperature and mass flow rates based on integrated forms of conservation laws and different modes of thermal transport [13,14]. The fundamental conservation laws are applied to each zonal volume. The usual form of the conservation laws are written as follows:

$$\sum_j \dot{m}_{j\to i} = 0 \tag{1}$$

$$\sum_j \phi_{j\to i} + \phi_{\text{source}} = \rho_i V_i c_p \frac{\partial T_i}{\partial t} \tag{2}$$

$$P_i = \rho_i R T_i \tag{3}$$

$$\dot{m}_{j\to i} = \rho_{j,i} A \cdot C_{\text{d}} \left(P_j - P_i\right)^n \tag{4}$$