CFD-Based Operational Thermal Efficiency Improvement of a Production Data Center

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ABSTRACT

Effective cooling of data centers presents a dual challenge: increased cooling power to meet the ever increasing device heat loads, and the need for energy efficient cooling. Detailed analysis of the thermal and flow conditions within a data center are necessary for obtaining optimal design and operational parameters. This paper describes the application of a computational fluid dynamics (CFD) based model in a production data center for improving its operational efficiency. The model used in the present work is based on conjugate heat transfer and fluid flow at data center level. The effect of heat dissipation from racks, and thermal and flow conditions at perforated tiles are bought into the model through boundary conditions. The model is rigorously validated by comparing simulation results with actual measurements. Extensive parametric studies have been performed, and key issues, resulting in mixing and ineffective cooling, have been identified. Several design and operational changes have been recommended in terms of placement of blanking panels, operation of CRAC units, and operating set-points. These recommendations have been implemented at the data center, resulting in energy savings to the tune of 20%. Further, the model has been used extensively for obtaining guidelines for efficient ramping up of the data center.

Key Words: **Computational Fluid Dynamics, Production Data Center, Energy Efficiency, Thermal Management**

I. INTRODUCTION

Energy usage in data centers has increased tremendously in the past few years primarily due to the widespread use of high heat-density equipments. Studies have indicated that cooling management now accounts for a major chunk of the energy usage in most data centers. Rising electricity costs and environmental concerns on carbon emissions have brought into focus the need to rapidly improve energy usage efficiency.

Efficient usage of energy in a data center depends on effective thermal management at various length scales. As described by Choi, et al. [1], heat transfer in a data center can be considered at three levels of granularity (a) processor and disk level, (b) rack level and (c) room level. In most cases, the design of data center at room level is based on simple energy balance through consideration of maximum heat loads and equivalent air-conditioning capability. However, as pointed out by Patel, et al. [2] And Rambo and Joshi [3], this approach is inadequate and thermal and flow conditions need to be considered in the design of an efficient data center.

Substantial work has been done on modeling of data centers in the past few years. A comprehensive review on thermal modeling of data center has been presented by Rambo and Joshi [3]. The problem of improving energy efficiency has been looked at from different perspectives by several researchers [3-25]. It is clear from these studies that the CFD-based models are ideally suited to model and optimize complex thermal and flow patterns present in most of the present day data centers. These studies clearly demonstrate the usefulness of various models in identifying hot spots, providing layout modifications, and providing design and operational solutions for efficient and reliable operation of data centers. However, there have been very few studies reported in literature where CFD-based models have been employed for the improvement of a production data center.

In this work, we carry out CFD analysis of a mid-size, partially filled, data center (~3000 sq. ft). Model-based recommendations are used to obtain guidelines for efficient operation as well as ramping up of the data center.

II. INFRASTRUCTURE FACILITY AND MEASUREMENTS

The operational facility had around 40% of its equipment in place, and was in the process of being ramped up to its full capacity. The general layout of the facility, computing equipments, and CRAC details are shown in Fig 1. The computing equipment in the data center was divided into three general types: blades server racks, HP SuperDome™ systems, and storage/network equipment racks. The room dimensions were 30m x 12.1m x 2.34m, with a total of 75 racks in place. The racks were set up in the hot/cold aisle arrangement, as shown. The cold plenum was divided into two sections, with one section devoted to the blade server racks and the network racks, while the other supported the SuperDome and storage racks. Standard perforated tiles (50% opening) were used. Heated air from the equipment was transported back to the CRACs through a hot plenum (false ceiling). Each high density blade server rack contained three blade enclosures. The total planned IT capacity of facility was above 400kW; with the average power consumption per rack as high as 12 to 14 kW.

