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Numerical simulation on a thermal management system for a small data center

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ABSTRACT

A system with optimum thermal control and noise control is proposed to allow placement of servers at workspace for low operation office cost. A computational fluid dynamics (CFD) model is developed to predict the air flow and temperature distribution of the system. To improve the accuracy of the simulation, the geometry of the axial-flow fan is reproduced in detail and the rotor region is treated with the multiple reference frame model. A porous model is applied to describe the hydraulic and thermal behavior of the evaporator. The integrated system simulation model is validated by measurements. Four layouts of fans are proposed to analyze the airflow organization and temperature distribution. The inhomogeneity of the temperature field is quantitatively evaluated via information entropy and variance. The results reveal that the airflow organization scheme avoids the occurrence of an evident stagnant zone or a hot spot. There are low-velocity zones with insufficient heat transfer in the evaporator. Increasing the number of fans can improve the heat transfer and result in a more uniform temperature distribution. Setting up ventilation fans to increase the ventilation rate of the server is an effective way to meet the challenges of higher heat density.

1. Introduction

Data centers are widely used in various industries where high-speed data processing is necessary, and are diverse in scale based on the computing requirements. For telecom operators, banks, and market transactions, data centers usually contain multiple racks with thousands of servers. For individuals or a small enterprise, several servers are sufficient to satisfy the computational requirements.

The thermal management in data centers is always a serious challenge. An appropriate thermal management in a data center should be able to reduce the energy consumption and maintain a uniform temperature distribution. Air cooling and liquid cooling are common methods for thermal management of data centers. And air cooling is a more common method. For a large-scale data center, standardized computing rooms are designed to provide an individual controlled working environment for the data center. Computer room air-conditioning (CRAC) units [1] provide cool air to the server racks through the perforated tiles placed over the underfloor plenum. Generally, the CRAC units adopt vapor compression refrigeration cycle system. Since the computer room is usually without staff, the design of cooling is preferable to noise reduction. Considering the optimal cooling, it is recommended that the acoustic attention module not be used [2].

For a small-scale data center containing only a few servers, an independent placement space will increase the operation cost. However, the considerable noise and heat from the server, particularly the former, seriously affect the personnel working in the same space. Epidemiologic studies show that annoyance in offices is considerable at equivalent sound levels above 55 dB. A few studies show that 35–40% of office workers are highly annoyed at noise levels from 55 to 60 dB [3]. Due to the mobility of staff, the data center might need to be moved. Therefore, for a small data center functioning in an office environment, the packaging architecture may be required for cooling, noise reduction, and mobility.

Commercially available blade packaging systems include HP C-Class blades, IBM BladeCenter, and Dell PowerEdge blade servers. The BladeCenter system is a widely used server packaging architecture for servers. It is a high-density and rack-mounted design to provide complete redundancy of power, cooling, and a midplane to support a high level of availability [2]. A typical IBM eServer BladeCenter consists of 14 servers in a 7U (1U = 44.45 mm) vertical space for installation in an industry-standard rack. The cooling of the BladeCenter system is realized by two blower module. Two reverse-impeller variable-speed blowers draw air from the front

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Nomenclature

S	source term of the momentum equation, N/m^3
D	prescribed matrices of the primary term
F	prescribed matrices of the secondary term
V	velocity of the airflow, m/s
u	x component of the velocity, m/s
v	y component of the velocity, m/s
w	z component of the velocity, m/s
P	pressure, Pa
h	average heat transfer coefficient, W/(m^2·K)
I	the number of nodes in circumferential direction
J	the number of nodes in radial direction
K	the number of nodes in thickness direction
$\dot{m}$	flow rate, kg/s
c_p	specific heat of air, J/(kg·K)
A	total heat transfer area, m^2
T_{in}	average inlet temperature, °C
T_{out}	average outlet temperature, °C
T_f	average fluid temperature, °C
T_w	tube wall temperature, °C
N_u	Nusselt number
Pr	Prandtl number
Re	Reynolds number
a	constant
b	constant
c	constant
D_t	outer diameter of the tube, m
U_∞	inlet average velocity, m/s
H_{local}	local heat transfer coefficient, W/(m^2·K)
S_{ex}	heat transfer area per unit volume of the evaporator, m^2/m^3
x_i	temperature of the grid, °C
$p(x_i)$	probability distribution of the temperature
$E(X)$	mathematical expectation of the temperature field, °C
$R(X)$	variance
$H(X)$	information entropy

