Renewable and Sustainable Energy Reviews 43 (2015) 981–996

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Advances in data center thermal management

Yogesh Fulpagare, Atul Bhargav*

Energy Systems Laboratory, Indian Institute of Technology Gandhinagar, VGEC Campus, Chandkheda, Ahmedabad, GJ 382424, India

A R T I C L E I N F O

Article history:
Received 18 March 2014
Received in revised form
2 November 2014
Accepted 8 November 2014

Keywords:
Data center
Thermal management
Heat dissipation
Performance metrics

A B S T R A C T

With the increase in electronic traffic, heat generated by electronic equipment, and the concomitant costs of powering cooling systems in electronic data centers are increasing continually. Various research groups working in academic institutions, research laboratories and industries have been applying a variety of tools to study and improve performance of data centers. This paper reviews recent contributions to the state of knowledge in data center thermal management. First, we review numerical and experimental studies on the most common air-cooled raised floor plenum type data centers. We then summarize published research on rack layout, efficiency and performance metrics for data centers, dynamic control and life cycle analyses, and validation of numerical models. Finally, we review some recently proposed cooling strategies and numerical optimization efforts. We find that the research carried out on thermal management of data centers has helped improve performance in many instances (such as rear door water cooled heat exchanger type rack), and has helped establish some physics-based criteria for data center designers. Based on the trends observed in this review, we expect further improvements to all aspects of data center design and operation in the near future, with a focus on real-time measurement & control, model validation and heuristics based optimization. In addition, some significant changes such as thermal energy storage and smart-grid capabilities are also expected to be incorporated into data center control strategies.

Contents

1. Introduction

Most large and medium business enterprises depend on some kind of data center usage, in addition to millions of individual users who access online content on the world wide web [1]. The most important requirement for a data center is uninterrupted, zero downtime operation. An interruption caused by equipment

* Corresponding author. Tel.: +91 814 030 7813; fax: +91 792 397 2324.
E-mail addresses: fulpagare_yogesh@iitgn.ac.in (Y. Fulpagare), atul.bhargav@iitgn.ac.in (A. Bhargav).

http://dx.doi.org/10.1016/j.rser.2014.11.056
1364-0321/

Nomenclature

ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
c	specific heat, kJ/kg K
I	Computational Fluid Dynamics
I	Cubic Foot per Minute
CRAC	Computer Room Air Conditioning
DC	data center
DCN	Data Center Networks
DRHx	Dry Cooler with Rack Heat Exchanger
EASE	Evaporative Air Side Economizer
EDRHx	Evaporative Dry Cooler with Rack Heat Exchanger
EPA	Environmental Protection Agency
ERE	Energy Reuse Effectiveness
GA	Genetic Algorithm
HT	heat transfer
HTS	Highest Thermostat Setting
HVAC	Heating Ventilation and Air-Conditioning
IASE	Indirect Air Side Economizer
ILP	Integer Linear Programming
IT	information technology
LPM	Liter Per Minute
m	mass flow rate, kg/s
MMT	Mobile Measurement Technology
NN	neural network
OH	overhead supply and returns
$P_{Cooling}$	power spent on cooling devices, kW
$P_{DataCenter}$	total power consumption of a data center, kW
P_{IT}	power spent on computing, storage, network equipment, kW
P_{reuse}	reused power, kW
PDU	Power Distribution Unit
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
PTFRD	Perforated Tile Flow-Rate Distribution
PUE	Power Usage Effectiveness
$\dot{Q}$	heat removal rate by coolant, kW
RFP	raised floor plenum
SHI	Supply Heat Index
SLA	service level agreement
STD	raised floor plenum supply
T_{in}	inlet temperature, K
T_{out}	outlet temperature, K
TEC	thermoelectric coolers
UPS	Uninterrupted Power Supply

failure would entail costly repairs and replacement. However, even more serious is the prohibitive cost of business interruption. Therefore, for uninterrupted operation, reliability of power and electronic cooling become crucial. During the last ten years, increasing demand for computer resources has led to significant growth in the number of data center servers, along with an estimated doubling in the energy used by these servers and the power and cooling infrastructure that supports them [2]. The increase in energy use includes increased energy costs for business and government, increased emissions, including greenhouse gases, from electricity generation, increased strain on the existing power grid to meet the increased electricity demand, and increased capital costs for expansion of data center capacity and construction of new data centers. According to 2006 USEPA estimates, 1.5% of the total United States' electricity consumption of 6 billion kWh was attributed to data centers (an increase from previous estimates [2]). To put this usage in a global perspective, this electricity consumption equaled Congo's electricity consumption in that year [3]. This goes on to show the importance of conservation and management of energy usage in data centers.

In 2011, ASHRAE developed a new set of guidelines [4] that helped categorize data centers (Fig. 1), thereby providing data center operators an opportunity to optimize energy efficiency and reliability to suit their particular business needs. High construction costs have forced data centers to maximize floor space utilization, with the use of higher power density racks. Several heat dissipation challenges result from this trend of packing higher computing power into available space. A large number of recent investigations have used numerical, experimental and CFD analysis on data centers thermal performance. A comprehensive review of these investigations conducted over the past decade is presented here in subsequent chapters.

The various modeling efforts have ranged from individual component modeling to rack and power layouts and can be classified into the following main categories:

1. Raised floor plenum (RFP) airflow modeling
2. Rack layout with thermal analysis and power distribution
3. Energy efficiency and thermal performance metrics

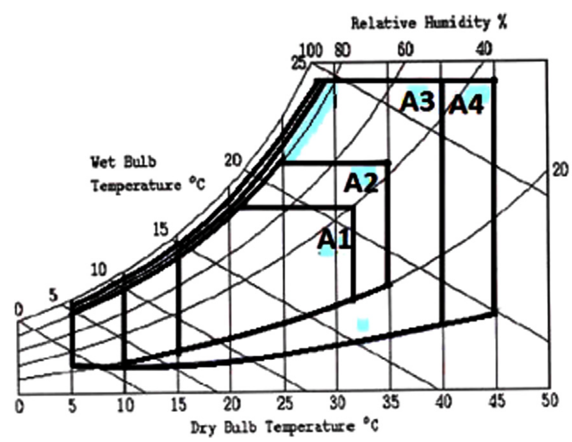

Fig. 1. ASHRAE environmental classes for data centers (Adopted from [4]).

4. Data center dynamics: control and lifecycle analysis
5. Model validation
6. Data center cooling strategies
7. Programming based optimization of Data Center

Previously, Bash et al. [5] focused on the immediate and long term research needs for efficient thermal management of data centers. Schmidt et al. [6] and Rambo et al. [7] had reviewed the literature dealing with various aspects of cooling computer and telecommunications equipment rooms of data centers to explore factors that affect cooling system design, and to improve or develop new configurations for electronic cooling, thereby improving equipment reliability. In this paper, we have retained the categories mentioned in this work, while making conscious attempts to divide the literature so as to minimize overlap between categories.

1.1. Raised floor plenum (RFP) models

A very commonly used standard raised floor plenum and room return cooling scheme airflow schematics is shown in (Fig. 2).