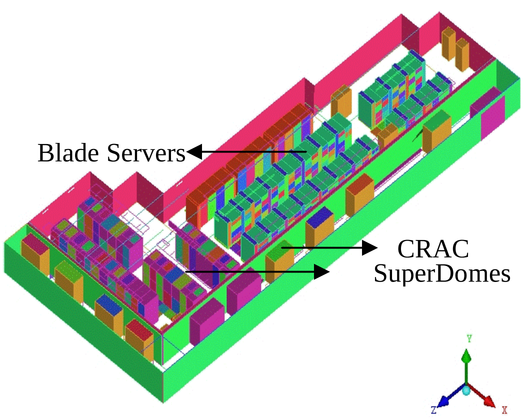
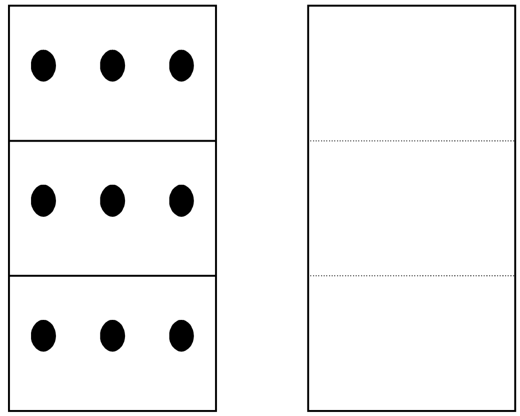


Fig. 1. Isometric geometrical view of the operational data center.

A total of eight CRAC units were installed in the facility. In addition to these, a special set 24 of in-row cooling facility (XDH units) were also installed to provide extra cooling to the high density blade servers. Each CRAC unit was controlled by its return-air set temperature, and therefore, the supply temperature typically varied within a window of 2 to 3 °C over a period of 30 minutes.

As a part of the study, extensive temperature measurements were carried out manually with the help of calibrated hand held thermocouples. For each rack, air temperature measurements were obtained at 18 locations, 9 each front and back with 3 measurements at each top, middle and bottom locations (on both sides of the rack, as shown in Fig. 2). Temperature and velocity measurements (with the help of anemometer) were also carried out at various tiles openings. These data were used in model calibration and validation.



Front view Cold aisle side Side view Hot aisle side

Fig. 2. Details of measurement locations at racks.

III. MATHEMATICAL MODEL

Considering the wide variety of equipments and layouts possible, the aim of the present work was to develop a model that could handle a range of configurations with relative ease, and thereby become an integral part of the design modification of data centers. A major challenge was to ensure that the energy transfer between equipments at multiple geometric length scales was effectively simulated. The production data center considered in this study is partially filled and is in the process of gradual ramp-up. The focus of simulation was on providing design/operational guidelines required for improving energy efficiency for its server-centric equipments. The guidelines relate to layout/airflow modifications required for efficient functioning of the cooling system, while ensuring prevention of hot-spot formation.

A. Modeling Framework

Energy transfer in a data center occurs over a large range of length scales, ranging from around 0.001m at processor level, to over 50m at the room level. Effective capturing of physical phenomena at different length scales, and ensuring proper inter-scale energy transfer makes the setting up of thermal model challenging. The accuracy of the solution depends on how well the heat transfer mechanisms that exist between the server, rack, and room level models are simulated. Inclusion of various length scales in a single framework is computationally prohibitive. In the present work, the concept outlined by Tang and Joshi [4] is used in the modeling framework.

Using commercial software ANSYS CFX^{TM}, the air-flow and heat transfer were modeled using the Reynolds Averaged Navier-Stokes equations (RANS) for mass, momentum and energy balance. The power-law upwinding scheme was used to descretize the convective terms in the equations, and SIMPLEC algorithm was used for solution of momentum and continuity equations.

Flow through the data processing equipment was considered as forced convection. Instantaneous variations in heat sources and air-flow were considered mild, and the system was approximated to be at steady state.

For the present simulations, rack level modeling has been carried out by dividing each rack into three parts. Volumetric heat sources were then applied corresponding to the actual types of servers present at different locations. Appropriate fan boundary conditions were also applied to model the air-flow realistically.

B. Modeling Methodology

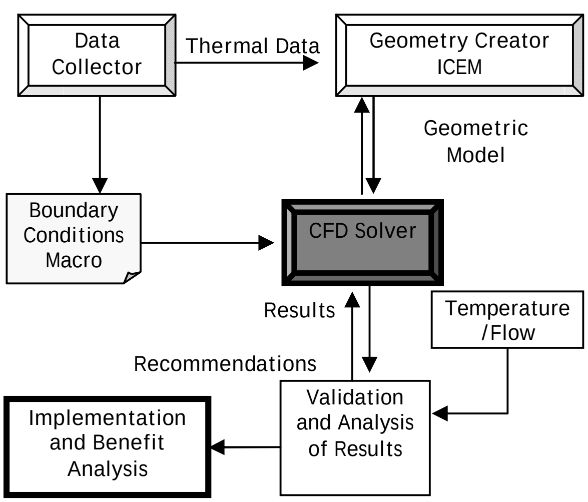


Fig. 3. Overview of the modeling procedure.