Greek symbols

μ	viscosity, Pa·s
ρ	fluid density, kg/m^3
λ	thermal conductivity, W/(m·K)

Subscripts

in	inlet
out	outlet
t	tube
ex	heat exchanger

of the system and exhaust it out the rear. The blower impeller size is 175 mm, and both blowers at full speed can provide a volume flow of 0.215 m3/s. The high airflow rates result in an acoustic noise threat. A BladeCenter chassis generates 74 dB [4]. An audio measurement indicated that the blower module have a dominant tone in the range of 140–490 Hz determined by the fan speed. And the dominant tone is the most perceptible and annoying to the human ear [5]. An acoustic attention module (a muffler) provides a 5 dB reduction in noise but results in an approximate 5% reduction in cooling capability. Guthridge et al. [5] proposed an acoustic noise cancellation technique by offsetting the phases of a pair of blower fans. Total reduction in the overall noise spectrum was negligible. Although dominant tones that are the most perceptible to a human ear are eliminates, the noise level after improvement has not been explained.

It is obvious that the concept of BladeCenter cannot solve the contradiction between noise and cooling. And the BladeCenter has no independent refrigeration system. It relies on the extra CRAC for heat dissipation. The CARC is fixed in the room, so the server cannot be moved. Therefore, a thermal management integrating noise reduction, different from the BladeCenter system, is necessary to allow the small data center to function in an office environment.

Numerical simulation is an important research method for thermal management of data centers [6–14]. Many published researches are concerned about thermal management simulation for large-scale data centers. A data center usually contains components such as servers, fans, and heat transfers. Considering that the geometric scale of components is much less than that of the data center. Components cannot be modeled in detail but are simplified in the simulation. Some researchers did not model the axial-flow fan and blade servers, instead the rack was treated as a cuboid box with assigned flow and heat generation rates [6–8]. However, the actual airflow from the axial-flow fan has a swirling flow. It does not flow normal to the fan plane but at an angle. Song [11] applied a 3D compact fan model to create a fan-assisted component, and the details of the fan blade are still not considered. The swirl speed was introduced according to the empirical relationship described by Papst. Besides, the flow and heat transfer details inside the CRAC are not considered. Furthermore, for a small data center, the scale difference between components and the enclosure is not significant. The flow and heat transfer details inside the component cannot be neglected. To acquire a more accurate prediction of flow and heat transfer, the simulation model in the present study preserves the details of components as much as possible. It introduces the fan blade to capture the swirl flow of the axial-flow fan. The inhomogeneous flow and heat transfer in the heat exchanger are also considered.

Fan modeling techniques, such as sliding mesh, the single and multiple reference frame (MRF), and lumped fan model, are frequently used in the electronic industry. The sliding mesh is the most accurate of these techniques with expensive computation cost [15]. Both the lumped fan model and MRF are computationally inexpensive. The lumped fan model is a highly simplified fan model. The fan geometry is a planar rectangular or circular shape. The lumped fan model only applies the continuity equation and the "pressure heat – flow rate" fan curve between the upstream and the downstream faces of the "fan plane" [16]. MRF is a steady-state approximation in which individual cell zones can be assigned different rotational and/or translational speeds. The flow in each moving cell zone is solved using the moving reference frame equations [17]. The fan blade is modeled in detail, and it can acquire a significantly larger swirl numbers compared to the lumped model. The comparison of flow characteristics shows that the MRF fan model approach is more representative of the fan prototype than that of the abstract fan model [18]. Compared with experiments, the accuracy of vector flow fields predicted by a MRF fan model is better than the lumped fan model [19]. Zhou and Yang [20,21] applied MRF and RNG k-ε to perform the design for CPU fan and heat sinks system. The fan curve of numerical simulation is in good agreement with the experimental data from a standard wind tunnel. The discrepancy between the results of CFD and experiment is within 8%.

It is impossible to model the heat transfer in detail in an integrated thermal management simulation. The heat exchanger has