Fig. 3 shows the overall modeling methodology. Details pertaining to geometrical layout of equipments, relevant thermal loads, instantaneous operational conditions pertaining to the production data center were collected. Using the geometrical details, a 3-dimensional layout of the data center was created with the help of ICEM, a pre-processor package from ANSYS-CFX^{TM}. While creating the geometry, important details at room and rack levels were considered. The geometric model was subsequently meshed using hexahedral elements. Fig. 4 shows the overall hexahedral mesh of the Data center containing wire hangers, beams, columns and other details. The data center geometry was divided into four parts room, rack, plenum (cold+hot) and CRAC room to reduce the unnecessary mesh count. Total mesh count for the simulations was over one million (1.1million) with quality of all elements being more than 0.9. Mesh files from ICEM were loaded into CFX pre platform and necessary boundary conditions were incorporated. The computational solution for the above problem setup was generated through the CFX –Solver and results for different parametric studies were carried out. This whole modeling through implementation process took nearly six months to get the optimum design and operational modifications.

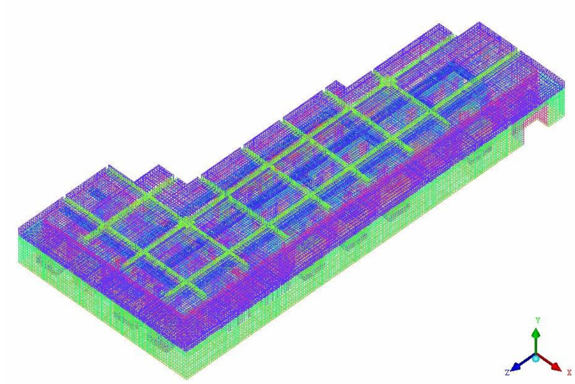


Fig. 4. Isometric view, overall mesh of the Data Center containing beams, columns and wire hangers.

Special cares were taken to incorporate thermal and flow parameters at CRAC, tiles and rack into the model with the help of appropriate boundary conditions and heat sources. While lumped heat-source type rack models have been employed in past, those are useful only in a restricted sense. As explained by Rambo and Joshi[3], there is thermal variation inside the rack due to recirculation. In this study, accurate temperature variations inside racks were taken into account by dividing them into several iso-flux planes, and then applying pressure-velocity relationships for each subdivided volume [3]. Since this is computationally expensive, each rack was divided into only three iso-flux planes and then modeled by applying pressure jump at each sub-volume inlet and outlet locations. Fan curves were used for each sub-volume of the rack by taking into account the actual type, number and CFM of the fans in each server.

Velocity boundary conditions were specified at cold and hot tiles using a data based model for tiles geometry. The data for this sub-model was generated through detailed flow modeling of tile geometry. It was assumed that the computer room air-conditioning (CRAC) units supplied air at a constant flow rate, and the corresponding flow inlet and outlet boundary conditions were employed. The velocities at CRAC inlets and outlets were determined using the following heat balance equation:

$$Q_d = m_c c_p \Delta T \qquad (1)$$

Where, Q_d is the CRAC net power, m_c is CRAC net mass flow rate, ΔT is the temperature change across the CRAC unit.

Considering the large number and repetitive nature of the boundaries, an automation macro was developed for setting up the boundary conditions. The simulations were then executed using ANSYS-CFX™ solver.

C. Model Tuning and Validation

Using the velocity data, parameters related to fan curve and tiles flow were fine-tuned. Subsequently, the model was extensively validated with temperature measurements obtained under different load conditions of production data center.

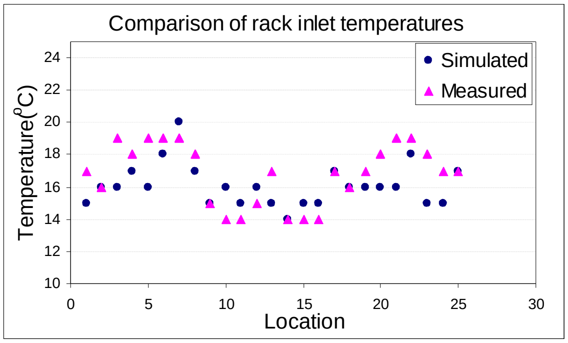


Fig. 5. Comparisons of simulated and measured temperature at the mid points of rack inlet.

Comparisons between average measured temperatures (average of three temperatures taken along rack width at same height) and averaged simulated temperature are shown in Fig. 5 and 6. The overall match at the inlet and outlet of the racks, shown in these figures are satisfactory. The standard deviation for the difference between the simulated and measured temperatures at all the locations (both rack inlet and outlet) is 2.5 °C. Overall, 80% of the data points are within ± 3 °C and 94% of the data points are within ± 4 °C. Considering that these comparisons are made in a production data center of medium size and the analysis is carried out with the help of a steady state model, the performance of the model is satisfactory. It should be noted that some variations between measured and predicted temperature values are on account of variation in AC supply temperature (due to AC cycling, the supply temperature varies by 2 to 3 °C over a period of time and this effect can be brought into the model through transient analysis).

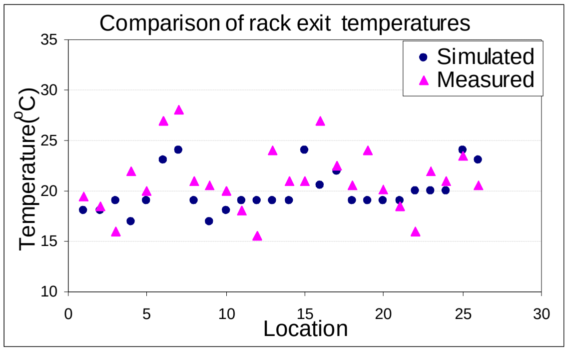


Fig. 6. Comparisons of simulated and measured temperature at the mid points of rack outlet.

IV. PARAMETRIC STUDIES

Using the validated model described above, a detailed parametric study was carried out for the production data center. Before the presentation of results of various parametric studies, the simulated results for the base configuration are discussed. The cold air temperature, supplied by CRAC, is kept at 16°C in this simulation.

Fig. 7 shows the pressure changes at rack inlets and outlets on a horizontal plane. The pressure drop at the rack inlets is due to the resistance provided by the rack grill and server inlets, and the pressure increase at the outlets is due to the server's induced draft fans. This modeling framework links pressure conditions inside to pressure conditions outside the rack. It should be noted that this pressure coupling is not possible if racks are treated as black-box.

Fig 8 shows velocity vectors on a typical vertical plane drawn across the racks. It is clearly seen that cold air starts from the CRAC outlet and is transferred to the server room through the cold plenum. This cold air then passes through various servers, picks up the heat, escapes through the hot tiles, and finally returns to CRACs through the hot plenum. It should be noted from this figure that there are couple of locations near top of the racks where air mixing is clearly seen. Mixing of hot air and cold air is also observed while analyzing horizontal sections of data center.

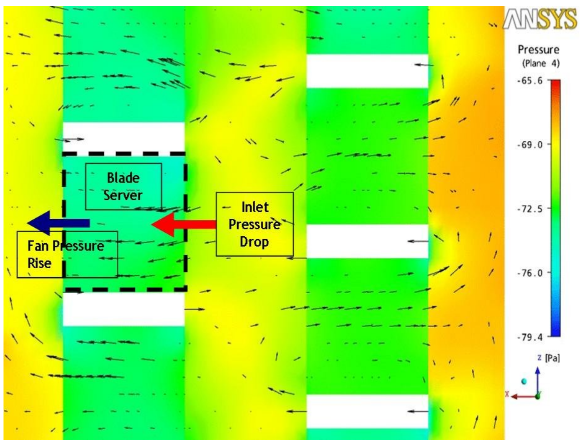


Fig. 7. Pressure Contours (Reference of 101325 Pa) (Top View Horizontal plane at height 0.9m).

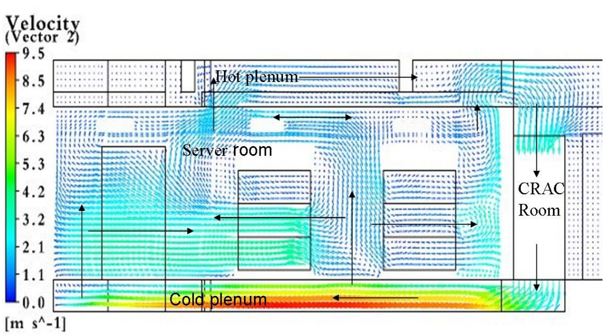


Fig 8. Velocity vectors at vertical plane across racks.

Fig 9 shows overall thermal profile of the data center on a horizontal plane at a height of 0.9m from the false floor. In this figure, the positions of cold aisles are marked as C1 to C6, and hot aisles are marked as H1 to H7. It is clearly seen form this figure that there are overcooled as well as overheated zones present on this plane. Of particular interest in this figure are the hot-spots (between H2 and H3, for example), generated due to the mixing of hot exhaust air with cold inlet air. This indicates that the particular rack near hot spot is either starved of cold air, or does not have a proper hot air removal path.

To investigate this aspect further, Fig 10 shows velocity vectors at the entry and exit of racks on the same plane (this figure is at a higher resolution and shows only part of Fig. 9). This figure is able to demonstrate the reverse flow due to presence of completely or partially empty racks. Overall, there is presence of high level of mixing of hot air with cold air, leading to inefficient operation of data center.

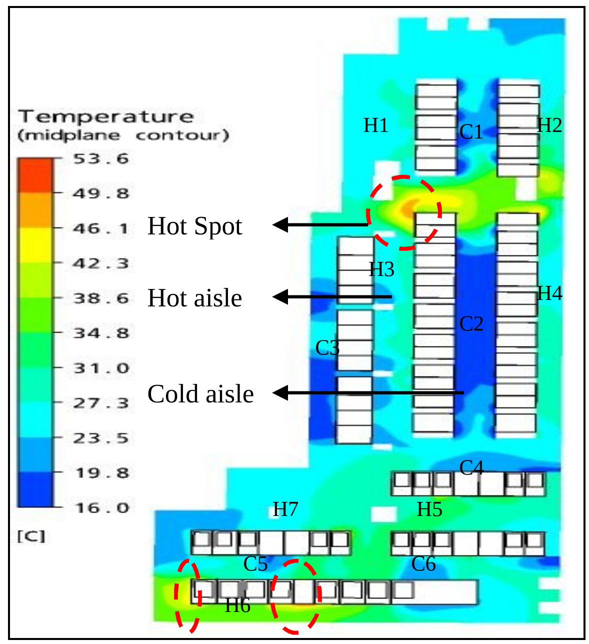


Fig.9. Thermal profile at horizontal plane, vertical height 0.9m and supply Temperature 16 ^{o}C.

To minimize the mixing related problems, parametric studies were carried out with provisions for blanking panels on partially filled and empty racks. Results from these simulations clearly showed that mixing at various locations could be minimized with introduction of blanking panels. With reduction in mixing, further simulations were performed with increased supply temperature from CRAC. Thermal profile for base configuration is compared with modified configuration (with blanking panels and increased supply temperature by 2 ^{o}C) in Figs. 11a and 11b. Results clearly demonstrate that with blanking panels in place, a 2 ^{o}C increase in the CRAC supply temperature leads to only marginal increase in the hot air temperature. Since the data center was only partially filled, there were numerous locations where provision for blanking panels could be recommended.

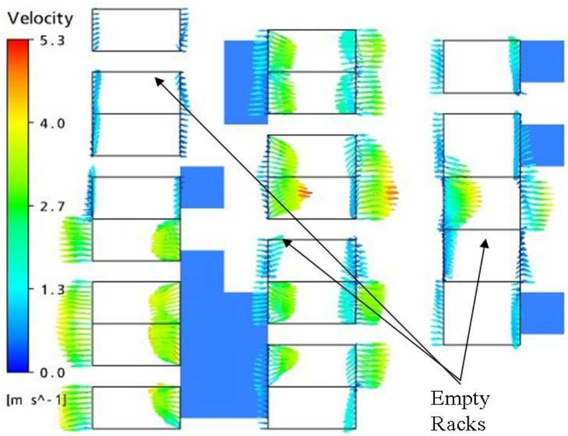


Fig. 10. Velocity vectors at inlet and exit of racks.

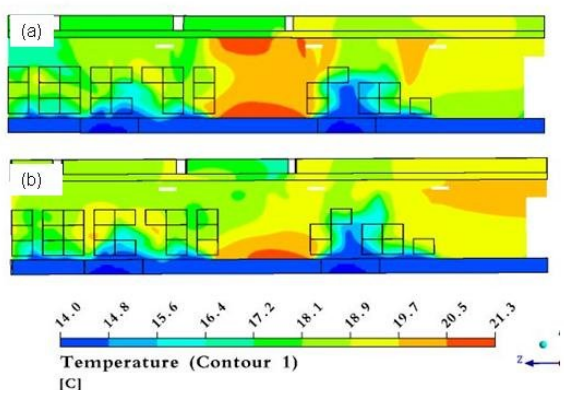


Fig. 11. Temperature contours at vertical plane between rack rows: (a) without panel and supply temperature 14 ^{o}C (b) With panel and supply temperature 16 ^{o}C.

Simulations on tile placement changes were also carried out, and the findings resulted in improvements in the inlet air flow at many racks. Issues of air leakage at some locations inside the data center were also identified and sorted out.

With all of the modifications suggested by the above parametric studies put in place, one of the CRAC units and some of the in-row units were identified for shut down, without affecting the overall cooling scenario in the data center. Energy savings to the tune of 20% were actually observed at the data center after the recommendations were implemented.

In addition to the technical issues, there was also a need for developing a systematic ramp-up plan for the data center, so that best possible locations for next set of servers to be added could be identified, both from the point of view of cooling efficiency, and to prevent hot-spot formation. Several simulation studies were carried out to draw the ramp up plan for data center and the same were shared with data center manager.

VI. SUMMMARY AND CONCLUSIONS

A CFD based model was developed for a partially filled production data center. The model was rigorously validated with temperature measurements. Detailed parametric studies were carried out which helped in identification of problems and potential solutions. Several recommendations were obtained from these studies which included provision of blanking panels, optimum placements of tiles in cold aisles and increase in supply temperature from CRAC units. These recommendations were implemented in the data center resulting in 20 % savings of energy cost. Further, the model was used extensively for obtaining guidelines for efficient ramping up of the data center.

VII. REFERENCES

[1] J. Choi, Y. Kim, A. Sivasubramaniam, J. Srebric, Q. Wang and J. Lee, “A CFD-based Tool for Studying Temperature in Rack-mounted Servers,” *IEEE Transactions On Computers*, vol. 1, pp. 1-17, 2007.

[2] C. D. Patel, C. E. Bash, C. Belady, L. Stahl and D. Sullivan, “Computational fluid dynamics modeling of high compute density data centers to assure system inlet air specifications," *Presented at Proc. IPACK'01 - The Pacific Rim/ASME International Electronics Packaging Technical Conference and Exhibition*, Kauai, HI, 2001.

[3] J. Rambo and Y. Joshi, “Thermal Modeling of Technology Infrastructure Facilities: A Case Study of Data Centers,” *The Handbook of Numerical Heat Transfer, 2nd ed.,* W. J. Minkowycz, E. M. Sparrow, and J. Y. Murthy, eds., Taylor & Francis, New York, 2006, pp.821-849,.

[4] L. Tang and Y. Joshi, “A Multi-Grid Based Multi-Scale Thermal Analysis Approach for Combined Mixed Convection, Conduction, and Radiation Due to Discrete Heating,” *Transactions of ASME Journal of Heat Transfer*, vol. 127, pp. 18-26, 2005.

[5] K. Karki, A. Radmehr, S. Patankar, “Use of computational fluid dynamics for calculating

flow rates through perforated tiles in raised-floor data centers," *International Journal of Heating, Ventilation, Air-Conditioning, and Refrigeration Research*, vol. 9, pp. 153-166, 2003.

[6] R. Schmidt, E. Cruz, M. Iyengar, "Challenges of data center thermal management," *IBM Journal of Research and Development*, vol. 49, No. 4/5, pp. 709-723, 2005.

[7] R. Sharma, C. Bash, C. Patel, R. Friedrich, J. Chase, "Balance of Power: Dynamic Thermal Management for Internet Data Centers," *IEEE Internet Computing*, vol. 9, pp. 42–49, 2005.

[8] C. E. Bash, C. D. Patel, R. K. Sharma, "Dynamic Thermal Management of Air Cooled Data Centers," *presented at Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*, San Diego, CA, 2006.

[9] T. Boucher, D. Auslander, C. Bash, C. Federspiel, and C. Patel, "*Viability of Dynamic Cooling Control in a Data Center Environment," Journal of Electronics Packaging*, vol. 128, pp. 137-144, 2006.

[10] E. Samadiani, Y. Joshi and F. Mistree, "The thermal design of a next generation data center: A conceptual exposition," *Journal of Electronic Packaging*, Vol 130, pp.1104 - 1112, 2008.

[11] A. J. Shah, V. P. Carey, C. E. Bash and C. D. Patel, " Exergy Analysis of Data Center Thermal Management Systems," *Journal of Heat Transfer*, Vol 130, pp. 1401-1411, 2008.

[12] R. K. Sharma, C. E. Bash, C. D. Patel, "Dimensionless Parameters for Evaluation of Thermal Design and Performance of Large Scale Data Centers," *AIAA2002-3091, American Institute of Aeronautics and Astronautics Conference*, St.Louis, MO, 2002.

[13]C. E. Bash, C. D. Patel and P. K. Sharma, "Efficient Thermal Management of Data Center - Immediate and Long-Term Research Needs," *Intl. J. Heat, Ventilating, Air-Conditioning and Refrigeration Research Needs*, Vol. 9, pp. 137–152, 2003.

[14] J. Cho, T. Lim and B S. Kim, "Measurements and predictions of the air distribution systems in high compute density (Internet) data centers," *Energy & Buildings*, Vol 41, pp. 1001-1116, 2009.

[15] J. F. Karlsson and B. Moshfegh, "Investigation of indoor climate and power usage in a data center," *Energy and Buildings*, Vol. 37, pp. 1075–1083, 2005.

[16] C. Patel, D. R. Sharma, C. E. Bash and A. Beitelmal, "Thermal Considerations in Cooling Large Scale High Compute Density Data Centers," *presented in Eighth Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM '02)*, San Diego, CA, 2002.

[17] C. D. Patel, C. E. Bash, R. K. Sharma, A. Beitelmal, R. J. Friedrich, "Smart Cooling of Data Centers," *IPACK2003-35059, The PacificRim/ASMEInternationalElectronics packaging Technical Conference and Exhibition (IPACK'03)*, Kauai, HI,2003.

[18] M. H. Beitelmal and C. D. Patel, "Thermo-Fluids Provisioning of a High Performance High Density Data Center," *HPL 2004-146 (R.1), HP Lab. Technical Report*, 2004.

[19] S. V. Patankar and K. C. Karki, "Distribution of Cooling Airflow in a Raised-Floor Data Center," *American Society of Heating, Refrigerating, and Air-Conditioning Engineers transaction.(ASHRAE)*, vol 110, pp. 629-635, 2004.

[20] M. Beitelmal and C. Patel, "Thermo-Fluids Provisioning of a High Performance High Density Data Center," *Internal Report, Palo Alto, HP Laboratories*, 2004.

[21] R. Sharma, C. Bash, C. Patel, R. Friedrich and J. Chase, "Balance of Power: Dynamic Thermal Management for Internet Data Centers," *IEEE Internet Computing*, Vol. 9, pp. 42–49, 2005.

[22] L. Tang and Y. Joshi, "A Multi-Grid Based Multi-Scale Thermal Analysis Approach for Combined Mixed Convection, Conduction, and Radiation Due to Discrete Heating," *Transactions of the ASME*, Vol. 127, pp. 18-26, 2005.

[23] K. Karki, A. Radmehr and S. Patankar, "Use of computational fluid dynamics for calculating flow rates through perforated tiles in raised-floor data centers," *International Journal of Heating, Ventilation, Air-Conditioning, and Refrigeration Research*, Vol. 9, pp. 153-166, 2003.

[24] X. Zhang, M. Iyengar, J.W. VanGilder and R R. Schmidt, "Effect of rack modeling detail on the numerical results of a data center test cell", ITHERM. Vol 31, pp. 1183 – 1190,2008.

[25] S. McAllister, , V P. Carey, , A C. Shah and C. Patel, "Strategies for effective use of exergy-based modeling of data center thermal management systems," *Microelectronics Journal*, Vol 39 , pp. 1023-1029, 2008.